

# Four problems related to maximal green sequences

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# Abstract

## Four problems related to maximal green sequences

A dissertation presented to the Faculty of  
the Graduate School of Arts and Sciences of  
Brandeis University, Waltham, Massachusetts

by Ying Zhou

Maximal green sequences were invented by Bernhard Keller and have a lot of applications in cluster algebra and particle physics. In this dissertation I will discuss four separate topics related to maximal green sequences. First of all I will discuss the problem of associated permutations of mutation sequences and establish a formula for the associated permutation in the case of  $A_n$  straight orientation which answers a question by Muller. Secondly I will introduce the concept of  $m$ -maximal green sequences and discuss the problem of  $m$ -maximal green sequence-finiteness of path algebras of tame quivers which generalizes a result by Brustle, Dupont and Perotin. Then I will introduce two alternative definitions of  $m$ -maximal green sequences of hereditary algebras and show that they are both equivalent to the known ones which extends a result by Igusa. Finally I will discuss the problem of maximal green sequences in quivers with multiple edges and fully describe maximal green sequences of quivers with multiple edges which is the first step towards a proof of the conjecture that all acyclic quivers have finitely many maximal green sequences.

# Contents

<b>Abstract</b>	<b>v</b>
<b>1 Background</b>	<b>1</b>
1.1 Notations . . . . .	1
1.2 Quivers and path algebras . . . . .	2
1.3 Mutations, mutation sequences and the associated permutation . . . . .	5
1.4 Bounded derived categories . . . . .	13
1.5 Tame quivers and tame hereditary algebras . . . . .	23
1.6 Wall-and-chamber structures . . . . .	29
<b>2 Permutation</b>	<b>34</b>
2.1 The general theory of permutations . . . . .	34
2.2 The associated permutation in $A_n$ . . . . .	37
<b>3 Tame path algebras are green sequence-finite</b>	<b>43</b>
3.1 Introduction . . . . .	43
3.2 Proof of Lemma 3.1.2 . . . . .	45
3.3 Proof of Lemma 3.1.3 . . . . .	47
3.4 Almost morphism finiteness . . . . .	49
<b>4 Two alternative definitions of <math>m</math>-maximal green sequences</b>	<b>53</b>
4.1 Introduction . . . . .	53
4.2 Alternative definition of the stability condition on module categories . . . . .	54
4.3 Maximal backward $Hom^{\leq 0}$ orthogonal sequences . . . . .	57
4.4 Harder-Narasimhan filtration . . . . .	58
4.5 Equivalence of the definitions . . . . .	63
<b>5 Quivers with multiple edges</b>	<b>65</b>
5.1 Introduction . . . . .	65
5.2 MGS-finiteness . . . . .	67
5.3 The acyclic case . . . . .	69

## *CONTENTS*

5.4	The general case . . . . .	75
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# Chapter 1

## Background

### 1.1 Notations

In this paper  $k$  is an algebraically closed field, all algebras will be finitely dimensional  $k$ -algebras. All modules are assumed to be right modules. When the category we are discussing is clearly  $\mathcal{C}$   $(M, N)$  will be an abbreviation of  $Hom_{\mathcal{C}}(M, N)$ .  $(M[> 0], N)$  is the union of  $(M[k], N)$  for all  $k > 0$ . If  $\mathcal{P}, \mathcal{Q}$  are subcategories  $D^b(\Lambda)$  then  $(\mathcal{P}, \mathcal{Q}) := \bigcup_{M \in \mathcal{P}} \bigcup_{N \in \mathcal{Q}} (M, N)$  and  $(\mathcal{P}[> 0], \mathcal{Q}) := \bigcup_{k > 0} (\mathcal{P}[k], \mathcal{Q})$ . Let  $S$  be a set of objects in an additive category  $\mathcal{C}$ .  $add(S)$  is defined as the set of all elements of  $\mathcal{C}$  such that they are finite direct sums of objects in  $S$ .  $\mathcal{E}(X)$  is the extension closure of  $X$ .

The definition of green and red are consistent with that of [24] and [5]. It is the exact opposite definition of green and red in [6].



## 1.2 Quivers and path algebras

### 1.2.1 Quivers

**Definition 1.2.1.** A *quiver*  $Q$  is a quadruple  $(Q_0, Q_1, s, t)$  with  $Q_0$  and  $Q_1$  sets and  $s, t: Q_1 \rightarrow Q_0$ . An element of  $Q_0$  is a *vertex* of  $Q$ . An element of  $Q_1$  is an *arrow* of  $Q$ .  $s$  maps each arrow to its source and  $t$  maps each arrow to its target.

Intuitively we can think of elements of  $Q_1$  as oriented edges. Any arrow has a unique source and a unique target both of which are vertices. This is how we obtain the  $s$  and  $t$  maps. Unless necessary we generally omit the  $s$  and  $t$  and denote a quiver by  $Q = (Q_0, Q_1)$ .

**Example 1.2.2.**  $1 \longrightarrow 2$        $1 \xleftarrow{\quad} 2 \longrightarrow 3$        $1 \longrightarrow 2 \longrightarrow 3$

These three are quivers.

Now we need to define subquivers.

**Definition 1.2.3.** A *subquiver*  $Q' = (Q'_0, Q'_1, s', t')$  in a quiver  $Q = (Q_0, Q_1, s, t)$  is a quiver such that  $Q'_0 \subseteq Q_0$ ,  $Q'_1 \subseteq Q_1$ ,  $s|_{Q'_1} = s'$  and  $t|_{Q'_1} = t'$ .

From now on we generally do not distinguish between  $s$  and  $s'$ ,  $t$  and  $t'$ .

Not all quivers are useful for the purpose of this paper. This is why we need to add restrictions. In order to do so we need to introduce several definitions.

**Definition 1.2.4.** An *oriented cycle* in a quiver  $Q$  is a subquiver  $Q' = (Q'_0, Q'_1, s, t)$  such that  $Q'_0 = \{v_0, v_1, \dots, v_{k-1}\}$ ,  $Q'_1 = \{a_0, a_1, \dots, a_{k-1}\}$ ,  $s(a_i) = v_i$ ,  $t(a_i) = v_{i+1}$ . Here  $v_k$  is defined as  $v_0$ .

## CHAPTER 1. BACKGROUND

**Definition 1.2.5.** A *k-cycle* is an oriented cycle with  $k$  vertices.

**Definition 1.2.6.** A *loop* in a quiver  $Q$  is an arrow from a vertex to itself, that is, a 1-cycle.

**Definition 1.2.7.** A *cluster quiver* is a quiver without loops or 2-cycles.

In all but Chapter 4 and a part of Chapter 5 all quivers we discuss will be acyclic. Here is the definition of an acyclic quiver.

**Definition 1.2.8.** An *acyclic quiver* is a quiver without any oriented cycles.

### 1.2.2 Path Algebras

**Definition 1.2.9.** A *path* in a quiver  $Q$  is a sequence of vertices  $\{v_0, \dots, v_k\}$  and a sequence of arrows  $\{a_0, \dots, a_{k-1}\}$  if  $k > 0$  such that  $t(a_i) = v_{i+1}$ ,  $s(a_i) = v_i$  for any  $i = 0, 1, \dots, k-1$ . The source of the path is  $v_0$  and the sink is  $v_k$ .

Paths with length 0 are known as *trivial paths*. A trivial path only has a single vertex  $v_0$  and no arrows at all. All other paths are uniquely determined by their arrows.

Now we need to define multiplication of paths. In order to do so we need to define compatibility and concatenation.

**Definition 1.2.10.** Paths  $v, w$  are *compatible* if  $t(v) = s(w)$ .

**Definition 1.2.11.** The *concatenation* of compatible paths  $v = \{a_0, \dots, a_{k-1}\}$  and  $w = \{b_0, \dots, b_{l-1}\}$  is  $vw = \{a_0, \dots, a_{k-1}, b_0, \dots, b_{l-1}\}$ .

**Definition 1.2.12.** The *path algebra* of a quiver  $Q$  is a  $k$ -algebra generated by all the paths of the quiver. Multiplication of paths  $v$  and  $w$  is defined as the concatenation if they are compatible and 0 if they aren't,

## CHAPTER 1. BACKGROUND

From a homological point of view path algebras are very nice, namely they are *hereditary*. In other words their global dimensions are at most one.

**Theorem 1.2.13.** *The path algebra  $kQ$  of any acyclic quiver  $Q$  is hereditary. That is, for any  $M, N \in \text{mod } kQ$  for all  $k > 1$  it is true that  $\text{Ext}^k(M, N) = 0$ .*

We mostly only discuss path algebras of acyclic quivers in this thesis because our results are only about finite dimensional algebras.

### 1.2.3 Modules in hereditary algebras

Now let's review some basic concepts about modules. In particular we will review the concepts of bricks and stones.

**Definition 1.2.14.** An indecomposable module  $M$  over an algebra  $\Lambda$  is *Schur* or a *brick* if its endomorphism ring  $\text{End}M$  is a division algebra. In particular if  $\Lambda$  is a  $k$ -algebra where  $k$  is an algebraically closed field then a brick is an indecomposable module such that  $\text{End}M = k$ .

**Definition 1.2.15.** An indecomposable module  $M$  over an algebra  $\Lambda$  is *rigid*, *exceptional* or a *stone* if  $\text{Ext}^1(M, M) = 0$ .

Here is a well-known result about Schur and rigid modules in hereditary algebras.

**Theorem 1.2.16.** *[3] Let  $k$  be an algebraically closed field, let  $\Lambda$  be a finite-dimensional  $k$ -algebra. Then any rigid  $\Lambda$ -module  $M$  is Schur.*

## 1.3 Mutations, mutation sequences and the associated permutation

In this section we will introduce mutations of quivers and matrices, different kinds of mutation sequences including green sequences, maximal green sequences, reddening sequences and loop sequences. We will also define the associated permutation. Results in this section are mostly used in Chapters 2 and 5.

### 1.3.1 Mutation of quivers

The concept of maximal green sequences has many different equivalent definitions. We will use a simple definition using quiver mutations in this subsection. Later we will introduce other definitions. Mutations of cluster quivers at vertex  $k$  are defined in the following way:

1. For any pair of arrows  $i \rightarrow k$  and  $k \rightarrow j$  add an arrow  $i \rightarrow j$ .
2. Reverse all arrows starting from or ending up in  $k$ .
3. Delete all 2-cycles that are formed due to process (1) and (2).

**Definition 1.3.1.** 1. The *framed quiver*  $\hat{Q}$  of  $Q$  is obtained from  $Q$  by adding a vertex  $i'$  and an arrow  $i \rightarrow i'$  for every  $i \in Q$ .

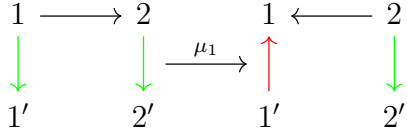
2. The *coframed quiver*  $\check{Q}$  of  $Q$  is obtained from  $Q$  by adding a vertex  $i'$  and an arrow  $i' \rightarrow i$  for every  $i \in Q$ .

3. An *ice quiver* is a quiver  $Q$  where a possibly empty set,  $F \subseteq Q_0$ , consists of vertices that can not mutate.

## CHAPTER 1. BACKGROUND

An ice quiver  $(Q, F)$  can not mutate at elements of  $F$ , so we call them *frozen vertices*.

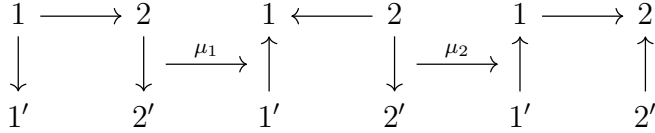
**Definition 1.3.2.** A non-frozen vertex  $i$  is *green* if and only if no arrow from a frozen vertex to  $i$  exists. Otherwise it is *red*. [24]



**Definition 1.3.3.** A *green sequence* is a sequence  $\mathbf{i} = (i_1, i_2, \dots, i_N)$  such that for all  $1 \leq t \leq N$  the vertex  $i_t$  is green in the partially mutated ice quiver  $\hat{Q}(\mathbf{i}, t) = \mu_{i_{t-1}} \cdots \mu_2 \mu_1(\hat{Q})$ .

**Definition 1.3.4.** A *maximal green sequence* is a green sequence such that  $\hat{Q}(\mathbf{i}, N)$  does not have any green vertices.

**Example 1.3.5.** For quiver  $1 \rightarrow 2$  here is one of its two maximal green sequences.



We also need the definition of reddening sequences which are generalized versions of maximal green sequences in order to discuss the phenomenon of almost morphism finiteness in Chapter 3.

**Definition 1.3.6.** A *red-to-green sequence* or a *reddening sequence*, is a sequence  $\mathbf{i} = (i_1, i_2, \dots, i_N)$  that transforms  $\hat{Q}$  to a quiver  $\hat{Q}(\mathbf{i}, N) = \mu_{i_N} \cdots \mu_2 \mu_1(\hat{Q})$  such that  $\hat{Q}(\mathbf{i}, N)$  does not have any green vertices. [27]

## CHAPTER 1. BACKGROUND

Now let's define a new concept, namely *loop sequences* which is essential to the discussion about the permutation in Chapter 2.

**Definition 1.3.7.** A *loop sequence*  $w$  is a sequence of mutations  $\mu_{i_k} \cdots \mu_{i_1}$  on an ice quiver  $(Q, F)$  such that  $\mu_{i_k} \cdots \mu_{i_1}(Q) = \rho(Q)$  for some permutation  $\rho$ .

### 1.3.2 Mutation of matrices

We can also use *c-vectors* for this purpose. To do so we need to reinterpret mutations of cluster quivers in terms of mutations of matrices. We recall that cluster quivers correspond to *exchange matrices* as defined below. For more details we recommend [13] and [14].

**Definition 1.3.8.** [13] An *exchange matrix* of a cluster quiver  $Q$  with  $n$  vertices is an  $n \times n$  matrix such that  $b_{ij}$  is the number of arrows from  $i$  to  $j$  minus the number of arrows from  $j$  to  $i$ .

It is easy to see that exchange matrices of cluster quivers are always antisymmetric which is not true in the more general case of *valued quivers* which we won't discuss in this paper. Moreover there is a 1-1 correspondence between antisymmetric exchange matrices and cluster quivers.

Mutations of exchange matrices are defined here which exactly agree with mutations of cluster quivers.

**Definition 1.3.9.** [13] If we mutate an  $n \times n$  exchange matrix  $B = (b_{ij})$  at  $k$  we obtain

## CHAPTER 1. BACKGROUND

$$B' = (b'_{ij}) \text{ defined here. } b'_{ij} = \begin{cases} -b_{ij} & \text{if } i = k \text{ or } j = k \\ b_{ij} + b_{ik}|b_{kj}| & \text{if } b_{ik}b_{kj} > 0 \\ b_{ij} & \text{in all other cases} \end{cases}$$

Each partially mutated ice quiver corresponds to an *extended exchange matrix* defined below.

**Definition 1.3.10.** The *extended exchange matrix*  $B'$  corresponding to a partially mutated ice quiver  $Q'$  is an  $2n \times n$  matrix with the rows corresponding to vertices  $\{1, 2, \dots, n, 1', 2', \dots, n'\}$  while the columns corresponds to the vertices  $\{1, 2, \dots, n\}$ . Here we use the number  $n + i$  to represent  $i'$ .  $b_{ij}$  is the number of arrows from  $i$  to  $j$  minus the number of arrows from  $j$  to  $i$ .

An extended exchange matrix  $B'$  has an upper and lower square submatrices,  $B$  and  $C$  respectively. The lower square matrix  $C$  is known as the *C-matrix*. Column vectors of an  $C$ -matrix are known as *c-vectors*. A  $c$ -vector is positive if all its entries are non-negative and at least one is positive. A  $c$ -vector is negative if all its entries are non-positive and at least one is negative. Due to [15] a  $c$ -vector is either positive or negative which is known as *sign coherence*.

A mutation on vertex  $k$  is *green* if the  $c$ -vector  $c_k$  before the mutation is negative. A mutation on vertex  $k$  is *red* if the  $c$ -vector  $c_k$  before the mutation is positive. A *maximal green sequence* is a mutation sequence from  $C = -I_n$  to a permuted version of  $I_n$ . We can use a sequence of  $c$ -vectors to denote a maximal green sequence because we can use the  $c$ -vector corresponding to vertex  $k$  to represent mutation at vertex  $k$  which is possible since all  $C$ -matrices are invertible.

## CHAPTER 1. BACKGROUND

Now we need to introduce two more results that are crucial to Chapter 5. The proof requires some knowledge of simple minded collections. For readers unfamiliar with this concept who want to understand the proofs the next section should be read first.

Positive  $c$ -vectors are dimension vectors of elements of simple-minded collections. Such elements are all bricks. That is, all  $c$ -vectors are Schur. However we can indeed prove more. They are in fact real as well.

**Lemma 1.3.11.** *Let  $k$  be an algebraically closed field. Let  $\Lambda$  be a hereditary algebra over  $k$ . Then any  $c$ -vector  $c$  that appears in any MGS is a real Schur root.*

*Proof.* Since the simples of  $\Lambda$  are all exceptional if the lemma were incorrect then there must be some  $c$ -matrix in the MGS,  $C$  such that all columns of  $C$  are real Schur roots while one green mutation can somehow generate a root that isn't real. Here there can only be two cases, namely some mutation performed on  $-v$  caused some  $-w$  to be transformed into  $-w' = -w - kv$  which isn't real, some mutation performed on  $-v$  caused some  $+w$  to be transformed into  $w' = w - kv$  which isn't real. In the second case  $w'$  may be positive or negative.

For an arbitrary  $c$ -vector  $v$  let  $M_v$  be the brick such that  $v$  is the dimension vector of  $M_v$ . In this case  $\langle v, v \rangle = 1 - \dim \text{Ext}^1(M_v, M_v)$ . Hence  $v$  being real is equivalent to  $\langle v, v \rangle = 1$ .

**Case 1:** Assume that some mutation performed on  $-v$  caused some  $-w$  to be transformed into  $-w' = -w - kv$  which isn't real.  $\langle w', w' \rangle = \langle w, w \rangle + k\langle v, w \rangle + k\langle w, v \rangle + k^2\langle v, v \rangle$ . Since  $\text{Hom}(M_v, M_w) = \text{Hom}(M_w, M_v) = 0$  due to  $M_v, M_w$  being two elements in a simple-minded collection and  $v, w$  are both real  $\langle w', w' \rangle = k^2 + 1 - k \dim \text{Ext}^1(M_v, M_w) - k \dim \text{Ext}^1(M_w, M_v)$ . Using properties of simple-minded collections  $\dim \text{Ext}^1(M_w, M_v) = k$ . Using Prop 6.4 in [25] we can see that  $\text{Ext}^1(M_v, M_w) = 0$ , Hence  $\langle w', w' \rangle = 1$ .  $w'$  is real.



## CHAPTER 1. BACKGROUND

**Case 2:** Assume that some mutation performed on  $-v$  caused some  $w$  to be transformed into  $-w' = w - kv$  which isn't real. Using properties of simple-minded collections it is obvious that  $Ext^1(M_v, M_w) = Hom(M_v, M_w) = 0$ . Regardless of whether  $w'$  is positive or negative  $\langle w', w' \rangle = \langle w, w \rangle - k\langle v, w \rangle - k\langle w, v \rangle + k^2\langle v, v \rangle = k^2 + 1 - k \dim Hom(M_w, M_v) + k Ext^1(M_w, M_v)$ . Using properties of simple-minded collections  $\dim Hom(M_w, M_v) = k$ . Using Prop 6.4 in [25] we can see that  $Ext^1(M_w, M_v) = 0$ , Hence  $\langle w', w' \rangle = 1$ .  $w'$  is real.

The assumption has been refuted. Any  $c$ -vector  $c$  that appears in any MGS is a real Schur root. □

In order to prove 5.1.1 we need to first prove a lemma.

**Lemma 1.3.12.** *If  $-c_1, -c_2$  are negative  $c$ -vectors in  $C$ -matrix  $C'$  in an MGS,  $c_1$  and  $c_2$  are dimension vectors of indecomposable modules  $M_1$  and  $M_2$ . If  $\dim Ext^1(M_1, M_2) > 1$  then the mutation on  $C'$  must not be done on  $M_2$ .*

*Proof.* Assume that  $-c_1$  is the  $i$ -th column and  $-c_2$  is the  $j$ -th column. According to [26] using the definition of left mutations of simple-minded collections if  $\dim Ext^1(M_1, M_2) > 1$  then the mutation on  $-c_2$  would cause  $-c_1$  to be transformed into  $-c_1 - kc_2$  with  $k > 1$  because which could only happen if there are multiple edges from  $i$  to  $j$ . Due to [6] this was impossible. □

### 1.3.3 Permutations

All reddening sequences have associated permutations. When comparing the quivers obtained from transforming the same framed quiver using two different reddening sequences, it is easy to see that they are just one permutation away from each other: If you do a correct

## CHAPTER 1. BACKGROUND

permutation of vertices (that means both rows and columns together) you can transform one such matrix into another. In particular any quiver obtained by using a reddening sequence to transform a framed quiver is one permutation away from the coframed quiver.

In this subsection if  $Q$  is a cluster quiver then  $\hat{Q}, \check{Q}$  are the framed and coframed quiver associated with cluster quiver  $Q$  respectively.

Here is the formal definition of such a permutation:

**Definition 1.3.13.** [5] A *permutation* from an ice quiver  $(Q, F)$  to  $(Q', F)$  is an isomorphism of quivers  $Q \rightarrow Q'$  that preserve  $F$ .

We have a result from [5] which helps us define the permutation:

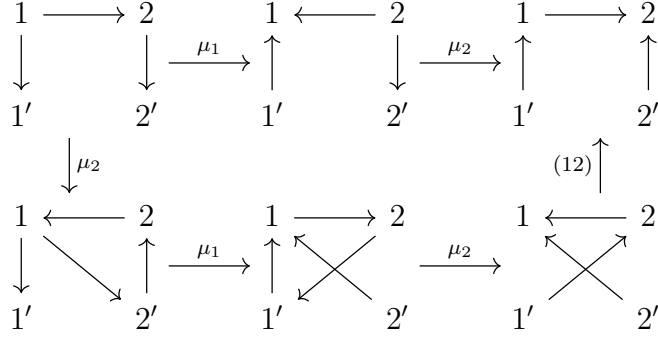
**Theorem 1.3.14.** [5] Let  $Q$  be a cluster quiver and let  $Q'$  be a quiver that is a result of a reddening sequence on  $\hat{Q}$ , then  $Q'$  equals to a permutation of  $\check{Q}$ .

Due to the proposition, for a reddening sequence  $\mathbf{i} = (i_1, \dots, i_N)$ , for some  $\rho \in S_n$  we have  $\mu_{i_N} \cdots \mu_{i_1} \hat{Q} = \rho \check{Q}$ .

**Definition 1.3.15.** [16] The *permutation of a reddening sequence*  $\mathbf{i}$  is  $\rho$  for which  $\mu_{i_N} \cdots \mu_{i_1} \hat{Q} = \rho \check{Q}$ .

Here is one of the simplest examples of the concept of the permutation:

## CHAPTER 1. BACKGROUND



It is obvious that the result of  $\mu_2\mu_1$  and  $\mu_2\mu_1\mu_2$  are not identical, though they can be transformed into each other by a single permutation on vertices.

The associated permutation is not only intuitive when defined on reddening sequences. In the case of loop sequences they are even more intuitive. Using the  $c$ -vector theorem from [35] we can see that the only nontrivial effect loop sequences can have on an extended matrix is a permutation. Hence loop sequences are equivalent to permutations on an extended matrix.

We can also define the associated permutation of sequences using extended exchange matrices.

**Definition 1.3.16.** The *matrix of a permutation*,  $\sigma \in S_n$ , is defined as the  $n \times n$  matrix  $P_\sigma = (\delta_{\sigma(i)j})$ .

**Definition 1.3.17.** (1) For an  $m \times n$  matrix  $M = (M_1, \dots, M_n)$  and a permutation  $\sigma \in S_n$ , if  $C = (M_{\sigma(1)}, \dots, M_{\sigma(n)})$  (or equivalently,  $(c_{ij}) = (m_{i\sigma(j)})$ ), we denote this as  $C = \sigma(M)$ .

(2) For an  $n \times n$  matrix  $A = (a_{ij})$  and a permutation  $\sigma \in S_n$ , if  $D = (d_{ij}) = (a_{\sigma(i)\sigma(j)})$ , we denote this as  $D = \tilde{\sigma}(A)$ .

## CHAPTER 1. BACKGROUND

It is easy to see that  $C = \sigma(M)$  if and only if  $C = MP_\sigma^{-1}$ .  $D = \tilde{\sigma}(A)$  if and only if  $D = P_\sigma AP_\sigma^{-1}$ .

**Definition 1.3.18.** For any loop sequence  $w$  the permutation  $\rho$  such that  $w(\tilde{B}) = \rho(\tilde{B})$  is defined as *the associated permutation of the loop sequence  $w$* .

In essence for all acyclic quivers, green-to-red sequences in general and maximal green sequences in particular do not have a natural definition of the permutation: The traditional one in essence is the permutation of an associated loop sequence: Take the reddening sequence and then do mutations at sinks only, go over all non-frozen vertices and return to the origin which constitutes the loop sequence we need.

## 1.4 Bounded derived categories

In this section we will go over the basics about bounded derived categories, approximations, silting objects, simple-minded collections, torsion classes,  $t$ -structures and introduce the definition of numerous mutation sequences. This section mostly consists of background for chapters 4 and 5.

### 1.4.1 Triangulated categories and bounded derived categories

In this subsection we need to use Auslander-Reiten Theory. However I'm not going to talk about the entire Auslander-Reiten theory even though some parts of it are crucial to the

## CHAPTER 1. BACKGROUND

understanding of Chapter 3. For Auslander-Reiten theory we refer the reader to Chapter IV of [3] and [2].

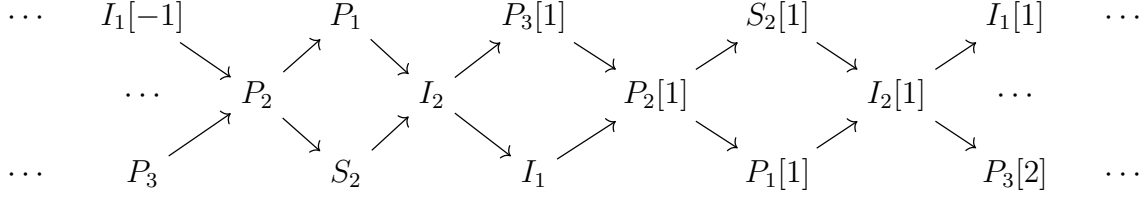
I'm not going to talk about what triangulated categories and bounded derived categories are in details. For those who want to read about them we recommend Daniel Murfet's notes [28][29][30] for introduction and [17] for its application in the theory of finite dimensional algebras. In particular [17] is a good source for Auslander-Reiten theory in bounded derived categories which we will use extensively here.

Let's recall some basic facts about triangulated categories that we will use a lot in this paper. In a triangulated category  $\mathcal{T}$  there exists an automorphism [1] known as the *translation functor*.  $[n] := ([1])^n$  for any integer  $n$ . The *cone* or *homotopy cokernel* of a morphism  $A \xrightarrow{f} B \in \mathcal{T}$  is some  $C \in \mathcal{T}$  such that there exists  $g, h \in \mathcal{T}$  such that  $A \xrightarrow{f} B \xrightarrow{g} C \xrightarrow{h} A[1]$  is a distinguished triangle. The *homotopy kernel* of a morphism  $A \xrightarrow{f} B \in \mathcal{T}$  is some  $C \in \mathcal{T}$  such that there exists  $g, h \in \mathcal{T}$  such that  $C \xrightarrow{g} A \xrightarrow{f} B \xrightarrow{h} C[1]$  is a distinguished triangle. Using axioms of triangulated categories any morphism  $A \xrightarrow{f} B \in \mathcal{T}$  has a homotopy kernel and a homotopy cokernel.

Let's recall that bounded derived categories  $D^b(\Lambda)$  are obtained by identifying homotopic chain maps in the category of chain complexes  $C(\Lambda)$  and then formally invert all quasi-isomorphisms through localization. In bounded derived categories of hereditary algebras the indecomposable objects are of the form  $M[i]$  where  $M$  is an indecomposable module and  $i$  is the amount of shifts we perform. In bounded derived categories it is true that  $M, N \in \text{mod } \Lambda$

$$\text{Hom}_{D^b(\Lambda)}(M[i], N[j]) = \begin{cases} \text{Ext}_{\Lambda}^{j-i}(M, N) & \text{if } j \geq i \\ 0 & \text{if } j < i \end{cases}.$$

**Example 1.4.1.** Let  $Q$  be  $1 \longrightarrow 2 \longrightarrow 3$ . Here is the Auslander-Reiten quiver of  $D^b(kQ)$ .



### 1.4.2 Approximations

According to [26] there are bijections between silting objects,  $t$ -structures, co- $t$ -structures and simple-minded collections in a wide range of cases and such bijections respect mutations. In [10] more bijections are mentioned. Here we only need to cover three of them, namely silting objects, simple-minded collections and  $t$ -structures. To understand their mutations we must first introduce the concept of approximations.

**Definition 1.4.2.** Let  $\mathcal{C}$  be a category and  $\mathcal{X}$  be one of its subcategories. Let  $M \in \text{Ob}\mathcal{C}, N \in \text{Ob}\mathcal{X}$  and  $f \in \text{Hom}_{\mathcal{C}}(M, N)$ .

1.  $f$  is a *left- $\mathcal{X}$  approximation* if for any  $N' \in \text{Ob}\mathcal{X}$  and for any  $q \in \text{Hom}_{\mathcal{C}}(M, N')$  we have  $q$  factors through  $f$ .
2.  $f$  is *left minimal* if for any  $g \in \text{End}_{\mathcal{C}}N$  such that  $g \circ f = f$  the morphism  $g$  is an isomorphism.
3.  $f$  is a *minimal left- $\mathcal{X}$  approximation* if it is both left minimal and is a left- $\mathcal{X}$  approximation.

$$\begin{array}{ccc}
 M & \xrightarrow{f} & N \\
 & \searrow q & \downarrow l \\
 & & N'
 \end{array}$$

## CHAPTER 1. BACKGROUND

**Definition 1.4.3.** Let  $\mathcal{C}$  be a category and  $\mathcal{X}$  be one of its subcategories. Let  $M \in \text{Ob}\mathcal{C}$ ,  $N \in \text{Ob}\mathcal{X}$  and  $f \in \text{Hom}_{\mathcal{C}}(M, N)$ .

1.  $f$  is a *right- $\mathcal{X}$  approximation* if for any  $M' \in \text{Ob}\mathcal{X}$  and for any  $q \in \text{Hom}_{\mathcal{C}}(M', N)$  we have  $q$  factors through  $f$ .
2.  $f$  is *right minimal* if for any  $g \in \text{End}_{\mathcal{C}}M$  such that  $f \circ g = f$  the morphism  $g$  is an isomorphism.
3.  $f$  is a *minimal right- $\mathcal{X}$  approximation* if it is both right minimal and is a right- $\mathcal{X}$  approximation.

$$\begin{array}{ccc}
 M & \xrightarrow{f} & N \\
 \uparrow \scriptstyle l & \nearrow \scriptstyle q & \\
 M' & & 
 \end{array}$$

**Example 1.4.4.** Let  $\mathcal{C}$  be  $D^b(\Lambda)$  for some finite dimensional algebra  $\Lambda$  and let  $\mathcal{X}$  be one of its full subcategories. If  $M \in \mathcal{X}$  then  $1_M$  is both a minimal left- $\mathcal{X}$  approximation and a minimal right- $\mathcal{X}$  approximation.

**Example 1.4.5.** Let  $Q$  be  $1 \rightarrow 2$ . Let  $\mathcal{C}$  be  $D^b(kQ)$ . Let  $M = P_2$  and  $\mathcal{X} = \text{add}(P_1)$ . The minimal left- $\mathcal{X}$  approximation is the canonical morphism  $P_2 \rightarrow P_1$  induced by the inclusion  $P_2 \rightarrow P_1$  in the module category.

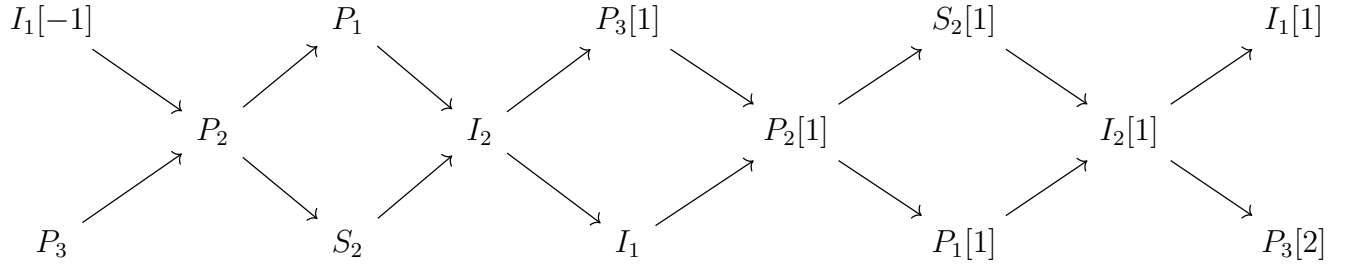
**Example 1.4.6.** Let  $Q$  be  $1 \rightarrow 2$ . Let  $\mathcal{C}$  be  $D^b(kQ)$ . Let  $M = P_2$  and  $\mathcal{X} = \text{add}(P_1)$ . The minimal right- $\mathcal{X}$  approximation is the zero morphism because there is no other morphism from  $P_1$  to  $P_2$ .

### 1.4.3 Silting objects

Now let's introduce silting objects.

**Definition 1.4.7.** Let  $\Lambda$  be an algebra with  $n$  primitive idempotents. A *silting object*  $T$  of  $D^b(\Lambda)$  is an object such that  $T$  has  $n$  direct summands and  $(T, T[m]) = 0$  for all  $m > 0$ . A *pre-silting object* is an object that only has to satisfy the second condition.

**Example 1.4.8.** Let's take  $A_3$  straight orientation as an example.



$\Lambda[i]$  is a silting object for any  $i$ .  $T_1 = P_3 \oplus P_1 \oplus I_1[1]$  is also a silting object.

Now that we already have the definition of silting objects we can discuss their mutations.

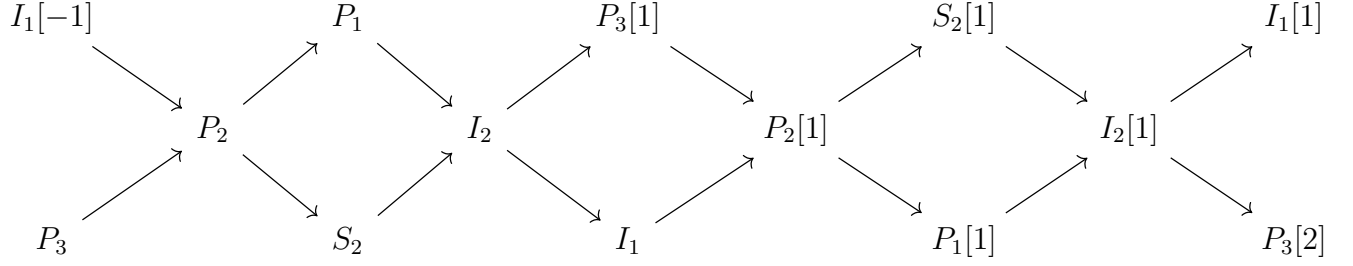
**Definition 1.4.9.** A *forward mutation* on the direct summand  $T_i$  of the silting object  $T$  is  $T'_i \oplus (T/T_i)$  where  $T'_i$  is the cone/homotopy cokernel of the minimal left- $\text{add}(T/T_i)$  approximation of  $T_i$ .

A *backward mutation* on the direct summand  $T_i$  of the silting object  $T$  is  $T'_i \oplus (T/T_i)$  where  $T'_i$  is homotopy kernel/  $[-1]$  of the cone/ of the minimal right- $\text{add}(T/T_i)$  approximation of  $T_i$ .

**Example 1.4.10.** Again let's take  $A_3$  straight orientation as an example.



## CHAPTER 1. BACKGROUND



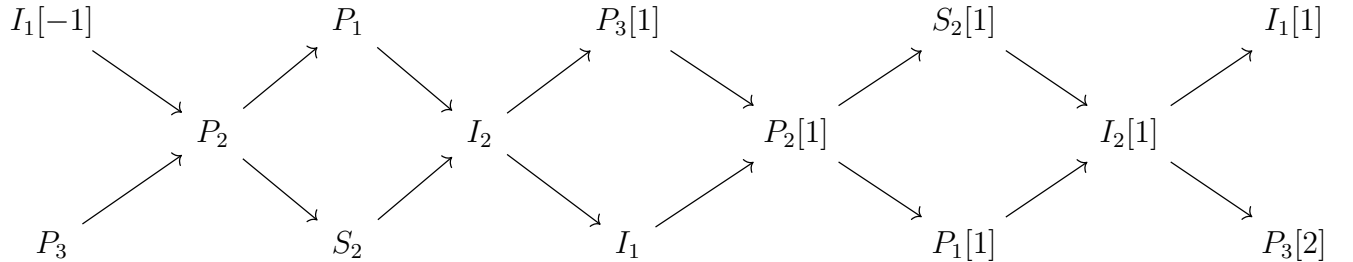
$\Lambda$  is a silting object. When we do a forward mutation at  $P_3$  we get  $T' = S_2 \oplus P_2 \oplus P_1$ . When we do a forward mutation at  $P_1$  now we get  $T'' = S_2 \oplus P_2 \oplus P_1[1]$ . When we do another forward mutation at  $P_2$  we get  $T''' = S_2 \oplus P_3[1] \oplus P_1[1]$ .

### 1.4.4 Simple-minded collections

Now let's introduce simple-minded collections. They are simple objects in some Abelian category known as hearts of  $t$ -structures.

**Definition 1.4.11.** Let  $\Lambda$  be an algebra with  $n$  primitive idempotents. A *simple-minded collection*  $\{S_i\}_{i \in [n]}$  of  $D^b(\Lambda)$  is an  $n$ -element set such that  $(S_i[\geq 0], S_j) = 0$  for all  $i \neq j$ ,  $(S_i[> 0], S_i) = 0$  for all  $i$  and  $(S_i, S_i)$  is a division algebra.

**Example 1.4.12.** As usual our example is  $A_3$  straight orientation.



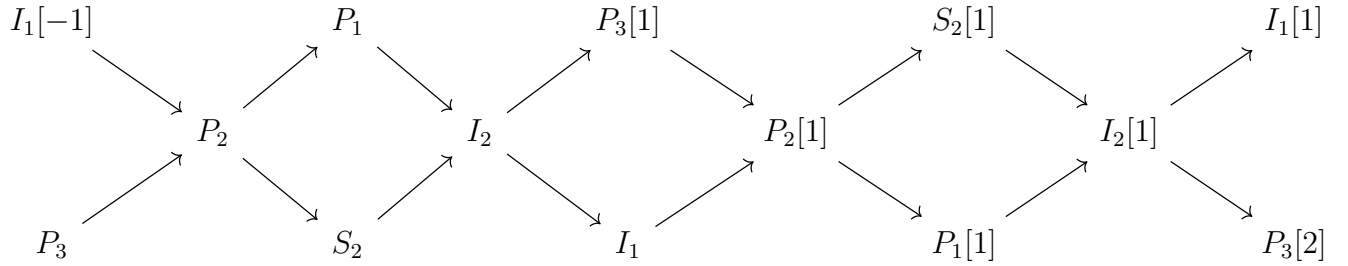
## CHAPTER 1. BACKGROUND

$\{I_1, S_2, P_3\}$  is a simple-minded collection.  $\{P_3[1], P_2, I_1\}$  is also a simple-minded collection.

**Definition 1.4.13.** A *forward mutation* on the element  $S_i$  of the simple-minded collection  $\{S_j\}$  is  $\{S'_j\}$  where  $S'_i = S_i[1]$  and  $S'_j$  ( $j \neq i$ ) is the cone/homotopy cokernel of the minimal  $\text{left-add}(S_i)$  approximation of  $S_j[-1]$ .

A *backward mutation* on the element  $S_i$  of the simple-minded collection  $\{S_j\}$  is  $\{S'_j\}$  where  $S'_i = S_i[-1]$  and  $S'_j$  ( $j \neq i$ ) is the cone/homotopy cokernel of the minimal  $\text{left-add}(S_i[-1])$  approximation of  $S_j$ .

**Example 1.4.14.** The quiver here is  $A_3$  straight orientation.



$\{I_1, S_2, P_3\}$  is a simple-minded collection. When we do a forward mutation at  $P_3$  we get  $\{P_3[1], P_2, I_1\}$ . When we do a forward mutation at  $P_2$  now we get  $\{S_2, P_2[1], P_1\}$ . When we then do a forward mutation at  $P_1$  we get  $\{S_2, I_1, P_1[1]\}$ .

### 1.4.5 $t$ -structures

Here is the definition of  $t$ -structures.

**Definition 1.4.15.** A  $t$ -structure on  $D^b(\Lambda)$  is a pair  $(D^{\leq 0}, D^{\geq 0})$  such that the following holds.

## CHAPTER 1. BACKGROUND

1. For any  $M \in D^b(\Lambda)$  there exists  $M' \in D^{\leq 0}, M'' \in D^{\geq 0}$  such that  $M' \rightarrow M \rightarrow M'' \rightarrow M'[1]$ .
2.  $D^{\leq 0}[1] \subseteq D^{\leq 0}, D^{\geq 0}[1] \supseteq D^{\geq 0}$ .
3.  $(D^{\leq 0}[1], D^{\geq 0}) = 0$

**Example 1.4.16.** Let  $\Lambda$  be any finite dimensional algebra.  $(\cup_{m=1}^{\infty} \Lambda[m], \cup_{m=0}^{\infty} \Lambda[-m])$  is clearly a  $t$ -structure.

Now let's define hearts which will be very useful for a crucial proof in 4, namely the proof of Lemma 4.3.3.

**Definition 1.4.17.** The *heart* of a  $t$ -structure  $(D^{\leq 0}, D^{\geq 0})$  is defined as  $\mathcal{H} = D^{\leq 0} \cap D^{\geq 0}$

**Theorem 1.4.18.** [4] *Hearts of  $t$ -structures are Abelian categories.*

$t$ -structures can be mutated just like silting objects and simple-minded collections. In order to do so we first need to define torsion pairs in Abelian categories.

**Definition 1.4.19.** A *torsion pair*  $(\mathcal{T}, \mathcal{F})$  in an Abelian category  $\mathcal{C}$  is a pair of two subcategories such that the following holds.

1.  $\text{Hom}(\mathcal{T}, \mathcal{F}) = 0$
2. For any  $M \in \mathcal{C} \exists T \in \mathcal{T}, F \in \mathcal{F}$  such that  $0 \rightarrow T \rightarrow M \rightarrow F \rightarrow 0$  is a short exact sequence.
3. If for  $M \in \mathcal{C}$  and  $\text{Hom}(M, \mathcal{F}) = 0$  then  $M \in \mathcal{T}$ .
4. If for  $M \in \mathcal{C}$  and  $\text{Hom}(\mathcal{T}, M) = 0$  then  $M \in \mathcal{F}$ .

## CHAPTER 1. BACKGROUND

**Example 1.4.20.** Let  $\mathcal{C}$  be  $\text{mod} kQ$  with  $Q$  being  $1 \rightarrow 2$  if we take  $\mathcal{T} = \text{add}(P_2)$  and  $\mathcal{F} = \text{add}(I_1)$  we can see that the pair  $(\mathcal{T}, \mathcal{F})$  satisfies the conditions above and is hence a torsion pair in  $\mathcal{C}$ .

**Example 1.4.21.** Let  $\mathcal{C}$  be  $\text{mod} kQ$  with  $Q$  being  $1 \rightarrow 2$  straight orientation if we take  $\mathcal{T} = \text{add}(P_1, I_1)$  and  $\mathcal{F} = \text{add}(P_2)$  we can see that the pair  $(\mathcal{T}, \mathcal{F})$  satisfies the conditions above and is hence a torsion pair in  $\mathcal{C}$ .

Now it is possible to define mutations of  $t$ -structures.

**Definition 1.4.22.** [26] Let  $\Lambda$  be a finite dimensional algebra, let  $D^b(\Lambda)$  be the bounded derived category of  $\Lambda$ . Let  $(\mathcal{C}^{\leq 0}, \mathcal{C}^{\geq 0})$  be a  $t$ -structure of  $D^b(\Lambda)$ . Let  $\mathcal{A}$  be its heart. Let  $(\mathcal{T}, \mathcal{F})$  be a torsion pair in  $\mathcal{A}$ . The *left mutation* or *forward mutation*  $\mu_i^+(\mathcal{C}^{\leq 0}, \mathcal{C}^{\geq 0}) = (\mathcal{C}'^{\leq 0}, \mathcal{C}'^{\geq 0})$  where  $\mathcal{C}'^{\leq 0} = \{M \in \mathcal{C} \mid H^m(M) = 0 \text{ for } m > 0 \text{ and } H^0(M) \in \mathcal{T}\}$ ,  $\mathcal{C}'^{\geq 0} = \{M \in \mathcal{C} \mid H^m(M) = 0 \text{ for } m < -1 \text{ and } H^{-1}(M) \in \mathcal{F}\}$ . Similarly we can define *right mutations* (or *backward mutations*).

For more information about mutations of  $t$ -structures we recommend [1], [10], [25] and [26].

### 1.4.6 Green sequences

Since we have maximal green sequences it is reasonable to look at the generalization of this concept, namely  $m$ -maximal green sequences. In order to do so we need to define the general concept of green and red sequences. In principle any forward mutation is considered green and any backward mutation red.

## CHAPTER 1. BACKGROUND

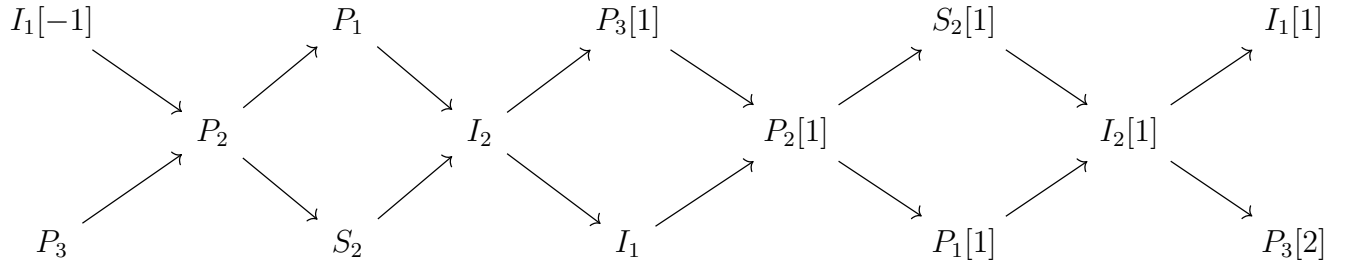
- Definition 1.4.23.**
1. Let  $\Lambda$  be a finite dimensional algebra of finite global dimension, a mutation sequence in  $D^b(\Lambda)$  is *green* if it contains only forward mutations.
  2. Let  $\Lambda$  be a finite dimensional algebra of finite global dimension, a mutation sequence in  $D^b(\Lambda)$  is *red* if it contains only backward mutations.
  3. Let  $\Lambda$  be a finite dimensional algebra of finite global dimension, a mutation sequence in  $D^b(\Lambda)$  is *k-red* if it contains  $k$  backward mutations.
  4. Let  $\Lambda$  be a finite dimensional algebra of finite global dimension, a mutation sequence in  $D^b(\Lambda)$  is *k-green* if it contains  $k$  forward mutations.

Note that a 0-red sequence is just a green one. A 0-green sequence is just a red one. Now we can introduce  $m$ -maximal green sequences. For the purpose of the proof in Chapter 3 it is much better to use silting objects.

**Definition 1.4.24.** An  $m$ -maximal green sequence is a green sequence of silting objects from  $\Lambda$  to  $\Lambda[m]$ .

It is easy to see that a 1-maximal green sequence is just a maximal green sequence.

**Example 1.4.25.** Again our example is  $A_3$  straight orientation.



## CHAPTER 1. BACKGROUND

So  $(P_1, P_2, P_3, P_1[1], P_2[1], P_3[1])$  is a 2-maximal green sequence, so is  $(P_1, P_3, P_2, S_2, P_1[1], P_2[1], P_3[1])$  because they are both sequences of indecomposable objects forward mutations on which produce  $\Lambda[2]$  from  $\Lambda$ .

### 1.5 Tame quivers and tame hereditary algebras

In this subsection we will review the basics about tame hereditary algebras, the components of their Auslander-Reiten quivers and the components of Auslander-Reiten quivers of their bounded derived categories for they are crucial to Chapter 3. For more details about tame algebras we would like to refer the readers to [11], [32] and [34].

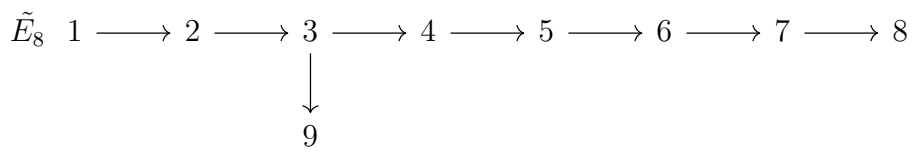
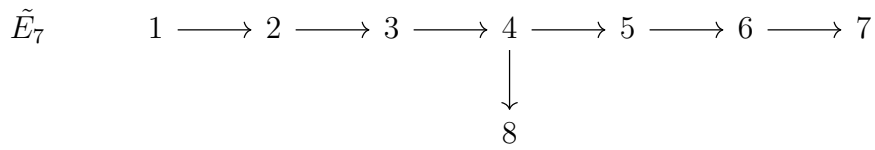
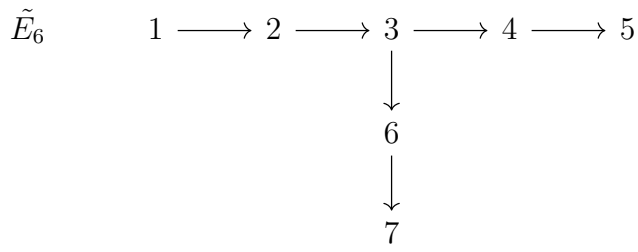
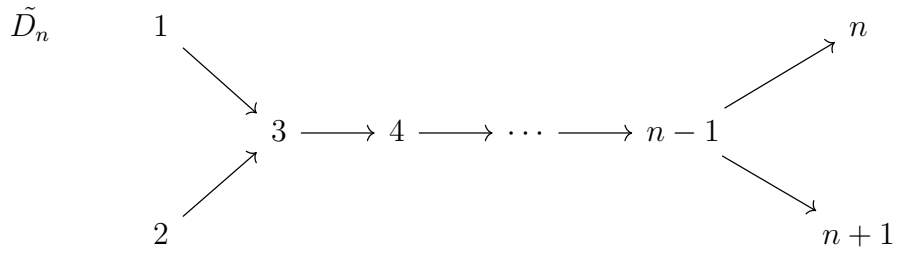
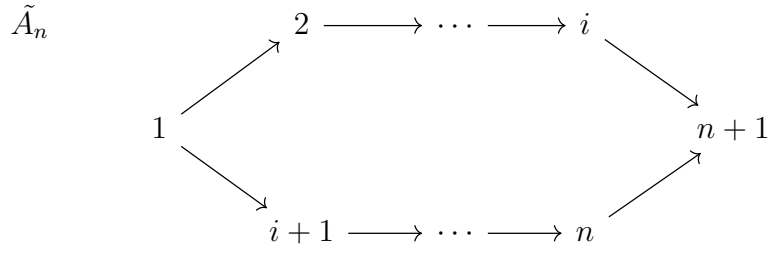
#### 1.5.1 Tame quivers

**Definition 1.5.1.** A *tame algebra* is a  $k$ -algebra such that for each dimension vector there are finitely many 1-parameter families that parametrize all but finitely many indecomposable modules of the algebra.

**Definition 1.5.2.** A *tame quiver* is a quiver such that its path algebra is a tame algebra.

**Example 1.5.3.** Here are all the (connected) tame quivers,  $\tilde{A}_n, \tilde{D}_n, \tilde{E}_6, \tilde{E}_7, \tilde{E}_8$ . The orientation of the edges can be arbitrary as long as the quiver remains acyclic in the case of  $\tilde{A}_n$ .

CHAPTER 1. BACKGROUND



## CHAPTER 1. BACKGROUND

### 1.5.2 Auslander-Reiten quivers of tame hereditary algebras

In this subsection I'm going to discuss Auslander-Reiten quivers of basic tame hereditary algebras because information about them is slightly less well known.

**Theorem 1.5.4.** *[11] The Auslander-Reiten quiver of a tame path algebra consists of three parts, the preprojectives, the preinjectives and the regulars.*

Here are some basic properties of preprojective and preinjective components of AR quivers of basic tame hereditary algebras.

**Theorem 1.5.5.** *1. The AR quiver of  $kQ$  has one preprojective component which is isomorphic to  $\mathbb{N}Q^{op}$*

*2. The AR quiver of  $kQ$  has one preinjective component which is isomorphic to  $-\mathbb{N}Q^{op}$ .*

*3. All preprojective and preinjective modules in  $kQ$  are rigid.*

*4. All but finitely many preprojectives and preinjectives are sincere.*

*5. There are infinitely many regular components, all of which are standard tubes  $\mathbb{Z}A_\infty/(\tau^k)$ .*

*6. All but at most three tubes have  $k = 1$ . In this case we consider the component homogeneous.*

*7. All elements in a homogeneous tube are non-rigid, hence they and their shifts can not be summands of any silting object.*

*8. In a nonhomogeneous component  $\mathbb{Z}A_\infty/(\tau^k)$  only indecomposables with quasi-length less than  $k$  are rigid. In other words there are only finitely many rigid indecomposables in any nonhomogeneous component.*

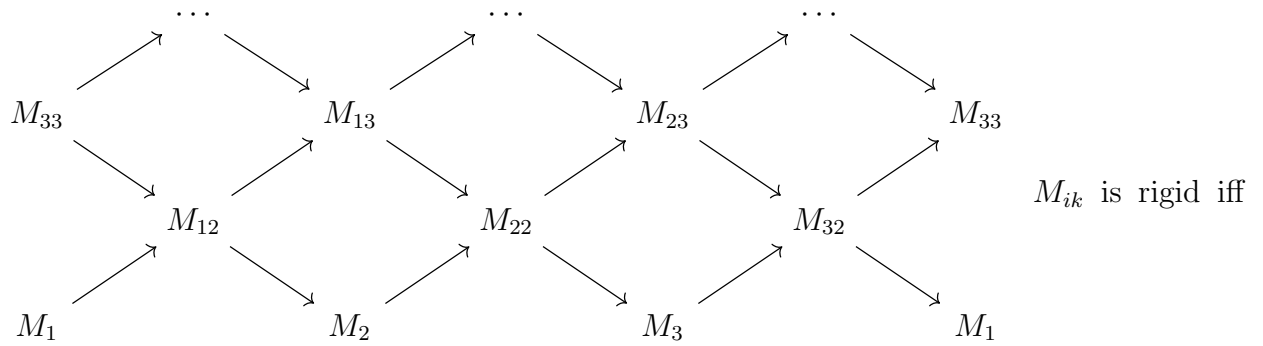


## CHAPTER 1. BACKGROUND

9. *Only finitely many regular indecomposable modules are rigid. Hence only finitely many regular indecomposables and their shifts can appear in an  $m$ -maximal green sequence.*

I'm going to introduce one example of nonhomogeneous and homogeneous standard stable tubes each. For more details we recommend Chapter X of [34].

**Example 1.5.6.** Here is a standard stable tube with rank 3.



$k \leq 2$ .

$M_{i+k-1}$

$\dots$

Here  $M_{ik} =$   . we define the *quasi-length* of  $M_{ik}$  as  $k$ .

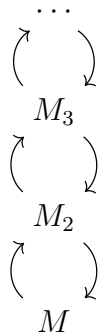
$M_{i+1}$

$M_i$

Now let's see a homogeneous tube.

**Example 1.5.7.** Here is a homogeneous standard stable tube.

# CHAPTER 1. BACKGROUND



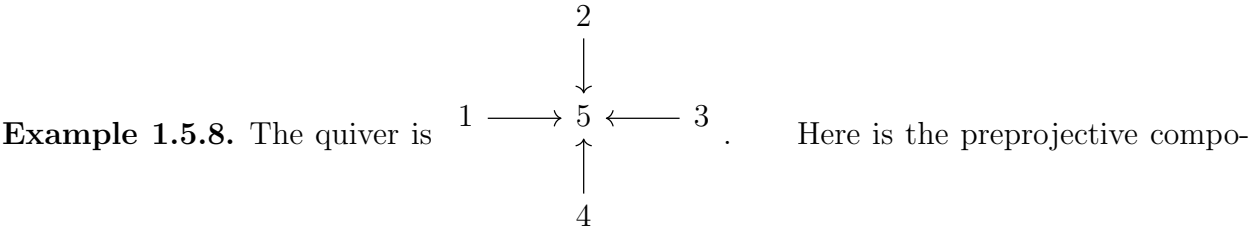
Note that no module in this tube is rigid.

$M$

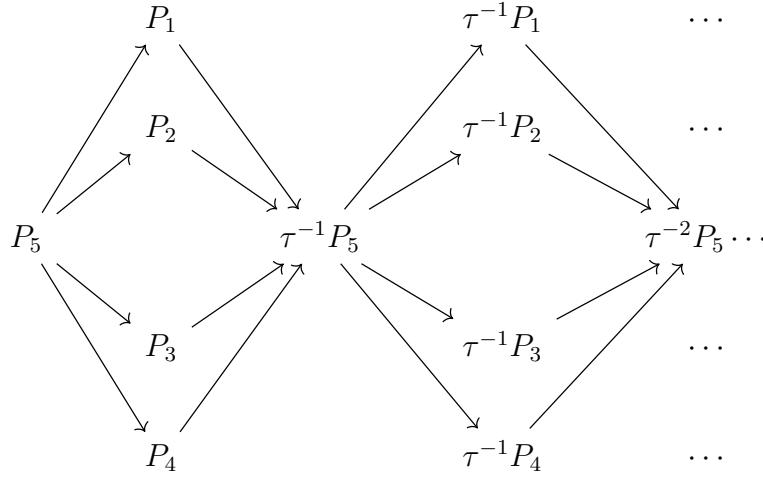
Here  $M_k = \dots$

$M$

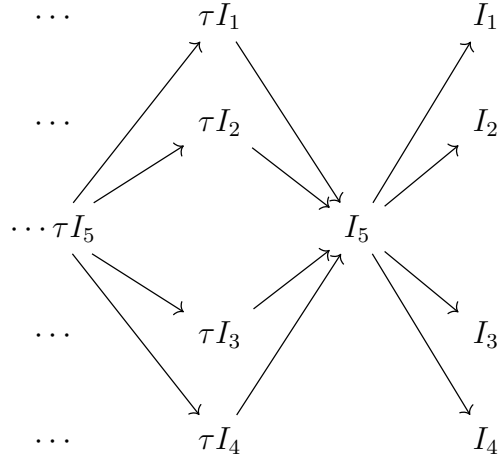
Now let's do an example of an AR quiver of a tame path algebra.



# CHAPTER 1. BACKGROUND



Here is the preinjective component,  $\mathcal{Q}$ .



Here are the regular components. There are infinitely many homogeneous tubes and 3 nonhomogeneous ones. All objects in the homogeneous ones are non-rigid. The quasi-simple in the homogeneous tubes has dimension vector is  $(1,1,1,1,2)$ . The quasi-simples in the three nonhomogeneous tubes have dimension vectors  $(1,1,0,0,1)$  and  $(0,0,1,1,1)$ ,  $(1,0,1,0,1)$  and  $(0,1,0,1,1)$ ,  $(1,0,0,1,1)$  and  $(0,1,1,0,1)$  respectively.

Finally let's discuss Auslander-Reiten quivers of  $D^b(kQ)$ . For a tame quiver  $Q$  there are

## CHAPTER 1. BACKGROUND

infinitely many components of  $D^b(kQ)$  consisting of shifts of preprojectives and preinjectives that are isomorphic to  $\mathbb{Z}Q^{op}$ . Let's label these components *transjective*. The transjective component containing  $\Lambda[m]$  is labelled  $\mathcal{P}_m$ .

There are also infinitely many regular components. There are at most 3 nonhomogeneous tubes in  $modkQ[m]$  for any  $m$ . There are also infinitely many homogeneous tubes in  $modkQ[m]$  for any  $m$ . However since no module in a homogeneous tube is rigid they don't affect our problem.

## 1.6 Wall-and-chamber structures

In this section we will discuss miscellaneous topics on the wall-and-chamber structures, namely picture groups and alternative definitions of maximal green sequences. This section is mostly relevant to Chapter 2 and Chapter 4. For more details we recommend [15][27][7][8][9][18] and [21].

### 1.6.1 Picture groups

We also need to use the concept of the picture groups in order to prove the formula in Chapter 2. For more details about picture groups we recommend [21].

For a quiver of finite type, any dimension vector of an indecomposable representation is referred to as a *root*. Let  $D(\beta) \subseteq \mathbb{R}^n$ ,  $D(\beta) = \{x \in \mathbb{R}^n : \langle x, \beta \rangle = 0, \langle x, \beta' \rangle \leq 0 \text{ when } \beta' \subseteq \beta\}$ . Here  $\beta' \subseteq \beta$  means the unique indecomposable representation of dimension vector  $\beta'$  is a subrepresentation of the unique indecomposable representation of dimension vector  $\beta$ .  $D(\beta)$  for all these roots divide  $\mathbb{R}^n$  into *compartments*. The boundary of each compartment is the

## CHAPTER 1. BACKGROUND

union of some  $D(\beta)$  which we call *walls*. [21][19] Sometimes we abuse notations and use the root  $\beta$  to mean the wall  $D(\beta)$  when the meaning is clear. We also use the notation  $+\beta$  to mean the wall  $\beta$  is a part of the boundary of a compartment  $\mathcal{U}$  and for any point  $x \in \mathcal{U}$ ,  $\langle x, \beta \rangle > 0$ . Similarly we have the notation  $-\beta$ . For example  $+\beta - \beta'$  means that  $\beta$  and  $\beta'$  are parts of the boundary of a compartment  $\mathcal{U}$  and for any point  $x \in \mathcal{U}$ ,  $\langle x, \beta \rangle > 0$  and  $\langle x, \beta' \rangle < 0$ .

**Definition 1.6.1.** A *picture group* of a cluster quiver of finite type  $Q$  is a group  $G(Q) = \langle S | R \rangle$  with  $S$  in bijection with the set of real Schur roots (the generator for  $\beta$  is  $x(\beta)$ ) and  $R$  the set of relations  $x(\beta_i)x(\beta_j) = \Pi x(\gamma_k)$  with  $\gamma_k$  running over all these real Schur roots which are linear combinations  $\gamma_k = a_k\beta_i + b_k\beta_j$  with  $a_k/b_k$  increasing (going from  $0/1$  where  $\gamma_1 = \beta_j$  to  $1/0$  where  $\gamma_k = \beta_i$ ) for any pair  $(\beta_i, \beta_j)$  such that they are Hom-orthogonal and  $\text{Ext}(\beta_i, \beta_j) = 0$ . [21]

Now we need to restrict the case to  $A_n$  straight orientation, namely quivers of the form  $1 \rightarrow 2 \rightarrow 3 \rightarrow \dots \rightarrow n$ .

**Definition 1.6.2.** Let  $Q$  be an acyclic quiver. A representation  $(\{V_i\}_{i \in Q_0}, \{\phi_a\}_{a \in Q_1})$  of  $Q$  is *thin* if  $\dim(V_i) \leq 1$  for all  $i \in Q_0$ .

In  $A_n$  in particular since all indecomposable representations are thin, the roots are  $\beta_{ij} = e_j - e_i$  ( $0 < i < j < n$ ,  $e_0$  is defined as the zero vector). The root  $\beta_{ij}$  corresponds to the picture group generator  $x_{ij}$  which we will define right now.

Note that for quiver  $A_n$  all roots are real and Schur hence a real Schur root is just a root. Also we often simplify the notation of  $x(\beta_{ij})$  to  $x_{ij}$  which we use interchangeably with  $x(\beta_{ij})$ .

## CHAPTER 1. BACKGROUND

The picture group for  $A_n$  straight orientation is  $G(A_n) = \{S|R\}$ ,  $S = \{x_{ij} | 0 \leq i < j \leq n\}$ ,  $R = \{x_{ij}x_{kl} = x_{kl}x_{ij} | [i, j] \cap [k, l] = \emptyset, [i, j] \text{ or } [k, l], i, j, k, l \text{ are distinct.}\} \cup \{x_{jk}x_{ij} = x_{ij}x_{ik}x_{jk} | 0 \leq i < j < k \leq n\}$ .

Igusa and Todorov proved [21] that there exists a bijection between the set of maximal green sequences and the set  $\mathcal{P}(c)$  of positive expressions of the Coxeter element of the picture group for any acyclic valued quiver of finite type which applies to  $A_n$  straight orientation.

### 1.6.2 Alternative definitions of maximal green sequences

In the following theorem by Kiyoshi Igusa multiple equivalent definition of maximal green sequences was introduced. The full version of Igusa's results includes more discussions about the wall-and-chamber structure which we will not discuss here. To understand more about the wall-and-chamber structure we suggest that the reader reads [15][27][7][8][9] and [18].

**Definition 1.6.3.** Let  $\Lambda$  be a finite dimensional algebra.  $\Lambda$ -modules  $M_1, \dots, M_m$  are a *backward Hom-orthogonal sequence* if  $\text{Hom}_\Lambda(M_i, M_j) = 0$  for  $i > j$ .

**Example 1.6.4.** In the  $Q : 1 \rightarrow 2$  example  $\{P_2, P_1\}$  is a backward Hom-orthogonal sequence because  $\text{Hom}(P_1, P_2) = 0$ .

**Example 1.6.5.** In the  $Q : 1 \rightarrow 2$  example  $\{P_1, P_2\}$  is not a backward Hom-orthogonal sequence because  $\text{Hom}(P_2, P_1) = k$ .

**Definition 1.6.6.** Let  $\Lambda$  be a finite dimensional algebra. A backward Hom-orthogonal sequence  $M_1, \dots, M_m$  is *maximal* if no other modules can be inserted into the sequence preserving the property of backward Hom-orthogonality.

## CHAPTER 1. BACKGROUND

**Example 1.6.7.** In the  $Q : 1 \rightarrow 2$  example  $\{P_2, P_1\}$  is not a maximal backward *Hom*-orthogonal sequence even though it is a backward *Hom*-orthogonal sequence because it can be extended to  $P_2, P_1, I_1$  without losing backward *Hom*-orthogonality.

**Example 1.6.8.** In the  $Q : 1 \rightarrow 2$  example  $\{I_1, P_2\}$  is a maximal backward *Hom*-orthogonal sequence because  $\text{Hom}(P_2, I_1) = 0$  and that there is no place to fit any other module in the sequence. For example  $P_1$  can not be inserted before  $P_2$  because  $\text{Hom}(P_2, P_1) \neq 0$ . At the same time it can not be inserted after  $I_1$  because  $\text{Hom}(P_1, I_1) \neq 0$ . Hence the sequence can not be extended to include  $P_1$ .

In fact  $Q : 1 \rightarrow 2$  only has two maximal backward *Hom*-orthogonal sequences, namely  $I_1, P_2$  and  $P_2, P_1, I_1$ . They are exactly the same as the two *c*-vectors in maximal green sequences of  $Q$ . Is this just a coincidence? No.

**Definition 1.6.9.** Let  $\{M_1, \dots, M_k\}$  be a fixed finite sequence of Schur objects in  $\text{mod}\Lambda$ . An *Harder-Narasimhan (HN) filtration* with respect to  $\{M_i\}$  aka an HN filtration of an object  $X$  is  $k$  short exact sequences  $0 \rightarrow X_i \rightarrow X_{i-1} \rightarrow X_{i-1}/X_i$  such that  $X_{i-1}/X_i \in \mathcal{E}M_i$ .

**Definition 1.6.10.** Let  $\{M_1, \dots, M_k\}$  be a fixed finite sequence of Schur objects in  $\text{mod}\Lambda$ .  $\{M_1, \dots, M_k\}$  is an *finite Harder-Narasimhan (HN) system* if any  $X \in \text{mod}\Lambda$  has a unique HN filtration with respect to  $\{M_i\}$ .

**Example 1.6.11.** In the  $Q : 1 \rightarrow 2$  example  $\{I_1, P_2\}$  is a finite HN system because any module  $X \in \text{mod}kQ$  has a unique HN filtration. In particular the unique HN filtration of  $P_1$  is  $0 \rightarrow P_2 \rightarrow P_1 \rightarrow I_1 \rightarrow 0$ .

**Example 1.6.12.** In the  $Q : 1 \rightarrow 2$  example  $\{P_2, P_1, I_1\}$  is a finite HN system because any module  $X \in \text{mod}kQ$  has a unique HN filtration.

## CHAPTER 1. BACKGROUND

There are only two finite HN systems of  $kQ$  where  $Q : 1 \rightarrow 2$ . They are exactly the same as the two maximal backward *Hom*-orthogonal sequences and the two maximal green sequences. This is in fact a general result.

**Theorem 1.6.13.** *[20] Let  $\Lambda$  be a finite dimensional hereditary algebra over a field  $K$ . Let  $\beta_1, \dots, \beta_m \in \mathbb{N}^n$  be any finite sequence of nonzero, nonnegative integer vectors. Then the following are equivalent.*

- (a) *There exist  $\Lambda$ -modules  $M_m, \dots, M_1$  with  $\dim M_i = \beta_i$  which form a finite Harder-Narasimhan system for  $\Lambda$ .*
- (b) *There exist a finite sequence of Schurian  $\Lambda$ -modules  $\{M_1, \dots, M_m\}$  with  $\dim M_i = \beta_i$  such that  $\{M_1, \dots, M_m\}$  is a maximal backward *Hom*-orthogonal sequence.*
- (c) *There is a maximal green sequence for  $\Lambda$  of length  $m$  whose  $i$ th mutation is at the  $c$ -vector  $\beta_i$ .*

Such results have been generalized to the case of  $m$ -maximal green sequences in Chapter 4.



# Chapter 2

## Permutation

### 2.1 The general theory of permutations

#### 2.1.1 Mutation systems

Let's define a natural setting of the theory of permutations which is completely combinatorial. Let  $[n] = \{1, 2, \dots, n\}$ . A *mutation graph* is defined as a connected  $n$ -regular graph without loops. Let  $T = (T_0, T_1)$  be a mutation graph. A *signed edge* of  $T$  is a triple  $(a, h, t)$  where  $a \in T_1$ ,  $h$  and  $t$  are the two endpoints of  $a$ , defined to be the head and tail of the signed edge respectively. For every signed edge  $a^{ht}$  there is its inverse signed edge  $a^{th}$ . Let  $\tilde{T}_1$  be the union of all signed edges of  $T$ . A *walk* is a path in  $\tilde{T}_1$  such that the sources and targets of each signed edge are compatible. Walks on  $T$  are in the form  $w = \Pi a_k^{i_{k-1}i_k}$ .

For each vertex  $x \in T_0$  we associate a set  $N(x)$  which is the set that contains all vertices adjacent to  $x$ . Note that  $|N(x)| = n$ . For each  $a^{ht} \in \tilde{T}_1$  we associate a bijection  $f_{a^{ht}} : N(x) \rightarrow N(y)$  such that  $a^{ht}$  and  $a^{th}$  are inverses of each other for any  $a \in T_1$ . This bijection is called *mutation* as per [14]. The set of all  $f_a$  is denoted  $A$ , the *set of muta-*

## CHAPTER 2. PERMUTATION

tions. The tuple  $(T, A)$  is called a *mutation system*. We can also define a natural bijection  $f_w : N(x) \rightarrow N(y)$  associated with each walk  $w = \Pi a_k^{i_k-1 i_k}$ , namely  $f_w = f_{a_k}^{i_k-1 i_k} \dots f_{a_1}^{i_0 i_1}$ .

Now let's define a bijection  $j_x : [n] \rightarrow N(x)$  for each  $x \in T_0$ . This bijection is called the *fixed ordering* of the seed  $N(x)$ . Let  $J$  be the set of all fixed orderings which we call a *fixed ordering set*. The tuple  $(T, A, J)$  is called a *ordered mutation system*. Now for each bijection  $j'_x : [n] \rightarrow N(x)$  we can define its *associated permutation relative to  $J$*  below:

**Definition 2.1.1.** For any  $(T, A, J)$  for any  $x \in T_0$  for any bijection  $g : [n] \rightarrow N(x)$  the *associated permutation relative to  $J$*  is defined as  $\rho(g) = j_x^{-1}g$ .

Now we can define what is the associated permutation of a mutation relative to  $J$ .

**Definition 2.1.2.** For any  $(T, A, J)$  for any  $x, y \in T_0$  for any mutation  $f_a : N(x) \rightarrow N(y)$  the *associated permutation relative to  $J$*  is defined as  $\rho(f_a) = j_y^{-1}f_a j_x$ .

In other words,  $\rho(f_a)$  is the permutation such that the following diagram commutes:

$$\begin{array}{ccc} [n] & \xrightarrow{\rho(f_a)} & [n] \\ \downarrow j_x & & \downarrow j_y \\ N(x) & \xrightarrow{f_a} & N(y) \end{array}$$

Now we can define what it means to be the associated permutation relative to  $J$  of any walk  $p = a_k^{i_k} \dots a_1^{i_1}$ , namely  $\rho(p) = j_y^{-1}f_p j_x$ . It is easy to see from the diagram below that  $\rho(p) = \rho(a_k)^{i_k} \dots \rho(a_1)^{i_1}$ .

## CHAPTER 2. PERMUTATION

$$\begin{array}{ccccccc}
 [n] & \xrightarrow{\rho(f_{a_1})^{i_1}} & [n] & \xrightarrow{\rho(f_{a_2})^{i_2}} & \cdots & [n] \\
 \downarrow j_{x_1} & & \downarrow j_{x_2} & & & \downarrow j_{x_k} \\
 N(x_1) & \xrightarrow{f_{a_1}^{i_1}} & N(x_2) & \xrightarrow{f_{a_2}^{i_2}} & \cdots & N(x_k)
 \end{array}$$

We can also discuss the relation between the permutation of a walk  $p$  relative to different fixed orderings.

**Theorem 2.1.3.** (*Change of fixed ordering formula*) For any mutation system  $(T, A)$  for any fixed ordering set  $J_1, J_2$  for any  $x, y \in T_0$  for any walk  $p : x \rightarrow y$ , let  $\rho_1(p), \rho_2(p)$  be the associated permutation of  $p$  relative to  $J_1, J_2$  respectively. Let  $\tau_x = j_{1x}^{-1} j_{2x}$ ,  $\tau_y = j_{1y}^{-1} j_{2y}$ . Then  $\rho_2(p) = \tau_y^{-1} \rho_1(p) \tau_x = j_{2y}^{-1} j_{1y} \rho_1(p) j_{1x}^{-1} j_{2x}$ .

The theorem can be verified easily by the diagram below.

$$\begin{array}{ccc}
 [n] & \xrightarrow{\rho_2(p)} & [n] \\
 \downarrow \tau_x & & \downarrow \tau_y \\
 j_{2x} \left( [n] \xrightarrow{\rho_1(p)} [n] \right) j_{2y} & & \\
 \downarrow j_{1x} & & \downarrow j_{1y} \\
 N(x) & \xrightarrow{f_a} & N(y)
 \end{array}$$

We can see that in essence the permutation of a reddening or loop sequence is just special cases of permutations of walks.

It is obvious that any  $(T, A, J)$  induces a map  $g : \tilde{T}_1 \rightarrow [n]$  that assigns a *fixed position* to each signed edge. We call the map  $g$  the *fixed position map*. It is also obvious that for any walk  $w : x \rightarrow y$ , we only need to fix  $j_x, j_y$  to have a fixed  $\rho(w)$ .  $\rho(w)$  is independent of  $j_z$  for any  $z \neq x, y$ . Hence the definition of  $\rho(w)$  can be done with any arbitrary choice of  $j_z$  for any  $z \neq x, y$ . In fact even not defining them is also fine since we can just define  $\rho(w)$  as

$$j_y^{-1} f_w j_x.$$

## 2.2 The associated permutation in $A_n$

When the quiver is  $A_n$  straight orientation we can make much stronger claims. In fact there is a canonical permutation of any mutation sequence. Using the notations in Section 1.6.1 the formula of the associated permutation of reddening sequences and loop sequences is given as the following.

**Theorem 2.2.1.** *In  $A_n$  straight orientation, the permutation associated with a picture group element that transforms the framed quiver into the coframed quiver or the framed quiver itself is  $\rho(\prod_k x_{i_k j_k}^{\delta_k}) = (\prod_k (i_k + 1, j_k))^{-1}$ . Here  $\delta_k \in \{+, -\}$ .*

This formula works for any maximal green, reddening, loop sequences that starts from and ends up in the framed quiver. It also extended the definition of an associated permutation to the set of arbitrary finite sequences of mutations in  $A_n$  straight orientation. One interesting property of  $A_n$  is that the associated permutation of a mutation only depends on the  $c$ -vector but not which cluster-tilting object on which the mutation is conducted. This is a highly nontrivial fact: The associated permutation in the general case seems way less regular.

### 2.2.1 Forbidden Pairs-of-Walls Lemmas

Since we use picture groups and related structures to prove the theorem, we need to examine what kind of pairs of walls can not exist in any compartment.

**Lemma 2.2.2.** *(First Forbidden Pairs-of-Walls Lemma) For any compartment for any short exact sequence of roots  $0 \rightarrow s \rightarrow r \rightarrow q \rightarrow 0$  it is impossible to have pairs of such walls:  $+s - r$  or  $-q + r$ .*

*(Second Forbidden Pairs-of-Walls Lemma) For quiver  $A_n$  for any compartment for any short exact sequence of roots  $0 \rightarrow s \rightarrow r \rightarrow q \rightarrow 0$  it is impossible to have pairs of such walls:  $-s - r$ ,  $-r - q$ ,  $+s + r$ , or  $+q + r$ .*

The first lemma is obvious since in either case  $\langle x, s \rangle > 0$  but the root  $R$  is stable which is impossible. As for the second lemma, the reason  $-s - r$  can not appear is that in  $A_n$  when you cross  $D(s)$  you are either going to have  $+s - r$  or  $+s - (r + s)$ . The former is impossible due to Forbidden Pairs-of-Walls Lemma. The latter is impossible due to c-vector theorem and the fact that the sum of a root and any of its subroots is no longer a root any more in  $A_n$ . The reason the other three cases can not happen is almost identical.

### 2.2.2 Proof of the formula

The basic idea in proving the theorem is below:

Since picture group elements freely commute with permutations, what we want to prove can be reduced to  $\rho(\prod_k (i_k + 1, j_k) x_{i_k j_k}) = id$ . This property can further be reduced to

## CHAPTER 2. PERMUTATION

proving that for all  $k$ ,  $(i_k + 1, j_k)x_{i_k j_k}$  in some sense does not permute the c-vectors. This in turn can be reduced to  $(i_k + 1, j_k)x_{i_k j_k}$  as an operation on extended exchange matrices maintain certain properties defined below:

**Definition 2.2.3.** An  $n \times n$  matrix  $M \in M_n(\mathbb{Z})$  is *standard* if the following holds:

1. The diagonal entries are all nonzero.
2. All positive entries can only exist on the diagonal or above. and all negative entries can only exist on the diagonal or below.
3. All columns are in the form  $\pm\beta_{ij}$ .

It is easy to see that all columns of the form  $-\beta_{ij}$  has to be the  $(i + 1)$ -th column and all columns of the form  $\beta_{ij}$  has to be the  $j$ -th column since all other positions violate either Axiom 1 or 2. It is also trivial that the only results of a permutation of columns of  $\pm I_n$  that are standard are  $\pm I_n$  themselves.

**Example 2.2.4.** Here are several examples:

$$\begin{bmatrix} 1 & 1 \\ 0 & -1 \end{bmatrix} \text{ and } \begin{bmatrix} 1 & 0 \\ -1 & -1 \end{bmatrix} \text{ are standard matrices because all three axioms hold.}$$

$$\begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \text{ and } \begin{bmatrix} -1 & -1 \\ 1 & 0 \end{bmatrix} \text{ are not standard matrices since axioms 1 and 2 are violated.}$$

The lemma to be proven that can almost immediately lead to the theorem is stated below:

## CHAPTER 2. PERMUTATION

**Lemma 2.2.5.** *In  $A_n$  straight orientation,  $(i_k + 1, j_k)x_{i_k j_k}$  or  $(i_k + 1, j_k)x_{i_k j_k}^{-1}$  transforms a standard matrix  $\tilde{B}_{k-1}$  into a standard matrix  $\tilde{B}_k$ .*

*Proof.* We will only prove in the green case since the red case is almost identical to the green one. In this proof  $i_k$  is simplified as  $i$  and  $j_k$  is simplified as  $j$ .

Case 1: If  $j - i = 1$ . Here we have a simple root and the associated permutation  $(i + 1, j)$  is identity. Hence the proof reduces to  $x_{ij}$  transforms a standard matrix to another standard one.  $x_{ij}$  merely flips the  $j$ -th column from  $-e_j$  to  $e_j$  and may lengthen some  $-\beta_{li}$  to  $-\beta_{lj}$  for  $l < i$  and shorten some  $\beta_{il}$  to  $\beta_{jl}$  for  $l > j$  without changing which column they are in, but no other operation happens or violations of First Forbidden Pairs-of-Wall Theorem  $(-q + r)$  will happen, hence the resulting matrix is still standard.

Case 2: If  $j - i > 1$ . Here we have an extra generator and the associated permutation is not identity. Now let's discuss what  $(i + 1, j)x_{ij}$  actually does on each column:

a)  $l \leq i$ . Due to  $c$ -vector theorem [18] all  $c$ -vectors have to be  $\pm\beta_{ab}$  for some  $0 \leq a < b \leq n$ . So the only change that can ever happen is that  $-\beta_{li}$  may be lengthen to  $-\beta_{lj}$ . Neither of these cause a  $C$ -matrix to violate standardness.

b)  $i + 1 < l < j$ . Again due to  $c$ -vector theorem in [18] the only plausible situation is  $\beta_{il}$  was transformed into  $-\beta_{lj}$ . But this constitutes a  $-q + r$  situation which violates the Forbidden Pairs-of-Wall Lemma.

c)  $l = j$ . We notice several facts:

(1). The  $c$ -vector  $c_j$  can not be negative. If this is the case we have a compartment with two walls  $D(\beta_{ij})$  and  $D(\beta_{j-1, m})$ . This can not happen since these two roots can not be both stable due to [35] when  $m > j$  or the  $+r + s$  situation appears when  $m = j$ . Hence we can assume that the  $j$ -th column is  $\beta_{mj}$  for some  $m < j$ .

## CHAPTER 2. PERMUTATION

(2).  $m$  can not be less than  $i$ . Otherwise we have a  $+s - r$  situation which violates the First Forbidden Pairs-of-Wall Lemma.

(3). Also it is impossible for  $\beta_{mj}$  to remain itself after doing  $x_{ij}$  since otherwise we have a  $-s - r$  situation which violates the Second Forbidden Pairs-of-Wall Lemma.

Hence the  $j$ -th column is positive,  $m > i$  and  $-\beta_{ij}$  actually add to the  $j$ -th column. So after  $(i + 1, j)x_{ij}$  is performed the  $i$ -th column is  $-\beta_{im}$  and the  $j$ -th column is  $\beta_{ij}$ .

d)  $l > j$ .  $\beta_{il}$  can be shortened to  $\beta_{jl}$ . Other than that, the only plausible case is  $l = j + 1$  and the  $k$ th c-vector is  $-\beta_{lm}$  for some  $m > l$ . In this case we can not let  $-\beta_{ij}$  add to the  $l$ -th column since otherwise  $-q + r$  will be created after the mutation which violates the Forbidden Pairs-of-Wall Lemma.

Using similar methods we can see that  $(i + 1, j)x_{ij}$  transforms a standard matrix into another one.

□

The theorem can be proven below:

*Proof.* The identity matrix  $I_n$  is standard. Since  $(i_k + 1, j_k)x_{i_k j_k}$  or  $(i_k + 1, j_k)x_{i_k j_k}^{-1}$  transforms a standard matrix into another standard for all  $k$ , the result of transforming a standard matrix,  $I_n$  by  $\prod_k (i_k + 1, j_k)x_{i_k j_k}^{\delta_k}$  is standard. Since we get a permutation of columns of  $\pm I_n$  at the end of this transformation and any permutation of columns of  $\pm I_n$  that result in a standard matrix has to be the trivial permutation,  $\rho(\prod_k (i_k + 1, j_k)x_{i_k j_k}^{\delta_k}) = id$ , hence the formula is correct.

□



### 2.2.3 The formula of associated permutation for any mutation sequences

Due to the theorem we can extend the definition of associated permutations to any arbitrary mutation sequence in  $A_n$  straight orientation which reduces to the existing definitions of the associated permutation of reddening and loop sequences due to the theorem above.

**Definition 2.2.6.** In  $A_n$  straight orientation, the *associated permutation of a mutation sequence* in correspondence to the picture group element  $\prod_k x_{i_k j_k}^{\delta_k}$  acting on a  $c$ -matrix with associated permutation  $\sigma$  is defined as  $\rho(\prod_k x_{i_k j_k}^{\delta_k}) = \sigma(\prod_k (i_k + 1, j_k))^{-1} \sigma^{-1}$ . Here  $\delta_k \in \{+, -\}$ .

In particular any mutation at a vertex with  $c$ -vector  $\pm\beta_{ij}$  has an associated permutation  $\sigma(i + 1, j)\sigma^{-1}$  with  $\sigma$  the permutation of the  $c$ -matrix before the mutation. In the special case when  $i + 1 = j$  which is when  $\beta_{ij}$  is a simple root the associated permutation is trivial.

# Chapter 3

## Tame path algebras are green sequence-finite

### 3.1 Introduction

In Brüstle-Dupont-Pérotin [5] and the paper by Brüstle, Hermes, Igusa and Todorov [6] it is proven that there are finitely maximal green sequences when the quiver is of finite, tame type or the quiver is mutation equivalent to a quiver of finite or tame type. Furthermore in [6] it is proven that any tame quiver has finitely many  $k$ -reddening sequences.

When we restrict our attention to the case where the algebra is basic, connected and hereditary it is a path algebra of a quiver [3]. From now on when we say an  $m$ -maximal green sequence of an algebra we mean an  $m$ -maximal green sequence of its path algebra. Here is the main theorem we have proven.

**Theorem 3.1.1.** *Any tame quiver has finitely many  $m$ -maximal green sequences.*

### CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE

To prove this theorem we only need to prove that only finitely many indecomposable objects can appear as summands of silting objects that can appear in  $m$ -maximal green sequences of tame quivers  $Q$ . Since all indecomposable objects of a basic tame path algebra have to be transjective or regular, only finitely many rigid regular objects between  $\Lambda$  and  $\Lambda[m]$  in  $D_b(\Lambda)$ , namely the modules on the nonhomogeneous tubes  $\mathbb{Z}A_\infty/\langle\tau^k\rangle$  with no repeating composition factors and their shifts. Hence the problem is reduced to proving that only finitely many indecomposable transjective objects between  $\Lambda$  and  $\Lambda[m]$  can appear in  $m$ -maximal green sequences.

To prove this theorem we need two lemmas.

**Lemma 3.1.2.** *For a tame quiver  $Q$  any silting object in  $D^b(kQ)$  contains at most  $n - 2$  regular summands. In other words, at least 2 summands have to be transjective.*

**Lemma 3.1.3.** *For a tame quiver  $Q$  there is a uniform bound, depending only on  $Q$  and  $m$ , on the transjective degree of any transjective summand in any silting object in any  $m$ -maximal green sequence  $D^b(kQ)$ .*

It is easy to see why 3.1.3 implies the theorem. Here the *transjective degree* of an indecomposable transjective object  $\tau^i P_j[k]$  is defined as  $\deg(\tau^i P_j[k]) = i$ . The *maximal transjective degree* and *minimal transjective degree* of a silting object are defined as the highest/lowest transjective degree of its indecomposable transjective summands respectively.

In Section 2 we prove 3.1.2. In Section 3 we prove 3.1.3. In Section 4 we further generalize the theorem to arbitrary finite mutation sequences with finitely many forward/green or backward/red mutations.

## 3.2 Proof of Lemma 3.1.2

To prove 3.1.2 we need to understand regular components of Auslander-Reiten quivers of  $D^b(kQ)$  for tame quivers. Regular components of Auslander-Reiten quivers of tame path algebras are all standard stable tubes with at most three tubes nonhomogeneous (see [11] and Chapter X of [34]). Note that no object on a homogeneous tube is rigid so no object there can appear in a silting object of  $D^b(kQ)$ . Hence we only need to discuss the nonhomogeneous tubes.

It is easy to see that in an indecomposable object in a standard stable tube  $\mathcal{T}$  of size  $n$ ,  $M$  and any of its shifts can not be in the same pre-silting object. If  $\{M_i\}_{i \in I}$  are a family of indecomposable objects of  $D^b(kQ)$  and  $\Pi_{i \in I} M_i[n_i]$  is not pre-silting for any  $\{n_i\}_{i \in I}$ . We say that  $\{M_i\}_{i \in I}$  is *silting-incompatible*. Otherwise we say that it is *silting-compatible*. From now on in this proof we identify  $[n]$  with  $\mathbb{Z}/n\mathbb{Z}$  and hence will no longer differentiate between 0 and  $n$  which we usually denote as  $n$ . It is also clear that it makes sense to define  $[a_1, a_2, \dots, a_k]$  on  $[n]$  in the sense of cyclic orders. Ex:  $[1, 2, 3]$  and  $[2, 3, 1]$  hold in  $[4]$ . Let  $M_i$  be the regular simples of the tube such that  $\tau M_i = M_{i-1}$ . We call a regular module in  $D^b(kQ)$  *regular sincere* if its composition series contain all regular simples. No indecomposable regular sincere modules or their shifts can appear as summands in any silting object because they are not rigid. (See Corollary X.2.7 of [34]). As for the remaining  $n(n-1)$  indecomposable regular modules that are actually rigid we can unambiguously label them as  $M_{ij}$  if the regular top and regular socle of the object are  $M_j$  and  $M_i$  respectively. Note that  $M_i = M_{ii}$ . It is clear that  $\tau M_{ij} = M_{i-1, j-1}$  and  $\tau^{-1} M_{ij} = M_{i+1, j+1}$ .

Now let's prove two easy lemmas on what can not appear in a pre-silting object in a regular component of the Auslander-Reiten quiver of  $D^b(kQ)$ .

### CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE

**Lemma 3.2.1.** 1. If  $M$  and  $N$  are regular modules in a nonhomogeneous tube in the Auslander-Reiten quiver of  $kQ$ . If  $\text{Hom}(M, N) \neq 0$  and  $\text{Ext}^1(N, M) \neq 0$ , then  $M$  and  $N$  are silting-incompatible.

2. If  $M_1, \dots, M_k$  are regular modules in a nonhomogeneous tube in the Auslander-Reiten quiver of  $kQ$ . If  $\text{Ext}^1(M_i, M_{i+1}) \neq 0$  for any  $1 \leq i < k$  and  $\text{Ext}^1(M_k, M_1) \neq 0$ , then  $\{M_i\}$  is silting-incompatible.

*Proof.* For (1) since  $\text{Hom}(M, N) \neq 0$ ,  $\text{Ext}^{i-j}(M[i], N[j]) \neq 0$  if  $i > j$ . Since  $\text{Ext}^1(N, M) \neq 0$ ,  $\text{Ext}^{j-i+1}(N[j], M[i]) \neq 0$  if  $i \leq j$ . Hence  $M[i] \oplus N[j]$  is not pre-silting for any arbitrary  $i$  and  $j$ .

For (2) for arbitrary  $n_1, \dots, n_k$  use the argument above it is easy to see that if  $\bigoplus_{i=1}^k M_i[n_i]$  is pre-silting, then  $n_2 > n_1, n_3 > n_2, \dots, n_1 > n_k$  which is impossible. Hence  $\{M_i\}$  is silting-incompatible.  $\square$

**Lemma 3.2.2.** Any pre-silting object in a standard stable tube of size  $n$  contains at most  $n - 1$  summands.

To prove this lemma we need the following lemma.

**Lemma 3.2.3.** Any pre-silting object in a standard stable tube of size  $n$  can not be regular sincere.

*Proof.* Assume that a pre-silting object  $T = \bigoplus_{i=1}^k T_i$  in a standard stable tube of size  $n$  is regular sincere. Let  $T_{l_1}, \dots, T_{l_m}$  be a minimal set of indecomposable summands of  $T$  such that their direct sum  $T' = \bigoplus_{i=1}^m T_{l_i}$  is regular sincere. Note that if  $M_{ij}$  and  $M_{kl}$  are both summands of  $T$ ,  $[i, k, l, j]$  holds  $M_{kl}$  and  $M_{ij}$  can not both be summands of  $T'$  due to

### CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE

minimality. If  $m = 1$   $T'$  is a regular sincere indecomposable regular object which contradicts the fact that  $T'$  is pre-silting. If  $m > 1$  without loss of generality assume that  $T_{l_1} = M_{1p}$  for some  $p \neq n$ . Any indecomposable object with its regular socle  $M_i, 1 \leq i \leq p$  can not be a summand of  $T'$  either due to silting incompatibility or minimality. Hence there has to be a summand of  $T'$  with its regular socle  $p + 1$ . Repeat this procedure it's easy to see that  $T' = \bigoplus_{i=1}^m M_{(t_{i-1}+1)t_i}$  with  $t_0 = t_m = n$ . In this case by Lemma 2.3 the object can not be pre-silting.  $\square$

Now we can prove 3.2.2.

*Proof.* Since any pre-silting object in a standard stable tube of size  $n$  can not be regular sincere, without loss of generality it is a pre-silting object in the exact subcategory of  $\mathcal{T}$  closed under extensions such that  $M_1, \dots, M_{n-1}$  are the only simple objects. It is easy to see using the condition that the tube is standard stable that the category  $\text{add}(\{M_{ij}\}_{1 \leq i < j \leq n-1})$  is isomorphic to the module category of  $KA_{n-1}$  with straight orientation and as a result any pre-silting object with all indecomposable summands in it or its shifts has at most  $n - 1$  summands.  $\square$

Finally we can prove 3.1.2.

*Proof.* Due to 3.2.2 and [11] there are at most  $n - 2$  regular components in  $D^b(kQ)$  when  $Q$  is a tame quiver. This is true for each type so this is true for all tame quivers.  $\square$

## 3.3 Proof of Lemma 3.1.3

To prove 3.1.3 we need to rephrase an argument in [5] using degrees.

### CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE

**Lemma 3.3.1.** ([5], Lemma 10.1) *Let  $H$  be a representation-infinite connected hereditary algebra. Then there exists  $N \geq 0$  such that for any  $k \geq N$ , for any projective  $H$ -module  $P$ , the  $H$ -modules  $\tau^{-k}P$  and  $\tau^k P[1]$  are sincere.*

**Lemma 3.3.2.** ([5]) *Let  $Q$  be a tame quiver and  $M_1, M_2$  two transjective modules of  $kQ$ . If  $\{M_1, M_2\}$  is silting-compatible, then  $|\deg(M_1) - \deg(M_2)| \leq N$*

*Proof.* If  $k - l > N$  we need to prove that  $\tau^k P_a$  and  $\tau^l P_b$  are silting-incompatible. If  $i \leq j$   $\text{Ext}^{j-i+1}(\tau^l P_b[j], \tau^k P_a[i]) = \text{Ext}^1(\tau^l P_b, \tau^k P_a) = \text{Hom}(\tau^{k-l} P_a, \tau^l P_b) = \text{Hom}(P_a, \tau^{l-k+1} P_b) \neq 0$  since  $\tau^{l-k+1} P_b$  is a sincere preprojective module. If  $i > j$   $\text{Ext}^{i-j}(\tau^k P_a[i], \tau^l P_b[j]) = \text{Ext}^1(\tau^k P_a[1], \tau^l P_b) = \text{Hom}(\tau^{l-k} P_a, \tau^l P_b[1]) = \text{Hom}(P_a, \tau^{k-l+1} P_b[1]) \neq 0$  since  $\tau^{k-l+1} P_b[1]$  is a sincere preinjective module. Hence  $\tau^k P_a$  and  $\tau^l P_b$  are silting-incompatible. Exchange the objects if  $k - l < -N$ . Hence the lemma has been proven.  $\square$

Now we can prove 3.1.3 following a modified version of the argument in [5].

*Proof.* We only need to prove that there is a lower bound of minimal transjective degrees of silting objects that can appear in  $m$ -maximal green sequences. Assume that  $\tau_k P_i[j]$  is in a silting object in an  $m$ -maximal green sequence of  $kQ$ . Note that due to 3.1.2 there are at least 2 transjective components in any silting object in  $D^b(kQ)$ . Note that each mutation on a transjective object  $T$  in  $\mathcal{P}_i$  can result in a transjective object in  $\mathcal{P}_{i+1}$ , a transjective object in  $\mathcal{P}_i$  with degree less than or equal to  $\deg(T)$  or a regular object in  $\mathcal{R}_i$ . Each mutation on a regular object  $T'$  in  $\mathcal{R}_i$  can result in an object of  $\mathcal{R}_i$ , an object of  $\mathcal{P}_{i+1}$  or an object of  $\mathcal{R}_{i+1}$ . Let  $L$  be the minimal transjective degree of a silting object. No green mutation within a component or green mutation from a regular component to another one can increase  $L$ . All other green mutations may increase  $L$  by at most  $N$ . However there are only  $n$  summands of a silting object,  $m + 1$  transjective components and  $m$  regular components so the amount

### CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE

of mutations that can increase  $L$  is finite. To reach  $\Lambda[m]$  which is of degree 0  $L$  has to be at least  $-2mnN$ . As a result no indecomposable transjective object in any silting object in an  $m$ -maximal green sequence can have a degree less than  $-2mnN$ . Similarly silting objects in  $m$ -maximal green sequences can not have maximal transjective degree higher than  $2mnN$  or it can not start from  $\Lambda$ .  $\square$

## 3.4 Almost morphism finiteness

Using the same method we can prove a stronger result.

**Theorem 3.4.1.** *If  $Q$  is a Dynkin or tame quiver and  $T_1, T_2$  are silting objects of  $D^b(kQ)$  then there are finitely many  $k$ -red and finitely many  $k$ -green mutation sequences from  $T_1$  to  $T_2$  for any  $k$ .*

Note that we only need to prove that part of the statement about  $k$ -red sequences. To prove the theorem we first need to prove the following lemma which is a generalization of Lemma 4.4.2 in [6].

**Lemma 3.4.2.** *1. Any  $k$ -red sequence from  $T_1$  to  $T_2$  can go through any silting object at most  $r + 1$  times.*

*2. Any  $k$ -green sequence from  $T_1$  to  $T_2$  can go through any silting object at most  $r + 1$  times.*

*Proof.* We only need to prove (1). It is clear from the definition of mutations that a green sequence can go through any silting object at most once. (See [10] and [26] for more details.) Let's define a *green arm* of a mutation sequence as a maximal subsequence of the mutation sequence that is green. Similarly we can define what is a *red arm*. Assume that an  $k$ -red



### CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE

sequence  $\{T_i\}$  has  $n_r$  red arms and  $n_g$  green arms.  $n_r \leq k$ .  $n_g \leq n_r + 1$ . Let  $n_1$  be the number of red arms of length 1 and  $n_2$  the number of red arms of length at least 2. It's clear that  $n_r = n_1 + n_2$  and  $n_1 + 2n_2 \leq k$ . Note that any silting object on a red arm of length 1 is on a green arm. Hence  $\{T_i\}$  can go through any silting object at most  $n_g + n_2 \leq n_1 + 2n_2 + 1 \leq k + 1$  times.  $\square$

It is easy to see that the bounds established in the lemma are optimal. Now we can prove the theorem. Note that the lemma above implies that in the Euclidean case if we can prove that for any  $k$  if there are finitely many rigid objects that  $ck$ -redn appear as summands of silting objects in  $k$ -red sequences Theorem 3.4.1 will be proven.

*Proof.* As we said above we will only prove the part about  $k$ -red sequences. Assume that all indecomposable summands of  $T_1$  and  $T_2$  are between  $\Lambda[i]$  and  $\Lambda[j]$ . Since there are only  $k$  red mutations, all indecomposable summands that appear in  $k$ -red sequences from  $T_1$  to  $T_2$  have to be between  $\Lambda[i - k]$  and  $\Lambda[j + k]$ .

If  $Q$  is Dynkin there are only finitely many indecomposable objects between  $\Lambda[i - k]$  and  $\Lambda[j + k]$  and hence only finitely many silting objects can exist on an  $k$ -red sequence. Due to Lemma 3.4.2 there are finitely many  $k$ -red sequences.

From now on we assume that  $Q$  is Euclidean. There are only finitely many regular rigid indecomposable objects between  $\Lambda[i - k]$  and  $\Lambda[j + k]$  so the problem has been reduced to proving that only finitely many transjective indecomposable components can appear in silting objects in  $k$ -red sequences.

Let the minimal degree of  $T_2$  be  $L$ . Note that a red mutation can increase the minimal degree of a silting object by at most  $N$ . Use an argument similar to that one used to prove Theorem 4.1.1 we can prove that no indecomposable transjective object with degree less than  $L - 2nN(2k + j - i) - kN$  can appear in any  $k$ -red sequences from  $T_1$  to  $T_2$ . Similarly

### CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE

let the maximal degree of  $T_1$  be  $U$ . No indecomposable transjective object with degree less than  $U + 2nN(2k + j - i) + kN$  can appear in any  $k$ -red sequence from  $T_1$  to  $T_2$ . Hence there are only finitely many indecomposable transjective objects can appear in any  $k$ -red sequence from  $T_1$  to  $T_2$  and the theorem is proven.  $\square$

Note that the bounds of transjective degrees in the proofs of theorem 4.1.1 and 3.4.1 above are very crude. In the future we will try to find better bounds.

Finally let's define a new term to characterize finite dimensional algebras that satisfy the conditions of Theorem 3.4.1.

- Definition 3.4.3.**
1. A finite dimensional algebra  $\Lambda$  of finite global dimension such that it has finitely many  $k$ -red sequences from any silting object  $T_1$  to any silting object  $T_2$  for any  $k$  is *almost morphism finite*.
  2. A finite dimensional algebra  $\Lambda$  of finite global dimension such that it has finitely many green sequences from any silting object  $T_1$  to any silting object  $T_2$  for any  $m$  is *green sequence finite*.

Hence we can rephrase Theorem 3.4.1 as the following:

**Theorem 3.4.4.** *If  $\Lambda$  is the path algebra of a quiver of finite or tame type, then  $\Lambda$  is almost morphism finite.*

Note that the condition of an algebra being almost morphism finite is stronger than the condition that it is green sequence finite which is stronger than the condition that there are finitely many  $m$ -maximal green sequences for any  $m$ . An almost morphism finite algebra has finitely many  $k$ -red sequences for any  $k$  hence it has finitely many green-to-red sequences

### *CHAPTER 3. TAME PATH ALGEBRAS ARE GREEN SEQUENCE-FINITE*

with  $k$  red mutations.

# Chapter 4

## Two alternative definitions of $m$ -maximal green sequences

### 4.1 Introduction

In Chapter 1 we introduced a result by Igusa, namely Theorem 1.6.13 namely there are new alternative definitions of maximal green sequences. How the result can possibly be generalized to  $m$ -maximal green sequences in general is an interesting question that we have mostly solved.

**Theorem 4.1.1.** *(Theorem 4.5.1) Let  $\Lambda$  be a finite dimensional hereditary algebra. Let  $\mathcal{T} = \text{add}(\cup_{i=0}^{m-1}(\text{mod } \Lambda)[i])$ . Let  $M_1, \dots, M_n$  be a finite sequence of nonzero objects in  $\mathcal{T}$ . The following are equivalent:*

1. *The sequence is a maximal sequence of backward  $\text{Hom}^{\leq 0}$ -orthogonal Schurian objects  $\{M_n\}$  in  $\mathcal{T}$ .*

## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

2. *The sequence is a finite sequence in  $\mathcal{T}$  that forms a finite HN system for  $\mathcal{T}$ .*
3. *The sequence is a sequence of simples from the simple-minded collection  $\{S_1, \dots, S_n\}$  to  $\{S_1[m], \dots, S_n[m]\}$ . that is, it is an  $m$ -maximal green sequence..*

In Section 2 we will discuss an alternative definition of the stability condition on module categoris. In Section 3 we will discuss maximal backward- $\text{Hom}^{\leq 0}$  orthogonal sequences. In Section 4 we will discuss Harder-Narasimhan filtrations. In Section 5 we will establish the fact that the two alternative definitions are equivalent to the original ones.

### 4.2 Alternative definition of the stability condition on module categories

This section is not used in the rest of the chapter. However it does provide new definitions of stability and semistability that are previously underdiscussed. Moreover the ideas in this section are related to  $\text{Hom}^{\leq 0}$ -backward orthogonal sequences.

In general in a triangulated category the concepts of monomorphisms and epimorphisms are less important because there are almost no nontrivial ones. Instead the concept of homotopy kernels and homotopy cokernels are much more important.

Before we can generalize the idea of a maximal green sequence we first need to generalize the idea of a stability condition without always relying on monomorphisms and epimorphisms.

**Theorem 4.2.1.** *If  $\Lambda$  is a finite dimensional hereditary algebra for an indecomposable module  $M$  in a module category  $\text{mod}\Lambda$  for a stability condition  $\phi$  the following are equivalent:*

## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

1.  $M$  is stable.
2. For any proper quotient module  $N$  of  $M$   $\phi(M) < \phi(N)$ .
3. For any indecomposable stable module  $N \not\cong M$  such that  $(M, N) \neq 0$   $\phi(M) < \phi(N)$ .
4. For any indecomposable stable module  $N \not\cong M$  such that  $(N, M) \neq 0$   $\phi(N) < \phi(M)$ .

*Proof.* (1)→(2) If  $N$  is a quotient module of  $M$ , we have the short exact sequence  $0 \rightarrow \sum_{i=1}^k R_i \rightarrow M \rightarrow N \rightarrow 0$ . Since  $M$  is stable  $\phi(\sum_{i=1}^k R_i) < \phi(M)$  hence  $\phi(N) > \phi(M)$ .

(2)→(1) This proof is analogous to the proof of (1)→(2).

(1),(2)→(3) If  $M$  is a submodule of  $N$  or  $N$  is a quotient module of  $M$  then due to (1) and (2) the statement is trivially true. Assume that there exists neither monomorphisms nor epimorphisms from  $M$  to  $N$ . Assume that there exists  $0 \neq f \in (M, N)$  it is easy to see that  $Im f \in mod \Lambda$ . Take one of its indecomposable summand,  $L$ . It is easy to see that  $L$  is a proper submodule of  $N$  and a proper quotient module of  $M$  at the same time. Since  $M, N$  are stable we have  $\phi(M) < \phi(L) < \phi(N)$ .

(1),(2)→(4) This proof is analogous to the proof of (1),(2)→(3).

(4)→(1) Use induction. If  $M$  is simple it is of course stable. Hence (4)→(1) is trivially true in the case of simples. Otherwise assume that (4)→(1) is already true for all indecomposable modules with dimension less than  $dim(M)$ . If  $M$  satisfies condition (4) then for any of its stable submodule  $N$  we already have  $\phi(N) < \phi(M)$  so we only need to focus on the non-stable ones. Assume that  $L$  is one of its minimal non-stable indecomposable proper submodules such that  $\phi(L) \geq \phi(M)$ . By induction since  $\neg(1) \rightarrow \neg(4)$  holds for  $L$  there has to be an indecomposable stable module  $N \not\cong L$  such that  $(N, L) \neq 0$  and  $\phi(N) \geq \phi(L)$ . Hence  $\phi(N) \geq \phi(L) \geq \phi(M)$  and  $(N, M) \neq 0$ . Hence  $M$  does not satisfy condition (4) and we have reached a contradiction. As a result (4)→(1) is proven.

## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

(3) $\rightarrow$ (2) This proof is analogous to the proof of (4) $\rightarrow$ (1). Use induction. If  $M$  is simple (2) of course holds. Hence (3) $\rightarrow$ (2) is trivially true in the case of simples. Otherwise assume that (3) $\rightarrow$ (2) is already true for all indecomposable modules with dimension less than  $\dim(M)$ . If  $M$  satisfies condition (3) then for any of its stable quotient submodule  $N$  we have  $\phi(M) < \phi(N)$  so we only need to focus on the non-stable ones. Assume that  $L$  is one of its minimal non-stable indecomposable proper quotient modules such that  $\phi(M) \geq \phi(L)$ . By induction since  $\neg(2) \rightarrow \neg(3)$  holds for  $L$  there has to be an indecomposable stable module  $N \not\cong L$  such that  $(L, N) \neq 0$  and  $\phi(L) \geq \phi(N)$ . Hence  $\phi(M) \geq \phi(L) \geq \phi(N)$  and  $(M, N) \neq 0$ . Hence  $M$  does not satisfy condition (3) and we have reached a contradiction. As a result (3) $\rightarrow$ (2) is proven. □

We can obtain a similar result in the case of semistability.

**Theorem 4.2.2.** *If  $\Lambda$  is a finite dimensional algebra for an indecomposable module  $M$  in a module category  $\text{mod}\Lambda$  for a stability condition  $\phi$  the following are equivalent:*

1.  *$M$  is semistable.*
2. *For any proper quotient module  $N$  of  $M$   $\phi(M) \leq \phi(N)$ .*
3. *For any indecomposable stable module  $N$  such that  $(M, N) \neq 0$   $\phi(M) \leq \phi(N)$ .*
4. *For any indecomposable stable module  $N$  such that  $(N, M) \neq 0$   $\phi(N) \leq \phi(M)$ .*

### 4.3 Maximal backward $Hom^{\leq 0}$ orthogonal sequences

In order to discuss maximal backward  $Hom^{\leq 0}$  orthogonal sequences we first need to define them.

**Definition 4.3.1.**  $M_1, M_2, \dots, M_k$  is a *backward  $Hom^{\leq 0}$  orthogonal sequence* of Schur objects if  $(M_i[\geq 0], M_j) = 0$  for all  $i > j$  and all  $M_i$ s are non-zero.

**Definition 4.3.2.**  $M_1, M_2, \dots, M_k \in \mathcal{T}$  is a *maximal backward  $Hom^{\leq 0}$  orthogonal sequence* of Schur objects on  $\mathcal{T}$  if  $(M_i[\geq 0], M_j) = 0$  for all  $i > j$ , all  $M_i$  are Schur and that for any other Schur object  $M' \in \mathcal{T}$  if it is inserted anywhere in the sequence it will no longer be backward  $Hom^{\leq 0}$  orthogonal.

Now let's prove a crucial lemma.

**Lemma 4.3.3.** *If  $H_1, H_2$  are two hearts of  $t$ -structures  $(C^{\leq 0}, C^{\geq 0})$  and  $(C'^{\leq 0}, C'^{\geq 0})$  respectively, there exists a maximal backward  $Hom^{\leq 0}$ -orthogonal sequence from  $H_1$  to  $H_2$  then the first term of the sequence has to be a simple of  $H_1$  that is not in  $H_2$ .*

*Proof.* Let's first assume that  $M \in H_1[l]$  with  $l \geq 0$  is the first term of the maximal backward  $Hom^{\leq 0}$ -orthogonal sequence. Let the truncation functors of  $(C^{\leq 0}, C^{\geq 0})$  be  $\tau_{\geq n}$  and  $\tau_{\leq n}$  respectively. There exists some simple  $S \in H_1$  such that  $S[l]$  is a subobject of  $M$  in  $H_1[l]$  which is Abelian. If there exists no non-initial term  $N$  in the sequence such that  $(N, S) \neq 0$  (note that it is impossible to have  $(N[i], S) \neq 0$  for positive  $i$  due to  $N = \tau_{\leq 0}N$ ) then the sequence is not maximal because  $S$  can be inserted before  $M$ . Hence we assume that such an  $N$  exists, In this case  $(N[l], M) = 0$  or the sequence would have no longer been backward



## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

$\text{Hom}^{\leq 0}$ -orthogonal. Let  $N' = \tau_{\geq 0}N$  and  $N'' = \tau_{< 0}N$ . So we have the canonical triangle  $N'' \rightarrow N \rightarrow N' \rightarrow N''[1]$ . Due to  $(N[l], M) = 0$  it is obvious that  $(N'[l], M) = 0$ . Note that  $M, N'[l], S[l] \in H_1[l]$ .  $(N'[l], S[l]) = 0$  since  $S[l]$  is a subobject of  $M$  in an Abelian category. As a result  $(N', S) = 0$  and hence  $(N, S) = 0$  which contradicts the assumption that  $(N, S) \neq 0$ .

Now let's assume that  $M \in \tau_{\geq -l}$  but not  $\tau_{\geq -l+1}$ . Let  $M' = \tau_{\leq -l}M$ . Let  $S[l]$  be a subobject of  $M'$  in  $H_1[l]$  which is Abelian. Note that  $(S[l], M) = (S[l], M') \neq 0$  because  $(S[l], M/M'[-1]) = 0$  since  $M/M'[-1] \in \tau_{\geq -l+1}$ . If there exists no non-initial term  $N$  in the sequence such that  $(N, S) \neq 0$  (note that again it is impossible to have  $(N[i], S) \neq 0$  for positive  $i$  due to  $N = \tau_{\leq 0}N$ ) then the sequence is not maximal because  $S$  can be inserted before  $M$ . Hence we assume that such an  $N$  exists, In this case  $(N[l], M) = 0$  or the sequence would have no longer been backward  $\text{Hom}_{\leq 0}$ -orthogonal. Let  $N' = \tau_{\geq 0}N$  and  $N'' = \tau_{< 0}N$ . So we have the canonical triangle  $N'' \rightarrow N \rightarrow N' \rightarrow N''[1]$ . Due to  $(N[l], M) = 0$  it is obvious that  $(N'[l], M) = 0$  and  $(N'[l], M') = 0$ . Note that  $M', N'[l], S[l] \in H_1[l]$ .  $(N'[l], S[l]) = 0$  since  $S[l]$  is a subobject of  $M'$  in an Abelian category. As a result  $(N', S) = 0$  and hence  $(N, S) = 0$  which contradicts the assumption that  $(N, S) \neq 0$ .

□

### 4.4 Harder-Narasimhan filtration

Now we need to introduce Harder-Narasimhan (HN) filtrations.

**Definition 4.4.1.** Let  $\mathcal{T}$  be a subcategory of a triangulated category.  $M_1, \dots, M_k \in \mathcal{T}$  are a finite sequence of nonzero objects. An *HN filtration of object  $X \in \mathcal{T}$  with respect to  $\{M_i\}$*  aka an HN filtration of an object  $X$  is the following diagram:

CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF  $M$ -MAXIMAL GREEN SEQUENCES

$$\begin{array}{ccccccc}
 0 = X_k & \xrightarrow{\quad\quad\quad} & X_{k-1} & \xrightarrow{\quad\quad\quad} & X_{k-2} & \cdots & \xrightarrow{\quad\quad\quad} & X_0 = X \\
 & \nwarrow \text{dashed} & \swarrow & \nwarrow \text{dashed} & \swarrow & & \nwarrow \text{dashed} & \swarrow \\
 & & X_{k-1}/X_k & & X_{k-2}/X_{k-1} & \cdots & & X_0/X_1
 \end{array}$$

where  $X_{i-1}/X_i$  is a self-extension of  $M_i$ .

**Definition 4.4.2.** Let  $\mathcal{T}$  be a subcategory of a triangulated category.  $M_1, \dots, M_k \in \mathcal{T}$  are a finite sequence of nonzero objects.  $M_1, \dots, M_k$  form a *finite HN system for  $\mathcal{T}$*  if any object  $X \in \mathcal{T}$  has a unique HN filtration with respect to  $M_1, \dots, M_k$ .

**Lemma 4.4.3.** Let  $\Lambda$  be a finite dimensional hereditary algebra. Let  $\mathcal{T} = \cup_{i=0}^{m-1} \text{mod } \Lambda$ . Let  $M_1, \dots, M_n$  be a finite sequence of nonzero objects in  $\mathcal{T}$ . If any object  $Y$  in  $\mathcal{T}$  accept a unique HN filtration  $0 \rightarrow Y_m \rightarrow \cdots \rightarrow Y_1 = Y$  with  $Y_i/Y_{i+1} \in \mathcal{E}(M_i)$ , the following holds.

1. For any  $i$   $M_i \in \text{mod } \Lambda[k]$  for a certain  $k$ .
2. For any  $i$   $M_i$  is indecomposable.
3. For any  $i$   $M_i$  is Schur.

*Proof.* For (1) assume that  $M_i = \oplus_k M_i^k$  such that  $M_i^k \in \text{mod } \Lambda[k]$ . Define the generalized dimension vector of  $M_i$  as  $\dim M_i = \sum_k (-1)^k \dim M_i^k$ . Any object  $X$  that only have  $i$ -th entry in its HN filtration has to satisfy  $\dim X = k \dim M_i$  for some nonnegative  $k$ . If not all entries of  $\dim M_i$  are non-negative then  $M_i^k = 0$  for all odd  $k$  for otherwise the unique HN filtration of  $M_i^k$  can not only have the  $i$ -th entry which violates the condition. Similarly if not all entries of  $\dim M_i$  are non-positive then  $M_i^k = 0$  for all even  $k$ . If  $\dim M_i = 0$  then all  $M_i^k$  has to be 0 because otherwise  $\dim M_i^k$  could never be a multiple of  $\dim M_i$ . Hence  $\dim M_i$  has to be either a positive vector or a negative vector. Without loss of generality let's assume that it is a positive one. In this case  $M_i^k = 0$  for all odd  $k$ . If  $M_i^k \neq 0$  and  $M_i^l \neq 0$  then  $\dim M_i^k < \dim M_i$ . This can not happen either.

## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

For (2) assume that  $M_i$  is decomposable. Then  $M_i = A \oplus B$  with  $A \neq 0$  and  $B \neq 0$ . In this case  $A$  and  $B$  have nontrivial HN filtrations with entries other than the  $i$ -th entry and adding them up we should obtain an HN filtration for  $M_i$  with entries other than the  $i$ -th entry which contradicts the fact that  $M_i$  has a unique HN filtration.

For (3) assume that  $M_i$  is not Schur. Then there exists  $f \in \text{End}(M_i)$  such that  $\text{Im} f \neq M_i$ . Take an indecomposable direct summand of  $\text{Im} f$ ,  $Q$ . Since  $Q$  is a quotient module of  $M_i$  and  $\Lambda$  is hereditary  $\text{Ext}^1(M_i/Q, M_i) \rightarrow \text{Ext}^1(M_i/Q, Q) \neq 0$  is a surjection. We have the following diagram.

$$\begin{array}{ccccccc} 0 & \longrightarrow & M_i & \longrightarrow & X & \longrightarrow & M_i/Q \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \parallel \\ 0 & \longrightarrow & Q & \longrightarrow & M_i & \longrightarrow & M_i/Q \longrightarrow 0 \end{array}$$

Due to  $0 \rightarrow M_i \rightarrow Q \oplus X \rightarrow M_i \rightarrow 0$  being a short exact sequence with is a consequence of a pushout diagram on the left and  $M_i \hookrightarrow X$  being monomorphic,  $Q \oplus X$  has two HN-filtrations, one containing the  $i$ -th entry only while the other definitely contain what is not in the  $i$ -th entry because  $Q$  can not only have the  $i$ -th entry.

□

**Lemma 4.4.4.** *Let  $\Lambda$  be a finite dimensional hereditary algebra. Let  $\mathcal{T} = \cup_{i=0}^{m-1} \text{mod } \Lambda$ . Let  $M_1, \dots, M_n$  be a finite sequence of nonzero objects in  $\mathcal{T}$ . If any object  $Y$  in  $D^b(\Lambda)$  accept a unique HN filtration  $0 \rightarrow Y_N \rightarrow \dots \rightarrow Y_1 = Y$  with  $Y_i/Y_{i+1} \in \mathcal{E}(M_i)$ , the following holds.*

1.  $\text{Hom}(M_i, M_j) = 0$  for any  $i > j$ .
2. If  $M_j = M_i[1]$  then  $j > i$ . Moreover if  $Y$  is any object and the lowest nonzero entry of the HN filtration of  $Y$  has index can not be higher than the highest nonzero entry of the HN filtration of  $Y[1]$ .
3. If  $Y_i \neq 0$   $\text{Hom}(Y_i, Y) \neq 0$  for any  $i$ .

## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

4. If  $Y/Y_i \neq 0$   $\text{Hom}(Y, Y/Y_i) \neq 0$  for any  $i > 1$ .

5.  $\text{Hom}(M_i[1], M_j) = 0$  for any  $i > j$ .

6. If  $M_j = M_i[m]$  where  $m > 0$  then  $j > i$ . Moreover if  $Y$  is any object and the lowest nonzero entry of the HN filtration of  $Y$  has index can not be higher than the highest nonzero entry of the HN filtration of  $Y[m]$  for any positive  $m$ .

7.  $\text{Hom}(M_i[m], M_j) = 0$  where  $m > 0$  for any  $i > j$ .

*Proof.* (1) is true because otherwise we have completely different HN filtrations for  $M_i \oplus M_j$ , namely  $M_i \xrightarrow{(1,0)^t} M_i \oplus M_j \xrightarrow{(0,1)} M_j \xrightarrow{0} M_i[1]$  and  $M_i \xrightarrow{(1,f)^t} M_i \oplus M_j \xrightarrow{(f,-1)} M_j \xrightarrow{0} M_i[1]$ .

(2) is true because otherwise  $M_i \rightarrow 0 \rightarrow M_i[1] \rightarrow M_i[1]$  will be an HN filtration of 0 and hence there will be at least two HN filtrations of 0. Similarly if the HN filtration of  $Y$  is strictly before the HN filtration of  $Y[1]$   $0 \rightarrow Y \rightarrow Y[1] \rightarrow 0$  will be an HN filtration of 0.

Let  $l \geq i$  be any number such that  $Y_l/Y_{l+1} \neq 0$ . Since  $Y_i \neq 0$  such  $l$  must exist. (3) is true because  $Y_i \rightarrow Y \rightarrow Y/Y_i \rightarrow Y_i[1]$  is a triangle. If  $\text{Hom}(Y_i, Y) = 0$  the triangle splits and  $Y/Y_i = Y \oplus Y_i[1]$ . Since  $Y_i[1]$  has a unique HN filtration  $Y/Y_i$  has two HN filtrations, one with the  $l$ -th entry 0 and one with a nontrivial  $l$ -th entry.

Let  $l < i$  be any number such that  $Y_l/Y_{l+1} \neq 0$ . Since  $Y/Y_i \neq 0$  such  $l$  must exist. (4) is true because  $Y_i \rightarrow Y \rightarrow Y/Y_i \rightarrow Y_i[1]$  is a triangle. If  $\text{Hom}(Y, Y/Y_i) = 0$  the triangle splits and  $Y_i = Y \oplus Y_i[-1]$ . Since  $Y_i[-1]$  has a unique HN filtration  $Y_i$  has two HN filtrations, one with the  $l$ -th entry 0 and one with a nontrivial  $l$ -th entry.

Now let's prove (5). Assume that  $i > j$  and  $\text{Hom}(M_i[1], M_j) \neq 0$ . Since  $\text{Hom}(M_i, M_j[-1]) \neq 0$  and that  $M_j \in \mathcal{T}$  it is clear that  $M_j[-1] \in \mathcal{T}$  and hence has a unique HN filtration. Let's first assume that the highest term of the HN filtration of  $M_j[-1]$  is a self-extension of  $M_i$ . If this is not the case assume that the highest term is a self-extension of  $M_{i'}$ . If

## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

$i' \leq j$  then it is clear that  $\text{Hom}(M_i, M_j[-1]) = 0$  since the Hom from  $M_i$  to all terms in the HN filtration of  $M_j[-1]$  is 0 due to (1). Hence  $i' > j$  and we can simply use  $i'$  instead of  $i$  since  $\text{Hom}(M_{i'}, M_j[-1]) \neq 0$ . So we can indeed assume that the highest entry of the HN filtration of  $M_j[-1]$  is a self-extension of  $M_i$ . Let such an entry be  $X_i$ . Since  $\text{Hom}(M_i[1], M_j) \neq 0$  and  $M_i \in \mathcal{T}$  we can see that  $M_i[1] \in \mathcal{T}$ . As a result  $X_i[1] \in \mathcal{T}$ . Let  $h$  be the highest nontrivial index of the HN filtration of  $X_i[1]$  then  $h$  is not higher than  $j$  or the highest nontrivial index of  $M_j[-1]/X_i$  both of which are lower than  $i$  due to (4) since  $M_j[-1] \rightarrow M_j[-1]/X_i \rightarrow X_i[1] \rightarrow M_j$  is a triangle. Apply (4) again to  $X_i[1]$  as a self-extension of  $M_i[1]$  the highest nontrivial index of the HN filtration of  $M_i[1]$  is lower than  $i$ . Apply (2) to  $M_i$  and we can reach a contradiction.

As for (6), since (2) is already proven let's assume that the result has been proven for all positive integers below  $m$  and use induction. For the first claim it is clear that  $M_i[1]$  can not be any  $M_l$  or the induction hypothesis would be violated. It is also clear that  $M_i[1] \in \mathcal{T}$  since  $M_i, M_i[m] \in \mathcal{T}$ . Take the lowest nonzero entry  $Y_k$  of the HN filtration of  $M_i[1]$ . If  $k = i$  then  $\text{Hom}(M_i[1], M_i) \neq 0$  which can not happen. If  $k > i$  then we can apply the induction hypothesis to the HN filtration of  $M_i[1]$  and  $M_i[m]$  and show that this is false. Hence  $k < i$ . In this case  $\text{Hom}(M_i[1], Y_k) \neq 0$ . Hence  $\text{Hom}(M_i[1], M_k) \neq 0$  which is impossible due to (5). Now let's prove the second claim. Here since  $Y, Y[m] \in \mathcal{T}$  so does  $Y[1]$ . Let the lowest entry of the HN filtration of  $Y[1]$  be  $N_k \in \mathcal{E}(M_k)$  and let  $0 \rightarrow Y_j \rightarrow \cdots Y_l \rightarrow 0$  be the HN filtration of  $Y$ . It is easy to see that  $k < l$  due to the induction hypothesis applied to  $Y[1]$  and  $Y[k]$ . Hence  $\text{Hom}(Y[1], M_k) \neq 0$ . Hence for some  $h > k$   $\text{Hom}(M_h[1], M_k) \neq 0$  which is impossible due to (5).

Finally we need to prove (7). Assume that the result is true for any positive integer below  $m$  which is legit because (5) is already proven. Assume that  $i > j$  and  $\text{Hom}(M_i[m], M_j) \neq 0$ . Since  $\text{Hom}(M_i, M_j[-m]) \neq 0$  and  $M_j \in \mathcal{T}$  it is clear that  $M_j[-m] \in \mathcal{T}$ . Let's first as-

sume that the highest entry of the HN filtration of  $M_j[-m]$  is a self-extension of  $M_i$ . If this is not the case assume that the highest term is a self-extension of  $M_{i'}$ . If  $i' \leq j$  then it is clear that  $\text{Hom}(M_i, M_j[-m]) = 0$  since the Hom from  $M_i$  to all terms in the HN filtration of  $M_j[-m]$  is 0 due to (1). Hence  $i' > j$  and we can simply use  $i'$  instead of  $i$  since  $\text{Hom}(M_{i'}, M_j[-m]) \neq 0$ . So we can indeed assume that the highest entry of the HN filtration of  $M_j[-m]$  is a self-extension of  $M_i$  and let such an entry be  $X_i$ . Since  $\text{Hom}(M_i[1], M_j[1-m]) \neq 0$  and  $M_i \in \mathcal{T}$  we can see that  $M_i[1] \in \mathcal{T}$ . As a result  $X_i[1] \in \mathcal{T}$ . Let  $h$  be the highest nontrivial index of the HN filtration of  $X_i[1]$  then  $h$  is no higher than the highest nontrivial index of  $M_j[-m]/X_i$  or  $\text{Hom}(M_h, M_j[1-m]) \neq 0$  in which case  $h \leq j$  by induction since  $M_j[-m] \rightarrow M_j[-m]/X_i \rightarrow X_i[1] \rightarrow M_j[1-m]$  is a triangle. Hence in both cases  $h < i$ . Apply (4) again to  $X_i[1]$  as a self-extension of  $M_i[1]$  the highest nontrivial index of the HN filtration of  $M_i[1]$  is lower than  $i$ . Apply (2) to  $M_i$  and we can reach a contradiction.

□

## 4.5 Equivalence of the definitions

**Theorem 4.5.1.** *Let  $\Lambda$  be a finite dimensional hereditary algebra. Let  $\mathcal{T} = \text{add}(\cup_{i=0}^{m-1} (\text{mod } \Lambda)[i])$ .*

*Let  $M_1, \dots, M_n$  be a finite sequence of nonzero objects in  $\mathcal{T}$ . The following are equivalent:*

1. *The sequence is a maximal sequence of backward  $\text{Hom}^{\leq 0}$ -orthogonal Schurian objects  $\{M_n\}$  in  $\mathcal{T}$ .*
2. *The sequence is a finite sequence in  $\mathcal{T}$  that forms a finite HN system for  $\mathcal{T}$ .*
3. *The sequence is a sequence of simples from the simple-minded collection  $\{S_1, \dots, S_n\}$  to  $\{S_1[m], \dots, S_n[m]\}$ , that is, it is an  $m$ -maximal green sequence.*

## CHAPTER 4. TWO ALTERNATIVE DEFINITIONS OF $M$ -MAXIMAL GREEN SEQUENCES

*Proof.* (1)→(3) By applying lemma 4.3.3 repeatedly it is easy to see that any maximal sequence of backward  $Hom^{\leq 0}$ -orthogonal Schurian objects  $\{M_n\}$  on  $\mathcal{T}$  is also a sequence of simples in hearts of t-structures related to each other by a finite sequence of forward mutations. Hence (1) implies (3).

(2)→(1) Schurness has been proved in Lemma 4.4.3. Backward  $Hom^{\leq 0}$  orthogonality has already been proven in Lemma 4.4.4. Maximality holds because of 4.4.4(3) and (4) due to the reasoning below. Since if the sequence is not maximal then there exists some  $M$ .such that it can be inserted in the backward  $Hom^{\leq 0}$  orthogonal sequence. However such an  $M$  must have a unique HN filtration. Hence there exists some  $i \leq j$  such that  $(M_j, M) \neq 0$  and  $(M, M_i) \neq 0$ . In this case  $M$  can not be inserted in the backward  $Hom^{\leq 0}$  orthogonal sequence which proves its maximality.

(3)→(2) This is obvious because using truncation functors we can easily show that any object in  $\cup_{i=0}^k mod kQ[i]$  can be written uniquely as an HN filtration.  $\square$

# Chapter 5

## Quivers with multiple edges

### 5.1 Introduction

Maximal green sequences (MGSs) were invented by Bernhard Keller [24]. Brustle-Dupont-Perotin [5] and the paper by the first author together with Brustle, Hermes and Todorov [6] have proven that there are finitely maximal green sequences when the quiver is of finite, tame type or the quiver is mutation equivalent to a quiver of finite or tame types. Furthermore in [6] it is proven that any tame quiver has finitely many  $k$ -reddening sequences.

However the situation is still pretty much uncharted in the wild case other than cases where the quiver has three vertices which was proven in [5] which contains a proof highly dependent on the quiver only having three vertices. Despite the fact that the wild case is still unknown in general we can indeed solve it for many easy cases. For example for quivers such as the  $k$ -Kronecker quiver and  $1 \rightrightarrows 2 \rightrightarrows 3$  things are really simple due to the Target before Source Theorem in [6].

In this chapter we will generalize the results and introduce three theorems that can significantly simplify understanding of maximal green sequences in simply-laced quivers with



## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

multiple edges.

We can completely describe MGSs of ME-ful quivers using MGSs of their ME-free versions.

**Theorem 5.1.1.** *(Theorem 5.3.12) MGSs of an acyclic quiver  $Q$  are a subset of the set of  $Q$ -ME-free MGSs of its ME-free version,  $Q'$ .*

**Theorem 5.1.2.** *(Theorem 5.3.13) Let  $Q$  be an ME-ful acyclic quiver and  $Q'$  be its ME-free version. The MGSs of  $Q$  are exactly the  $Q$ -ME-free MGSs  $(C_0, C_1, \dots, C_m)$  of  $Q'$  such that for any multiple edge from  $i$  to  $j$  in  $Q$  for any  $C$ -matrix  $C_i$  in the MGS such that there exists a negative  $c$ -vector with support containing  $i$  the mutation on  $C_i$  in the MGS isn't done on any negative  $c$ -vector with support containing  $j$ .*

In other words to understand MGSs of an acyclic quiver  $Q$  we only need to understand the MGSs of its ME-free version which makes multiple edges largely irrelevant in understanding MGSs of acyclic quivers.

We can obtain the following crucial corollaries in the acyclic case:

**Corollary 5.1.3.** *(Corollary 5.3.14) The following statements are true:*

1. *The number of maximal green sequences of a quiver  $Q$  is no greater than that of its ME-free version.*
2. *All quivers with an MGS-finite ME-free version must themselves be MGS-finite.*
3. *No minimally MGS-infinite quiver can contain multiple edges.*
4. *Any two ME-equivalent quivers are MGS-equivalent to each other.*

If the quiver isn't necessarily acyclic we still have the following result:

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

**Theorem 5.1.4.** *(Theorem 5.4.3) Assume that  $(\tilde{Q}, \check{Q})$  are  $k$ -partition of  $Q$  for some  $k > 1$  any MGS of  $Q$  is an MGS of  $\tilde{Q} \cup \check{Q}$ .*

In Section 2 we will discuss MGS-finiteness in general. In Section 3 we will prove Theorems 5.1.1 and 5.1.2. In Section 4 we will prove Theorem 5.1.4.

### 5.2 MGS-finiteness

In this section let's review the basics about what kind of quivers have finitely many maximal green sequences.

**Definition 5.2.1.** A quiver  $Q$  is *MGS-finite* if  $Q$  has finitely many maximal green sequences. Any quiver that isn't MGS-finite is *MGS-infinite*.

Here are some results that are either already known or easily proven about MGS-finiteness of quivers.

**Theorem 5.2.2.** *[5] Any acyclic quiver  $Q$  of finite type or tame type as well as any acyclic quiver  $Q$  of wild type with three vertices are MGS-finite.*

**Theorem 5.2.3.** *Any quiver  $Q$  mutation equivalent to an acyclic quiver of finite or tame type is MGS-finite.*

*Proof.* Due to [6] the result is already proven in the mutation-equivalent to tame type case. For the mutation-equivalent to finite type case using the Rotation Lemma in [6] it is obvious that any MGS in such a quiver must be an  $k$ -reddening sequence of an acyclic quiver of finite type for a fixed  $k$ . There are only finitely many such sequences because a  $k$ -reddening sequence can only repeat a cluster  $k+1$  times as shown in [6] and [23] and in an acyclic quiver of finite type there are only finitely many cluster-tilting objects and hence clusters.  $\square$

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

**Lemma 5.2.4.** *If  $Q$  is a quiver that isn't connected,  $Q^1, Q^2, \dots, Q^n$  are its connected components. Each  $Q^i$  is MGS-finite if and only if  $Q$  is MGS-finite.*

*Proof.* Any MGS of  $Q$  is essentially formed from taking an MGS  $w_i$  of  $Q^i$  for each  $i$  and then put these mutations together such that the order of elements in each  $w_i$  is preserved.

Since we can obtain all MGSs of  $Q^i$  by deleting all  $c$ -vectors not supported on  $Q_0^i$  from all MGSs of  $Q$  it is easy to see that if  $Q$  is MGS-finite so is  $Q^i$  for any  $i$ .

On the other hand if all  $Q^i$ s are MGS-finite it is easy to see that so is  $Q$  because the set of admissible  $c$ -vectors of  $Q$  is the union of admissible  $c$ -vectors in MGSs of  $Q^i$  all of which are finite.

□

There is also an unrelated result about MGS-finiteness we proved which we will include here.

**Definition 5.2.5.** A quiver is of *finite green mutation type* if there are finitely many exchange matrices along its maximal green sequences.

It is easy to see that any quiver that has finitely many maximal green sequences is of finite green mutation type.

**Lemma 5.2.6.** *If the coframed quiver  $\check{Q}$  of a quiver  $Q$  is of finite green mutation type,  $Q$  has finitely many maximal green sequences.*

*Proof.* For a quiver  $Q$  with  $|Q_0| = n$ , let  $Q' = \check{Q}$  be its coframed quiver and  $Q''$  be the coframed quiver of  $Q'$ . Let's label the extra vertices of  $Q'$  as  $1', \dots, n'$ . Note that any maximal green sequence  $w = (w_1, \dots, w_k)$  of  $Q$  can be extended into a maximal green

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

sequence of  $Q'$ ,  $w' = (w_1, \dots, w_k, 1', 2', \dots, n')$ . Note that any extended exchange matrix that appears in any maximal green sequence of  $Q$  is an exchange matrix in some maximal green sequence of  $Q'$ . Since  $Q'$  is of finite green mutation type, there are only finitely many exchange matrices in all maximal green sequences of  $Q'$ . Hence there are only finitely many extended exchange matrices in any maximal green sequence of  $Q$ . Since extended exchange matrices can not be repeated in a maximal green sequence,  $Q$  has finitely many maximal green sequences.

□

Here is an easy corollary of the lemma above:

**Corollary 5.2.7.** *If all quivers are of finite green mutation type, all quivers have finitely many maximal green sequences.*

Lemma ?? and Corollary ?? also hold for valued quivers which we won't discuss in this paper. The proofs don't change when generalized to valued quivers.

### 5.3 The acyclic case

Now we need some basic definitions in order to describe and prove the results.

**Definition 5.3.1.** A quiver with at least one multiple edge is *ME-ful*. Otherwise it is *ME-free*.

**Definition 5.3.2.** A *multiple edges-free (ME-free)* version of a quiver  $Q$  is produced by removing all multiple edges from  $Q$  while retaining single edges and vertices.

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

For example the ME-free version of the  $m$ -Kronecker quiver for any  $m$  is the quiver  $A_1 \times A_1$ , namely the quiver with two vertices and no arrows.

In this section we will use the fact that a path in the semi-invariant picture of  $Q$  is also a path in the semi-invariant picture of its ME-free version,  $Q'$ . Since the definition of whether a path is green and generic differ in semi-invariant pictures of different quivers we will use the concept of *strong genetic green paths* to exclude problematic cases.

**Definition 5.3.3.** Let  $Q$  be an ME-ful quiver,  $Q'$  be its ME-free version. A path in the semi-invariant pictures of  $Q$  and  $Q'$  is *strong genetic green* if it is a generic green path in both pictures.

**Definition 5.3.4.** Let  $Q$  be an ME-ful quiver.

1. A  $c$ -vector in  $Q$  is *ME-free* if it is ME-free if considered as a dimension vector of  $Q$ . Any  $c$ -vector in  $Q$  that isn't ME-free is *ME-ful*.
2. An MGS in  $Q$  is *ME-free* if all its  $c$ -vectors are ME-free. An MGS of  $Q$  that isn't ME-free is *ME-ful*.
3. A generic green path in the semi-invariant picture of  $Q$  is *ME-free* if it crosses no wall corresponding to an ME-ful  $c$ -vector. A generic green path in the semi-invariant picture of  $Q$  that isn't ME-free is *ME-ful*.
4. A module of  $kQ$  is *ME-free/ME-ful* if its  $c$ -vector is ME-free/ME-ful.

Note that if an MGS is ME-free all  $c$ -vectors in all  $c$ -matrices in it including those that aren't mutated must be ME-free.

If  $Q$  is an ME-ful quiver and  $Q'$  is its ME-free version it does not technically make sense to discuss ME-fulness of any module of  $kQ'$ . Here we are going to use the same definition we used in defining ME-fulness of vectors and MGSs of  $Q$ .

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

**Definition 5.3.5.** Let  $Q$  be an ME-ful quiver and let  $Q'$  be its ME-free version.

1. A  $c$ -vector in  $Q'$  is  $Q$ -ME-free if it is ME-free if considered as a dimension vector of  $Q$ . Any  $c$ -vector in  $Q'$  that isn't  $Q$ -ME-free is  $Q$ -ME-ful.
2. An MGS in  $Q'$  is  $Q$ -ME-free if all its  $c$ -vectors are  $Q$ -ME-free. An MGS of  $Q'$  that isn't  $Q$ -ME-free is  $Q$ -ME-ful.
3. A generic green path in the semi-invariant picture of  $Q'$  is  $Q$ -ME-free if it crosses no wall corresponding to a  $Q$ -ME-ful  $c$ -vector. A generic green path in the semi-invariant picture of  $Q'$  that isn't  $Q$ -ME-free is  $Q$ -ME-ful.
4. A strongly generic green path in the semi-invariant picture of  $Q'$  is *strongly*  $Q$ -ME-free if it is  $Q$ -ME-free and does not cross any wall corresponding to a  $Q$ -ME-ful  $c$ -vector in the semi-invariant picture of  $Q$ . A generic green path in the semi-invariant picture of  $Q'$  that isn't strongly  $Q$ -ME-free is *weakly*  $Q$ -ME-ful.
5. A module of  $kQ'$  is  $Q$ -ME-free/ $Q$ -ME-ful if its  $c$ -vector is  $Q$ -ME-free/ $Q$ -ME-ful.

We will sometimes abuse the notations and use the term  $Q$ -ME-free for  $c$ -vectors/MGSs of  $Q$ . In this case they are just ME-free  $c$ -vectors/MGSs.

**Definition 5.3.6.** If  $Q$  and  $Q'$  have the same number of vertices, a GS  $w$  of  $kQ$  is *equivalent* to a GS  $w'$  of  $kQ'$  if  $w$  and  $w'$  mutates on the same sequence of  $c$ -vectors and start from the same  $c$ -matrix up to permutations.

Using the equivalence it makes sense to identify certain MGSs of  $Q$  and  $Q'$ . It is in this sense that we claim and prove that all MGSs of an ME-ful quiver  $Q$  are MGSs of its ME-free version,  $Q'$ . In order to state a corollary we also need three more definitions.

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

**Definition 5.3.7.** The *skeleton* of a quiver  $Q$  is produced by replacing all multiple edges from  $Q$  by single edges with the sources and targets unchanged.

For example the ME-free version of the  $m$ -Kronecker quiver for any  $m$  is the quiver  $A_2$ .

**Definition 5.3.8.**  $Q$  and  $Q'$  are quivers. If they have the same ME-free version and the same skeleton then they are *ME-equivalent*.

**Definition 5.3.9.** If every MGS of  $Q$  corresponds to some MGS of  $Q'$  and vice versa then  $Q$  and  $Q'$  are MGS-equivalent.

**Lemma 5.3.10.** *Let  $Q$  be a quiver and  $Q'$  be its ME-free version. The following holds:*

1. *The set of  $Q$ -ME-free  $c$ -vectors of  $Q$  and  $Q'$  coincide.*
2. *If  $Q$  is an ME-ful quiver then for any positive  $Q$ -ME-ful vector  $c \in \mathbb{R}^n$   $\langle M, M \rangle_{kQ} - \langle M, M \rangle_{kQ'} \leq -2$ .*
3. *If  $Q$  is an ME-ful quiver. Then any of the  $Q$ -ME-ful  $c$ -vectors can not be a dimension vector of an exceptional module for  $Q'$ . Any of the  $Q$ -ME-ful  $c$ -vectors of  $Q'$  can not be a dimension vector of an exceptional module for  $Q$ .*

*Proof.* For (1). Let the Euler matrices of  $Q, Q'$  be  $E = e_{ij}, E' = (e'_{ij})$  respectively.  $\langle c, c \rangle_{kQ} = \langle c, c \rangle_{kQ'}$  because whenever  $e_{ij}, e'_{ij}$  differ  $c_i = 0$  or  $c_j = 0$  leaving the term related to  $(i, j)$  0. Hence the set of  $Q$ -ME-free  $c$ -vectors of  $Q, Q'$  corresponding to exceptional modules coincide.

For (2) Assume that such a vector,  $c$  exists.  $\langle c, c \rangle_{kQ} = \langle c, c \rangle_{kQ'} = 1$ . However the Euler matrix  $E = (e_{ij})$  of  $Q$  and the Euler matrix  $E' = (e'_{ij})$  of  $Q'$  differ in the sense that there exists some pair  $(i, j) \in [n]$  such that  $c_i \neq 0, c_j > 0$  and  $0 = e'_{ij} > -2 \geq e_{ij}$ . Since for any  $k, l \in [n]$   $e'_{kl} \geq e_{kl}$  it is easy to see that  $\langle c, c \rangle_{kQ'} > \langle c, c \rangle_{kQ}$  and that  $\langle M, M \rangle_{kQ} - \langle M, M \rangle_{kQ'} \leq -2$ .

(3) is a consequence of (2) since  $\langle M, M \rangle_{kQ}$  and  $\langle M, M \rangle_{kQ'}$  can not both be 1.  $\square$

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

**Lemma 5.3.11.** *Let  $Q$  be an ME-ful quiver. Any MGS of an ME-ful quiver  $Q$  must not contain any  $Q$ -ME-ful  $c$ -vector of  $Q'$  or any vector  $c$  which is an imaginary root of  $Q'$ .*

*Proof.* Due to 5.3.10(3) we only need to prove the second part. In that case  $\langle c, c \rangle_{kQ} \leq \langle c, c \rangle_{kQ'} < 1$ . Hence  $c$  is not a  $c$ -vector of  $Q$ .  $\square$

Now we can easily establish the following theorem.

**Theorem 5.3.12.** *MGSs of an acyclic quiver  $Q$  are a subset of the set of  $Q$ -ME-free MGSs of its ME-free version,  $Q'$ .*

*Proof.* If the statement is incorrect along an MGS of  $Q$  pick the first  $C$ -matrix that isn't shared by  $Q'$  assuming that such an MGS exists.

In this case either at least one  $c$ -vector is  $Q$ -ME-ful or none is. If some  $c$ -vector is  $Q$ -ME-ful it must be formed by extending one  $Q$ -ME-free exceptional module by another  $Q$ -ME-free exceptional module in  $Q$  (i.e.  $\dim Ext_{kQ}(A, B) = 1$  because it can not be larger due to Lemma 1.3.12. Let's label the indecomposable module formed by the extension  $M$ . We need  $Ext_{kQ}(B, A) = 0$  so that  $\langle M, M \rangle_{kQ} = 1$  while in  $Q'$  there are no such extensions (i.e.  $\dim Ext_{kQ'}(A, B) = 0$ ). However this is impossible because  $A, B$  are rigid,  $Hom$ -orthogonal and indecomposable because  $\langle M, M \rangle_{kQ} - \langle M, M \rangle_{kQ'} \leq -2$  which causes  $\langle M, M \rangle_{kQ'}$  to be at least 3 which is impossible because  $\langle M, M \rangle_{kQ'} = \langle A, A \rangle_{kQ'} + \langle A, B \rangle_{kQ'} + \langle B, A \rangle_{kQ'} + \langle B, B \rangle_{kQ'} = 2 - \dim Ext_{kQ'}(A, B) - \dim Ext_{kQ'}(B, A)$  is at most 2.

If no  $c$ -vector is  $Q$ -ME-ful then in  $kQ, kQ'$  the relevant  $Hom$  and  $Ext$  groups shouldn't differ because neither of them involve the multiple edges that are absent in  $kQ'$ . As a result that can't happen either.

Hence the  $C$ -matrices corresponding to  $Q, Q'$  in the MGS are all the same. Any MGS of  $Q$  must be an MGS of  $Q'$  with the same  $C$ -matrices. Since all the  $C$ -matrices of the two



## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

quivers are the same they have the same associated permutation.

□

Now we can prove a stronger result.

**Theorem 5.3.13.** *Let  $Q$  be an ME-ful acyclic quiver and  $Q'$  be its ME-free version. The MGSs of  $Q$  are exactly the  $Q$ -ME-free MGSs  $(C_0, C_1, \dots, C_m)$  of  $Q'$  such that for any multiple edge from  $i$  to  $j$  in  $Q$  for any  $C$ -matrix  $C_i$  in the MGS such that there exists a negative  $c$ -vector with support containing  $i$  the mutation on  $C_i$  in the MGS isn't done on any negative  $c$ -vector with support containing  $j$ .*

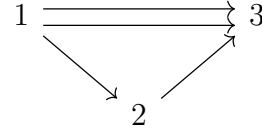
*Proof.* Let's compare  $\langle M, N \rangle_{kQ}$  and  $\langle M, N \rangle_{kQ'}$ . They differ if and only if there exists some multiple edge from  $i$  to  $j$  such that  $i$  is in the support of  $M$  and  $j$  is in the support of  $N$ . In this case since  $\text{Hom}_{kQ}(M, N) = \text{Hom}_{kQ'}(M, N) = \text{Ext}_{kQ'}(M, N) = 0$   $\dim \text{Ext}_{kQ}(M, N) > 0$ . Repeating the argument in 5.3.13 we can show that this is the only possible scenario for a  $Q$ -ME-free MGSs of  $Q'$  to not be identical to an MGS in  $Q$ . □

**Corollary 5.3.14.** *The following statements are true:*

1. *The number of maximal green sequences of a quiver  $Q$  is no greater than that of its ME-free version.*
2. *All quivers with an MGS-finite ME-free version must themselves be MGS-finite.*
3. *No minimally MGS-infinite quiver can contain multiple edges.*
4. *Any two ME-equivalent quivers are MGS-equivalent to each other.*

## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

*Proof.* Only (4) needs to be proven even though it is still obvious. For ME-equivalent quivers  $Q$  and  $Q'$  the conditions of 5.3.13 are identical which is why the number of MGS are identical.  $\square$

**Example 5.3.15.** The maximal green sequences of  $Q$  :  are maximal

green sequences of its ME-free version  $Q' : 1 \rightarrow 2 \rightarrow 3$  that has no  $c$ -vector with support containing  $\{1, 3\}$  and satisfies the conditions in ?? with respect to the arrow  $1 \rightrightarrows 3$  . It's easy to see that  $Q$  is MGS-finite. In fact it has 3 MGSs.

**Example 5.3.16.** The maximal green sequences of  $Q : 1 \rightarrow 2 \rightrightarrows 3 \rightarrow 4$  are some maximal green sequences of its ME-free version  $Q' : 1 \longrightarrow 2 \qquad 3 \longrightarrow 4$  that has no  $c$ -vector with support containing  $\{2, 3\}$  and satisfies the conditions in ?? with respect to the arrow  $2 \rightrightarrows 3$  . It's easy to see that  $Q$  is MGS-finite because  $A_2$  is.

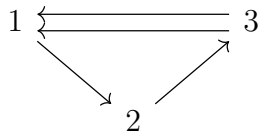
Now we can provide a much shorter proof to the fact that all acyclic quivers with three vertices are MGS-finite which was originally proven in [5].

**Corollary 5.3.17.** *Any acyclic quiver with at most three vertices is MGS-finite.*

*Proof.* Due to the theorem we only need to show that any ME-free acyclic quiver with at most three vertices is MGS-finite. Such a quiver is either of finite or tame type and is hence MGS-finite.  $\square$

## 5.4 The general case

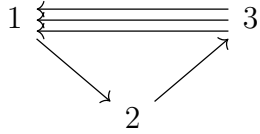
In the general case the theorem above isn't correct. We can show that using the following counterexample. The quiver  $Q$  here is



# CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

$$\begin{bmatrix} 0 & 1 & -2 \\ -1 & 0 & 1 \\ 2 & -1 & 0 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 0 & 2 & -1 \\ -2 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \xrightarrow{\mu_2} \begin{bmatrix} 0 & -1 & -1 \\ 1 & 0 & -1 \\ 1 & 1 & 0 \\ -1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \xrightarrow{\mu_1} \begin{bmatrix} 0 & 1 & 1 \\ -1 & 0 & -1 \\ -1 & 1 & 0 \\ 1 & -1 & -1 \\ 1 & 0 & -1 \\ 0 & 0 & -1 \end{bmatrix} \xrightarrow{\mu_3} \begin{bmatrix} 0 & 2 & -1 \\ -2 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & 1 \\ -1 & 0 & 1 \end{bmatrix} \xrightarrow{\mu_1} \begin{bmatrix} 0 & -2 & 1 \\ 2 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \xrightarrow{\mu_2}$$

Here we have a maximal green sequence with at least one ME-full  $c$ -vector. Moreover it is easy to see that if we replace the double edge by triple edge and obtain  $Q'$  :



$(2,1,3,1,2)$  is not a  $c$ -vector of the quiver  $Q'$  nor is it an MGS of the

ME-free version or skeleton of  $Q$ .

However we can still perform quiver cutting in more limited situations. Let's first introduce a concept.

**Definition 5.4.1.** A  $k$ -edge is a tuple  $(i, j)$  where  $i, j \in [n]$  and  $k|b_{ij}, k|b_{ji}$ .

**Definition 5.4.2.** Let  $Q$  be a quiver possibly having oriented cycles, let  $k$  be an integer greater than 1. Assume that  $Q_0 = \tilde{Q}_0 + \check{Q}_0$ ,  $P = Q|_{\tilde{Q}_0}$ ,  $R = Q|_{\check{Q}_0}$ . If for all  $i \in \tilde{Q}_0, j \in \check{Q}_0$   $k|b_{ij}$  and  $k|b_{ji}$  we say  $Q$  is  $k$ -partible and  $(\tilde{Q}, \check{Q})$  is a  $k$ -partition of  $Q$ .

**Theorem 5.4.3.** Assume that  $(\tilde{Q}, \check{Q})$  are  $k$ -partition of  $Q$  for some  $k > 1$  any MGS of  $Q$

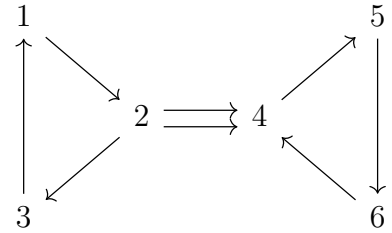
## CHAPTER 5. QUIVERS WITH MULTIPLE EDGES

is an MGS of  $\tilde{Q} \cup \check{Q}$ .

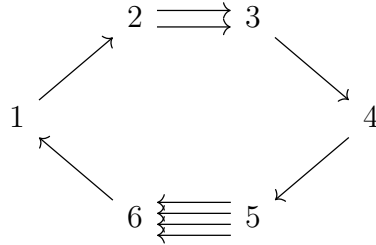
*Proof.* The property that for any  $i \in Q_1$  and  $j \in Q_2$   $k|c_{ij}$  is preserved by mutation. Hence any mutation that cause any  $c$ -vector to cross bot has to violate the Sink before Source Theorem.  $\square$

**Corollary 5.4.4.** *Under the conditions of the theorem above, if  $\tilde{Q}$  and  $\check{Q}$  are MGS-finite so is  $Q$ .*

*Proof.* If  $\tilde{Q}$  and  $\check{Q}$  are MGS-finite so is  $\tilde{Q} \cup \check{Q}$ . As a result so is  $Q$  due to the theorem.  $\square$

**Example 5.4.5.**  $Q :$   is a quiver with oriented cycles. Due to

the theorem we can cut the  $2 \rightrightarrows 4$  arrow. After cutting this arrow it is easy to see that  $Q$  is MGS-finite.

**Example 5.4.6.**  $Q :$   is another quiver with oriented cycles.

Due to the theorem we can cut the  $2 \rightrightarrows 3$  and  $6 \rightrightarrows 5$  arrows. After cutting these arrows it is easy to see that  $Q$  is MGS-finite.

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