

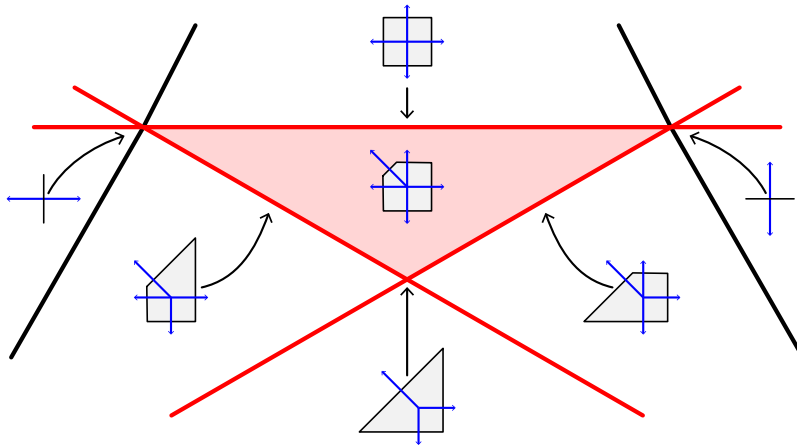
# ASSOCIAHEDRA FOR FINITE TYPE CLUSTER ALGEBRAS AND MINIMAL RELATIONS BETWEEN $g$ -VECTORS

ARNAU PADROL, YANN PALU, VINCENT PILAUD, AND PIERRE-GUY PLAMONDON

ABSTRACT. We show that the mesh mutations are the minimal relations among the  $g$ -vectors with respect to any initial seed in any finite type cluster algebra. We then use this algebraic result to derive geometric properties of the  $g$ -vector fan: we show that the space of all its polytopal realizations is a simplicial cone, and we then observe that this property implies that all its realizations can be described as the intersection of a high dimensional positive orthant with well-chosen affine spaces. This sheds a new light on and extends earlier results of N. Arkani-Hamed, Y. Bai, S. He, and G. Yan in type  $A$  and of V. Bazier-Matte, G. Douville, K. Mousavand, H. Thomas and E. Yildirim for acyclic initial seeds.

Moreover, we use a similar approach to study the space of polytopal realizations of the  $g$ -vector fans of other generalizations of the associahedron. For non-kissing complexes (a.k.a. support  $\tau$ -tilting complexes) of gentle algebras, we show that the space of realizations of the non-kissing fan is simplicial when the gentle bound quiver is brick and 2-acyclic, and we describe in this case its facet-defining inequalities in terms of mesh mutations. For graphical nested complexes, we show that the space of realizations of the nested fan is simplicial only in the case of the associahedron, and we describe its facet-defining inequalities in general.

Along the way, we prove algebraic results on 2-Calabi–Yau triangulated categories, and on extriangulated categories that are of independent interest. In particular, we prove, in those two setups, an analogue of a result of M. Auslander on minimal relations for Grothendieck groups of module categories.



The type cone of the cluster fan of type  $A_2$ .

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## INTRODUCTION

The associahedron is a “mythical polytope” [Hai84] whose facial structure encodes Catalan families: its vertices correspond to parenthesizations of a non-associative product, triangulations of a convex polygon, or binary trees; its edges correspond to applications of the associativity rule, diagonal flips, or edge rotations; and in general its faces correspond to partial parenthesizations, diagonal dissections, or Schröder trees. Its combinatorial and topological structure was introduced in early works of D. Tamari [Tam51] and J. Stasheff [Sta63], and a first 3-dimensional polytopal model was realized by J. Milnor for the PhD defense of J. Stasheff. The first systematic polytopal realizations were constructed by M. Haiman [Hai84] and C. Lee [Lee89]. Since then, the associahedron has been largely “demystified” with several polytopal constructions and generalizations (some are discussed below). Its realizations can be classified into three species: the secondary polytopes [GKZ08, BFS90], the  $\mathbf{g}$ -vectors realizations [Lod04, HL07, LP18, HLT11, HPS18, Pos09, PS12, PS15] and the  $\mathbf{d}$ -vector realizations [CFZ02, CSZ15]. See [CSZ15] for a discussion of some of these realizations and their connections.

The associahedron appears as a fundamental structure in several mathematical theories, such as moduli spaces and topology [Sta63, Kel01], operads and rewriting theory [Str12, MTTV19], combinatorial Hopf algebras [LR98, CP17, Pil18], diagonal harmonics [BPR12, PRV17], mathematical physics [AHBHY18, BLR18, Ram19], etc. Another striking illustration of the ubiquity of the associahedron lies in the theory of cluster algebras introduced by S. Fomin and A. Zelevinsky in [FZ02] with motivation coming from total positivity and canonical bases. Cluster algebras are commutative rings generated by variables obtained from an initial seed by the discrete dynamical process of seed mutations. Finite type cluster algebras, whose mutation graph is finite, were classified in [FZ03a] using the Cartan-Killing classification for crystallographic root systems. Finite type cluster complexes were geometrically realized first by F. Chapoton, S. Fomin and A. Zelevinsky [CFZ02] based on the  $\mathbf{d}$ -vector fans [FZ03b, FZ03a] of the bipartite initial seed, then by C. Hohlweg, C. Lange and H. Thomas [HLT11] based on the Cambrian fans [Rea06, RS09] of acyclic initial seeds, and finally by C. Hohlweg, V. Pilaud and S. Stella [HPS18] based on the  $\mathbf{g}$ -vector fans [FZ07] with respect to an arbitrary initial seed. The resulting polytopes are known as generalized associahedra, and the classical associahedra corresponds to the type  $A$  cluster algebras.

This paper focuses on a surprising construction of the associahedron that recently appeared in mathematical physics. Motivated by the prediction of the behavior of scattering particles, N. Arkani-Hamed, Y. Bai, S. He, and G. Yan recently described in [AHBHY18, Sect. 3.2] the kinematic associahedron. It is a class of polytopal realizations of the classical associahedron obtained as sections of a high-dimensional positive orthant with well-chosen affine subspaces. This construction provides a large degree of freedom in the choice of the parameters defining these affine subspaces, and actually produces all polytopes whose normal fan is affinely equivalent to that of J.-L. Loday’s associahedron [Lod04] (see Section 2.1). These realizations were then extended by V. Bazier-Matte, G. Douville, K. Mousavand, H. Thomas and E. Yıldırım [BMDM<sup>+</sup>18] in the context of finite type cluster algebras using tools from representation theory of quivers. More precisely, they fix a finite type cluster algebra  $\mathcal{A}$  and consider the real euclidean space  $\mathbb{R}^{\mathcal{V}}$  indexed by the set  $\mathcal{V}$  of cluster variables of  $\mathcal{A}$ . Starting from an acyclic initial seed  $\Sigma_{\circ}$ , they consider a set  $\mathcal{M}$  of mesh mutations and compute the corresponding linear dependences between the  $\mathbf{g}$ -vectors, which can be interpreted as linear spaces in  $\mathbb{R}^{\mathcal{V}}$ . Finally, they perturb these mesh linear spaces by a collection  $\ell \in \mathbb{R}_{>0}^{\mathcal{M}}$  of positive parameters and intersect the resulting perturbed mesh affine spaces with the positive orthant  $\mathbb{R}_{\geq 0}^{\mathcal{V}}$  (see Section 2.2). They show that the resulting polytope is always a generalized associahedron, and that its normal fan is the  $\mathbf{g}$ -vector fan of  $\mathcal{A}$  with respect to the initial acyclic seed  $\Sigma_{\circ}$ . An implicit by-product of their construction is that the space of all polytopal realizations of the  $\mathbf{g}$ -vector fan of  $\mathcal{A}$  with respect to the initial acyclic seed  $\Sigma_{\circ}$  is a simplicial cone.

In this paper, we revisit, extend and explore further this construction using a reversed approach. Given a complete simplicial fan  $\mathcal{F}$ , we consider the space  $\mathbb{TC}(\mathcal{F})$  of all its polytopal realizations. This space was called type cone in [McM73] and deformation cone in [Pos09, PRW08], who studied the case when  $\mathcal{F}$  is the braid arrangement leading to the rich theory of generalized permutahedra (recently extended to all finite Coxeter arrangements in [ACEP19]). The type cone is known to be

a polyhedral cone defined by a collection of inequalities corresponding to the linear dependences among the rays of  $\mathcal{F}$  contained in pairs of adjacent maximal cones of  $\mathcal{F}$  (see Definition 1.3). Our approach is based on an elementary but powerful observation: for any fan  $\mathcal{F}$ , all polytopal realizations of  $\mathcal{F}$  can be described as sections of a high dimensional positive orthant with a collection of affine subspaces parametrized by the type cone  $\mathrm{TC}(\mathcal{F})$  (see Proposition 1.10); if moreover the type cone  $\mathrm{TC}(\mathcal{F})$  is a simplicial cone, it leads to a simple parametrization of all polytopal realizations of  $\mathcal{F}$  by a positive orthant corresponding to the facets of the type cone  $\mathrm{TC}(\mathcal{F})$  (see Corollary 1.11). To prove that the type cone  $\mathrm{TC}(\mathcal{F})$  is simplicial, we just need to identify which pairs of adjacent maximal cones of  $\mathcal{F}$  correspond to the facets of  $\mathrm{TC}(\mathcal{F})$  and to show that the corresponding linear dependences among their rays positively span the linear dependence among the rays of any pair of adjacent maximal cones of  $\mathcal{F}$ . When applied to the  $\mathbf{g}$ -vector fans of cluster algebras (see Section 2.2), the type cone approach yields all polytopal realizations of the  $\mathbf{g}$ -vector fans and thus efficiently revisits and extends the construction of [BMDM<sup>+</sup>18]. This new perspective has several advantages, as our proof uniformly applies to:

- **any initial seed**, regardless of whether it is acyclic or not (see Example 2.18 and Figures 6 to 8 for examples in types  $A_3$  and  $C_3$  cyclic). In contrast, the proof of [BMDM<sup>+</sup>18] only treats acyclic initial seeds (although H. Thomas announced in a lecture given at RIMS in June 2019 that this restriction will disappear in a future version of [BMDM<sup>+</sup>18]).
- **all finite type cluster algebras**, regardless of whether it is simply-laced or not (see Example 2.18 for an example in type  $C_3$ ). In contrast, even with the acyclicity restriction, the result of [BMDM<sup>+</sup>18] is first proved in simply-laced cases ( $A$ ,  $D$  and  $E$ ) using representation theory of quivers. Extension to the non simply-laced cases is then argued by a folding argument. Although not presented in detail, this argument is subtle and technical.
- **any positive real-valued parameters**, regardless of whether they are rational or not. In contrast, the proof of [BMDM<sup>+</sup>18] naturally applies to rational parameters and then requires an approximation argument.

These advantages all follow from one essential feature of the type cone approach. Namely, it enables to completely separate the algebraic aspects from the geometric aspects of the problem:

- On the **algebraic side**, we study the relations between the  $\mathbf{g}$ -vectors of a finite type cluster algebra and we show that the mesh mutations minimally generate these relations. For this, we use representation theory in the setting of 2-Calabi–Yau triangulated categories, and we adapt M. Auslander’s proof that the relations in the Grothendieck group of an Artin algebra are generated by the ones given by almost-split sequences precisely when the algebra is of finite representation type [Aus84] (see Section 3).
- On the **geometric side**, we use elementary manipulations to show that a fan whose type cone is simplicial is affinely equivalent to the normal fan of sections of a high dimensional positive orthant with well-chosen affine subspaces (see Section 1). We then observe that our algebraic result precisely states that all type cones of  $\mathbf{g}$ -vector fans of cluster algebras are simplicial from which we derive all our geometric consequences (see Section 2).

These two aspects are interesting in their own right and might be useful in different communities: the geometric side enables to simply describe all polytopal realizations of a fan with simplicial type cone (which is sometimes easier to check than to find an explicit realization), while the algebraic side provides fundamental new results on the  $\mathbf{g}$ -vectors of cluster algebras and on (an extriangulated variant of) the Grothendieck groups of 2-Calabi–Yau triangulated categories with cluster tilting objects. We have therefore deliberately split our presentation into two clearly marked parts that can be read independently. The geometric side, which uses elementary techniques, is presented in Part I together with all its consequences on polytopal realizations. The algebraic side, which is of independent interest, is presented in Part II.

Besides revisiting the construction of [AHBY18, BMDM<sup>+</sup>18] and extending it to any initial seed (acyclic or not) in any finite type cluster algebra (simply-laced or not), our type cone approach is also successful when applied to the  $\mathbf{g}$ -vector fans of other families of generalizations of the associahedron. In the present paper, we explore specifically two families of such generalizations.

- **Gentle associahedra** were constructed in [PPP17] as polytopal realizations of finite non-kissing complexes of gentle bound quivers. These complexes encompass two families of simplicial complexes studied independently in the literature: on the one hand the grid associahedra introduced by T. K. Petersen, P. Pylyavskyy and D. Speyer in [PPS10] for a staircase shape, studied by F. Santos, C. Stump and V. Welker [SSW17] for rectangular shapes, and extended by T. McConville in [McC17] for arbitrary grid shapes; and on the other hand the Stokes polytopes and accordion associahedra studied by Y. Baryshnikov [Bar01], F. Chapoton [Cha16], A. Garver and T. McConville [GM18] and T. Manneville and V. Pilaud [MP19]. The latter, sometimes called accordiohedra, have also recently appeared in the mathematical physics literature concerning scattering amplitudes [BLR18, Ram19], with realizations inspired by those in [AHBHY18]. It was shown in [PPP17, BDM<sup>+</sup>17] that the non-kissing complex of a gentle bound quiver provides a combinatorial model for the support  $\tau$ -tilting complex [AIR14] of the associated gentle algebra. Even for finite non-kissing complexes, it turns out that the type cone of the non-kissing fan is not always simplicial (see Remark 2.47). We prove however that the type cone is always simplicial when the gentle bound quiver is brick (at least 2 relations in any cycle) and 2-acyclic (no oriented cycle of length 2). Moreover, we precisely describe the facet-defining inequalities of the type cone in terms of linear dependences of  $\mathbf{g}$ -vectors involved in certain mesh relations. We thus automatically derive a construction similar to that of [AHBHY18, BMDM<sup>+</sup>18] describing all polytopal realizations of the  $\mathbf{g}$ -vector fans of these brick and 2-acyclic gentle bound quivers as sections of a positive orthant by well-chosen affine spaces (see Section 2.2). Again, this result mainly relies on finding which relations minimally generate the relations between the  $\mathbf{g}$ -vectors in the non-kissing complex. We present both a purely combinatorial proof (see Section 2.2) and a purely algebraic proof for (non-necessarily gentle) brick algebras making use of extriangulated categories (see Section 4). Our algebraic proof is based on an analogue of a result of M. Auslander [Aus84] relating to minimal generators of Grothendieck groups. Along the way, we need to generalize, for extriangulated categories, several results from cluster-tilting theory on indices [DK08] and on abelian quotients [BMR07, KR07] that were known for triangulated categories. We note, however, that our assumptions are not quite the expected ones. This is related to the fact that the Grothendieck groups of cluster categories are badly behaved (*e.g.* the Grothendieck group of a cluster category of type  $A_2$  is trivial). So as to overcome this difficulty, we replace the triangulated structure of cluster categories by some relative extriangulated structure, before considering Grothendieck groups. This explains why we consider projective objects rather than cluster-tilting objects for extriangulated categories.
- **Graph associahedra** were defined by M. Carr and S. Devadoss [CD06] in connection to C. De Concini and C. Procesi's wonderful arrangements [DCP95]. As illustrated in Figure 17, the graph associahedra of certain special families of graphs coincide with well-known families of polytopes: complete graph associahedra are permutahedra, path associahedra are classical associahedra, cycle associahedra are cyclohedra, and star associahedra are stellohedra. The graph associahedra were extended to the nestohedra, which are simple polytopes realizing the nested complex of arbitrary building sets [Pos09, FS05]. Graph associahedra and nestohedra have been geometrically realized in different ways: by successive truncations of faces of the standard simplex [CD06], as Minkowski sums of faces of the standard simplex [Pos09, FS05], or from their normal fans by exhibiting explicit inequality descriptions [Dev09, Zel06]. All these realizations have the same normal fan, called nested fan. We study the type cones of these nested fans (see Section 2.4): we describe their facet-defining inequalities in terms of certain specific pairs of neighboring tubings and count them for the specific families of graph associahedra described earlier. For instance the type cone of the permutahedron coincides with the classical submodular functions on  $2^{[n]}$ , described by  $2^{n-2} \binom{n}{2}$  inequalities. In fact, we observe that the type cone of a graphical nested fan is never simplicial except in the case of the classical associahedron (when the graph is the path). Our results describe nevertheless all polytopal realizations of the graphical nested fans.

Further families of generalizations of the associahedron certainly deserve to be studied with our type cone approach. We are investigating in particular brick polytopes [PS12, PS15] and quotientopes [Rea04, Rea06, PS19]. In fact, as already mentioned, it seems sometimes easier to find all polytopal realizations of a fan (by describing its type cone in terms of certain specific pairs of adjacent maximal cones) than to identify one specific explicit realization. This is clearly the case when the type cone is simplicial as illustrated by the results of this paper: we naturally obtained all polytopal realizations of the  $\mathbf{g}$ -vector fans of cluster algebras from cyclic seeds and of gentle algebras whose polytopality was only established very recently [HPS18, PPP17]. Even when the type cone is not simplicial, describing the type cone sometimes leads to relevant explicit realizations of the fan, as we illustrate on graph associahedra (see Example 2.57). We believe that this approach gives reasonable hope that the polytopality of further fans could in the future be established using our type cone approach. Tempting candidates are quotientopes for hyperplane arrangements beyond type  $A$ , which are particularly interesting since the coarsenings of a fan essentially correspond to the faces of its type cone (see Section 1.5).

Last but not least, the type cone approach naturally opens many research questions. First, it raised the fundamental problem of describing the minimal relations among  $\mathbf{g}$ -vectors in 2-Calabi–Yau and extriangulated categories that we treat in Part II. It also motivates the study of relevant objects revealed by the type cone dictionary between geometry and algebra:

- The facet-defining inequalities of the type cone of  $\mathcal{F}$  correspond to very specific pairs of adjacent maximal cones of  $\mathcal{F}$  whose corresponding linear dependences minimally generate all such dependences. While they correspond to mesh mutations for cluster algebras and brick and 2-acyclic gentle algebras, they are not understood in general (see for instance Figure 14 (right)). It would be particularly interesting to fully understand these specific mutations for arbitrary (non-kissing finite) gentle algebras.
- The rays of the type cone of  $\mathcal{F}$  correspond to specific polytopes which form a positive Minkowski basis of all realizations of  $\mathcal{F}$  (see Section 1.6). In particular, when the type cone is simplicial, any polytopal realization of  $\mathcal{F}$  has a unique representation (up to translation) as a Minkowski sum of positive dilates of these polytopes. For cluster algebras, it follows from [BMDM<sup>+</sup>18, Sect. 6] that these polytopes are Newton polytopes of the  $F$ -polynomials. It would be interesting to obtain similar algebraic interpretations for the rays of the type cones of the non-kissing fans of gentle algebras.
- Once we get a representation of a polytope  $P$  as a signed Minkowski sum  $P = \sum_{i \in [k]} \alpha_i Q_i$ , we get a formula for the volume of  $P$  as a multivariate polynomial in  $\alpha_1, \dots, \alpha_k$  whose coefficients are the mixed volumes of  $Q_1, \dots, Q_k$  [ABD10, McM77]. These encode rich combinatorial information when representing generalized permutahedra as positive Minkowski sums of coordinate simplices or hypersimplices [Pos09], and in particular for matroid polytopes [ABD10]. It would be interesting to get such volume formulas for polytopal realizations of  $\mathbf{g}$ -vector fans of cluster algebras and gentle algebras, and combinatorial interpretations for their coefficients.

Another question related to this paper is to understand the complete realization space of the combinatorics of the associahedra. The associahedra constructed in [AHBHY18, BMDM<sup>+</sup>18] and the present paper describe all polytopal realizations of the  $\mathbf{g}$ -vector fans, but there are other polytopal realizations of the combinatorial type of the associahedron with different normal fans. Is it possible to similarly understand the complete realization space of the cluster complex, including all realizations not having the  $\mathbf{g}$ -vector fan as their normal fan?

To conclude, it is our hope that the present paper will participate to the interactions between combinatorial geometry, representation theory, and mathematical physics; in particular through further developments of the geometric approach to scattering amplitudes that has flourished during the last years [AHT14, AHBC<sup>+</sup>16]. The kinematic associahedron from [AHBHY18] is one of the most recent “positive geometries” [AHBL17] that has emerged in the study of scattering amplitudes.

## Part I. Type cones of $g$ -vector fans

### 1. POLYTOPAL REALIZATIONS AND TYPE CONE OF A SIMPLICIAL FAN

**1.1. Polytopes and fans.** We briefly recall basic definitions and properties of polyhedral fans and polytopes, and refer to [Zie98] for a classical textbook on this topic.

A hyperplane  $H \subset \mathbb{R}^d$  is a *supporting hyperplane* of a set  $X \subset \mathbb{R}^d$  if  $H \cap X \neq \emptyset$  and  $X$  is contained in one of the two closed half-spaces of  $\mathbb{R}^d$  defined by  $H$ .

We denote by  $\mathbb{R}_{\geq 0}\mathbf{R} := \{\sum_{\mathbf{r} \in \mathbf{R}} \lambda_{\mathbf{r}} \mathbf{r} \mid \lambda_{\mathbf{r}} \in \mathbb{R}_{\geq 0}\}$  the *positive span* of a set  $\mathbf{R}$  of vectors of  $\mathbb{R}^d$ . A *polyhedral cone* is a subset of  $\mathbb{R}^d$  defined equivalently as the positive span of finitely many vectors or as the intersection of finitely many closed linear halfspaces. The *faces* of a cone  $C$  are the intersections of  $C$  with the supporting hyperplanes of  $C$ . The 1-dimensional (resp. codimension 1) faces of  $C$  are called *rays* (resp. *facets*) of  $C$ . A cone is *simplicial* if it is generated by a set of linearly independent vectors.

A *polyhedral fan* is a collection  $\mathcal{F}$  of polyhedral cones such that

- if  $C \in \mathcal{F}$  and  $F$  is a face of  $C$ , then  $F \in \mathcal{F}$ ,
- the intersection of any two cones of  $\mathcal{F}$  is a face of both.

A fan is *simplicial* if all its cones are, *complete* if the union of its cones covers the ambient space  $\mathbb{R}^d$ , and *essential* if it contains the cone  $\{\mathbf{0}\}$ . Note that every complete fan is the product of an essential fan with its linearity space. For two fans  $\mathcal{F}, \mathcal{G}$  in  $\mathbb{R}^d$ , we say that  $\mathcal{F}$  *refines*  $\mathcal{G}$  (and that  $\mathcal{G}$  *coarsens*  $\mathcal{F}$ ) if every cone of  $\mathcal{F}$  is contained in a cone of  $\mathcal{G}$ .

A *polytope* is a subset  $P$  of  $\mathbb{R}^d$  defined equivalently as the convex hull of finitely many points or as a bounded intersection of finitely many closed affine halfspaces. The *dimension*  $\dim(P)$  is the dimension of the affine hull of  $P$ . The *faces* of  $P$  are the intersections of  $P$  with its supporting hyperplanes. The dimension 0 (resp. dimension 1, resp. codimension 1) faces are called *vertices* (resp. *edges*, resp. *facets*) of  $P$ . A polytope is *simple* if its supporting hyperplanes are in general position, meaning that each vertex is incident to  $\dim(P)$  facets (or equivalently to  $\dim(P)$  edges).

The (outer) *normal cone* of a face  $F$  of  $P$  is the cone generated by the outer normal vectors of the facets of  $P$  containing  $F$ . In other words, it is the cone of vectors  $\mathbf{c}$  such that the linear form  $\mathbf{x} \mapsto \langle \mathbf{c} \mid \mathbf{x} \rangle$  on  $P$  is maximized by all points of the face  $F$ . The (outer) *normal fan* of  $P$  is the collection of the (outer) normal cones of all its faces. We say that a complete polyhedral fan  $\mathcal{F}$  in  $\mathbb{R}^d$  is *polytopal* when it is the normal fan of a polytope  $P$  of  $\mathbb{R}^d$ , and that  $P$  is a *polytopal realization* of  $\mathcal{F}$ .

**1.2. Type cone.** Fix an essential complete simplicial fan  $\mathcal{F}$  in  $\mathbb{R}^n$ . Let  $\mathbf{G}$  the  $N \times n$ -matrix whose rows are the rays of  $\mathcal{F}$  and let  $\mathbf{K}$  be a  $(N - n) \times N$ -matrix that spans the left kernel of  $\mathbf{G}$  (i.e.  $\mathbf{K}\mathbf{G} = 0$ ). For any height vector  $\mathbf{h} \in \mathbb{R}^N$ , we define the polytope

$$P_{\mathbf{h}} := \{\mathbf{x} \in \mathbb{R}^n \mid \mathbf{G}\mathbf{x} \leq \mathbf{h}\}.$$

We say that  $\mathbf{h}$  is  *$\mathcal{F}$ -admissible* if  $P_{\mathbf{h}}$  is a polytopal realization of  $\mathcal{F}$ . The following classical statement characterizes the  $\mathcal{F}$ -admissible height vectors. It is a reformulation of regularity of triangulations of vector configurations, introduced in the theory of secondary polytopes [GKZ08], see also [DRS10]. We present here a convenient formulation from [CFZ02, Lem. 2.1].

**Proposition 1.1.** *Let  $\mathcal{F}$  be an essential complete simplicial fan in  $\mathbb{R}^n$ . Then the following are equivalent for any height vector  $\mathbf{h} \in \mathbb{R}^N$ :*

- (1) *The fan  $\mathcal{F}$  is the normal fan of the polytope  $P_{\mathbf{h}} := \{\mathbf{x} \in \mathbb{R}^n \mid \mathbf{G}\mathbf{x} \leq \mathbf{h}\}$ .*
- (2) *For any two adjacent maximal cones  $\mathbb{R}_{\geq 0}\mathbf{R}$  and  $\mathbb{R}_{\geq 0}\mathbf{R}'$  of  $\mathcal{F}$  with  $\mathbf{R} \setminus \{\mathbf{r}\} = \mathbf{R}' \setminus \{\mathbf{r}'\}$ ,*

$$\alpha h_{\mathbf{r}} + \alpha' h_{\mathbf{r}'} + \sum_{\mathbf{s} \in \mathbf{R} \cap \mathbf{R}'} \beta_{\mathbf{s}} h_{\mathbf{s}} > 0,$$

where

$$\alpha \mathbf{r} + \alpha' \mathbf{r}' + \sum_{\mathbf{s} \in \mathbf{R} \cap \mathbf{R}'} \beta_{\mathbf{s}} \mathbf{s} = 0$$

is the unique (up to rescaling) linear dependence with  $\alpha, \alpha' > 0$  between the rays of  $\mathbf{R} \cup \mathbf{R}'$ .

**Notation 1.2.** For any adjacent maximal cones  $\mathbb{R}_{\geq 0}\mathbf{R}$  and  $\mathbb{R}_{\geq 0}\mathbf{R}'$  of  $\mathcal{F}$  with  $\mathbf{R} \setminus \{\mathbf{r}\} = \mathbf{R}' \setminus \{\mathbf{r}'\}$ , we denote by  $\alpha_{\mathbf{R},\mathbf{R}'}(\mathbf{s})$  the coefficient of  $\mathbf{s}$  in the unique linear dependence between the rays of  $\mathbf{R} \cup \mathbf{R}'$ , *i.e.* such that

$$\sum_{\mathbf{s} \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R},\mathbf{R}'}(\mathbf{s}) \mathbf{s} = 0.$$

These coefficients are *a priori* defined up to rescaling, but we additionally fix the rescaling so that  $\alpha_{\mathbf{R},\mathbf{R}'}(\mathbf{r}) + \alpha_{\mathbf{R},\mathbf{R}'}(\mathbf{r}') = 2$  (this convention is arbitrary, but will be convenient in Section 2).

In this paper, we are interested in the set of all possible realizations of  $\mathcal{F}$  as the normal fan of a polytope  $P_{\mathbf{h}}$ . This was studied by P. McMullen in [McM73] (see [DRS10, Sect. 9.5] for a formulation in terms of chambers of triangulations of vector configurations).

**Definition 1.3.** The *type cone* of  $\mathcal{F}$  is the cone  $\mathbb{T}\mathbb{C}(\mathcal{F})$  of all  $\mathcal{F}$ -admissible height vectors  $\mathbf{h} \in \mathbb{R}^N$ :

$$\begin{aligned} \mathbb{T}\mathbb{C}(\mathcal{F}) &:= \{ \mathbf{h} \in \mathbb{R}^N \mid \mathcal{F} \text{ is the normal fan of } P_{\mathbf{h}} \} \\ &= \left\{ \mathbf{h} \in \mathbb{R}^N \mid \sum_{\mathbf{s} \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R},\mathbf{R}'}(\mathbf{s}) \mathbf{h}_{\mathbf{s}} > 0 \text{ for any adjacent maximal cones } \mathbb{R}_{\geq 0}\mathbf{R} \text{ and } \mathbb{R}_{\geq 0}\mathbf{R}' \text{ of } \mathcal{F} \right\}. \end{aligned}$$

Note that the type cone is an open cone and contains a linearity subspace of dimension  $n$  (it is invariant by translation in  $\mathbf{G}\mathbb{R}^n$ ). It is sometimes useful to get rid of the linearity space by considering the projection  $\mathbf{K}\mathbb{T}\mathbb{C}(\mathcal{F})$ .

We denote by  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$  the closure of  $\mathbb{T}\mathbb{C}(\mathcal{F})$ , and call it the *closed type cone* of  $\mathcal{F}$ . It is the closed polyhedral cone defined by the inequalities  $\sum_{\mathbf{s} \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R},\mathbf{R}'}(\mathbf{s}) \mathbf{h}_{\mathbf{s}} \geq 0$  for any adjacent maximal cones  $\mathbb{R}_{\geq 0}\mathbf{R}$  and  $\mathbb{R}_{\geq 0}\mathbf{R}'$ . If  $\mathcal{F}$  is the normal fan of the polytope  $P$ , then  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$  is called the *deformation cone* of  $P$  in [Pos09], see also [PRW08].

**Example 1.4.** Consider the 2-dimensional fan  $\mathcal{F}$  depicted in Figure 1 (left) (we will encounter this fan again in Examples 1.14, 1.19 and 2.5). It has five rays labeled  $1, \dots, 5$  and five maximal cones labeled  $a, \dots, e$ . Its type cone  $\mathbb{T}\mathbb{C}(\mathcal{F})$  lies in  $\mathbb{R}^5$ , but has a 2-dimensional linearity space. The five pairs of adjacent maximal cones of  $\mathcal{F}$  give rise to following five defining inequalities for  $\mathbb{T}\mathbb{C}(\mathcal{F})$ :

$$\begin{aligned} H_{ab}^> : \mathbf{h}_1 + \mathbf{h}_3 - \mathbf{h}_2 > 0 & \quad H_{bc}^> : \mathbf{h}_2 + \mathbf{h}_4 - \mathbf{h}_3 > 0 & \quad H_{cd}^> : \mathbf{h}_3 + \mathbf{h}_5 - \mathbf{h}_4 > 0 \\ H_{de}^> : \mathbf{h}_1 + \mathbf{h}_4 > 0 & \quad H_{ae}^> : \mathbf{h}_2 + \mathbf{h}_5 > 0, \end{aligned}$$

where  $H_{ij}^>$  denotes the halfspace defined by the inequality corresponding to the two adjacent maximal cones  $i$  and  $j$ . Note that the inequalities  $H_{ae}^>$  and  $H_{de}^>$  are redundant. For example, the height vector  $(1/2, 3/4, 5/4, 1, 5/4)$  belongs to the type cone  $\mathbb{T}\mathbb{C}(\mathcal{F})$ , and the corresponding polytope is represented in Figure 1 (middle). To represent this type cone, it suffices to represent  $\mathbf{K}\mathbb{T}\mathbb{C}(\mathcal{F})$  which is an essential simplicial cone in  $\mathbb{R}^3$ . One can further reduce the dimension by intersecting with a transversal hyperplane to get a 2-dimensional representation. This is the red triangle depicted in Figure 1 (right).

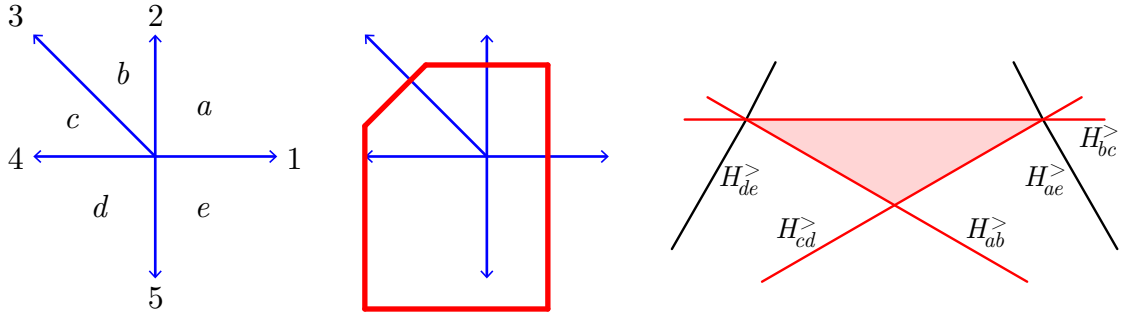


FIGURE 1. A 2-dimensional fan  $\mathcal{F}$  with five rays  $1, \dots, 5$  and five maximal cones  $a, \dots, e$  (left), its polytopal realization corresponding to the height vector  $(1/2, 3/4, 5/4, 1, 5/4)$  (middle), and the intersection of  $\mathbf{K}\mathbb{T}\mathbb{C}(\mathcal{F})$  with a hyperplane to get a 2-dimensional slice (right).



**Definition 1.5.** An *extremal adjacent pair* of  $\mathcal{F}$  is a pair of adjacent maximal cones  $\{\mathbb{R}_{\geq 0}\mathbf{R}, \mathbb{R}_{\geq 0}\mathbf{R}'\}$  of  $\mathcal{F}$  such that the corresponding inequality  $\sum_{\mathbf{s} \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R}, \mathbf{R}'}(\mathbf{s}) \mathbf{h}_{\mathbf{s}} \geq 0$  in the definition of the type cone  $\overline{\text{TC}}(\mathcal{F})$  actually defines a facet of  $\overline{\text{TC}}(\mathcal{F})$ .

In other words, extremal adjacent pairs define the extremal rays of the polar of the closed type cone  $\overline{\text{TC}}(\mathcal{F})$ . Understanding the extremal adjacent pairs of  $\mathcal{F}$  enables to describe its type cone  $\text{TC}(\mathcal{F})$  and thus all its polytopal realizations. For instance, for the 2-dimensional fan of Example 1.4, the extremal adjacent pairs are  $\{a, b\}$ ,  $\{b, c\}$  and  $\{c, d\}$ .

**Remark 1.6.** Since the type cone is an  $N$  dimensional cone with a linearity subspace of dimension  $n$ , it has at least  $N - n$  facets (thus  $N - n$  extremal adjacent pairs). We say that the type cone is *simplicial* when it has precisely  $N - n$  facets.

Although we will only deal with simplicial fans, note for completeness that Proposition 1.1 and Definition 1.3 can be easily adapted to non-simplicial fans. To describe the type cone of an arbitrary complete fan, it suffices to consider any simplicial refinement, and to set some of the strict inequalities of the definition of the type cone to equality (see [PS19, Prop. 3] for a proof).

**Proposition 1.7.** *Let  $\mathcal{F}$  be a complete fan that coarsens the essential complete simplicial fan  $\mathcal{G}$ . The type cone  $\text{TC}(\mathcal{F})$  of all  $\mathcal{F}$ -admissible height vectors  $\mathbf{h} \in \mathbb{R}^N$  is*

$$\text{TC}(\mathcal{F}) = \left\{ \mathbf{h} \in \mathbb{R}^N \left| \begin{array}{l} \sum_{\mathbf{s} \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R}, \mathbf{R}'}(\mathbf{s}) \mathbf{h}_{\mathbf{s}} = 0 \\ \sum_{\mathbf{s} \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R}, \mathbf{R}'}(\mathbf{s}) \mathbf{h}_{\mathbf{s}} > 0 \end{array} \right. \begin{array}{l} \text{for any adjacent maximal cones} \\ \mathbb{R}_{\geq 0}\mathbf{R} \text{ and } \mathbb{R}_{\geq 0}\mathbf{R}' \text{ of } \mathcal{G} \text{ belonging} \\ \text{to the same maximal cone of } \mathcal{F}, \\ \\ \text{for any adjacent maximal cones} \\ \mathbb{R}_{\geq 0}\mathbf{R} \text{ and } \mathbb{R}_{\geq 0}\mathbf{R}' \text{ of } \mathcal{G} \text{ belonging} \\ \text{to distinct maximal cones of } \mathcal{F} \end{array} \right\}.$$

**1.3. Unique exchange property.** Two rays  $\mathbf{r}$  and  $\mathbf{r}'$  of  $\mathcal{F}$  are *exchangeable* if there are two adjacent maximal cones  $\mathbb{R}_{\geq 0}\mathbf{R}$  and  $\mathbb{R}_{\geq 0}\mathbf{R}'$  of  $\mathcal{F}$  with  $\mathbf{R} \setminus \{\mathbf{r}\} = \mathbf{R}' \setminus \{\mathbf{r}'\}$ .

**Definition 1.8.** We say that two exchangeable rays  $\mathbf{r}, \mathbf{r}'$  of  $\mathcal{F}$  admit a *unique exchange relation* when the linear dependence

$$\sum_{\mathbf{s} \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R}, \mathbf{R}'}(\mathbf{s}) \mathbf{s} = 0.$$

does not depend on the pair  $\{\mathbf{R}, \mathbf{R}'\}$  of adjacent maximal cones of  $\mathcal{F}$  with  $\mathbf{R} \setminus \{\mathbf{r}\} = \mathbf{R}' \setminus \{\mathbf{r}'\}$ , but only on the pair of rays  $\{\mathbf{r}, \mathbf{r}'\}$ . This implies in particular that the rays  $\mathbf{s}$  for which  $\alpha_{\mathbf{R}, \mathbf{R}'}(\mathbf{s}) \neq 0$  belong to  $\mathbf{R} \cup \mathbf{R}'$  for any pair  $\{\mathbf{R}, \mathbf{R}'\}$  of adjacent maximal cones of  $\mathcal{F}$  with  $\mathbf{R} \setminus \{\mathbf{r}\} = \mathbf{R}' \setminus \{\mathbf{r}'\}$ .

We say that the fan  $\mathcal{F}$  has the *unique exchange property* if any two exchangeable rays  $\mathbf{r}, \mathbf{r}'$  of  $\mathcal{F}$  admit a unique exchange relation.

When  $\mathcal{F}$  has the unique exchange relation property, we change the notation  $\alpha_{\mathbf{R}, \mathbf{R}'}(\mathbf{s})$  to  $\alpha_{\mathbf{r}, \mathbf{r}'}(\mathbf{s})$  and we obtain that the type cone of  $\mathcal{F}$  is expressed as

$$\text{TC}(\mathcal{F}) = \left\{ \mathbf{h} \in \mathbb{R}^N \left| \sum_{\mathbf{s}} \alpha_{\mathbf{r}, \mathbf{r}'}(\mathbf{s}) \mathbf{h}_{\mathbf{s}} > 0 \text{ for any exchangeable rays } \mathbf{r} \text{ and } \mathbf{r}' \text{ of } \mathcal{F} \right. \right\}.$$

**Definition 1.9.** In a fan  $\mathcal{F}$  with the unique exchange relation property, an *extremal exchangeable pair* is a pair of exchangeable rays  $\{\mathbf{r}, \mathbf{r}'\}$  such that the corresponding inequality  $\sum_{\mathbf{s}} \alpha_{\mathbf{r}, \mathbf{r}'}(\mathbf{s}) \mathbf{h}_{\mathbf{s}} \geq 0$  defines a facet of the closed type cone  $\overline{\text{TC}}(\mathcal{F})$ .

In this paper, we will only consider fans with the unique exchange relation property, and our objective will be to describe their extremal exchangeable pairs.

**1.4. Alternative polytopal realizations.** In this section, we provide alternative polytopal realizations of the fan  $\mathcal{F}$ . We also discuss the behavior of these realizations in the situation when the type cone  $\text{TC}(\mathcal{F})$  is simplicial.

We still consider an essential complete simplicial fan  $\mathcal{F}$  in  $\mathbb{R}^n$ , the  $N \times n$ -matrix  $\mathbf{G}$  whose rows are the rays of  $\mathcal{F}$ , and the  $(N - n) \times N$ -matrix  $\mathbf{K}$  which spans the left kernel of  $\mathbf{G}$  (i.e.  $\mathbf{K}\mathbf{G} = 0$ ).

**Proposition 1.10.** *The affine map  $\Psi : \mathbb{R}^n \rightarrow \mathbb{R}^N$  defined by  $\Psi(\mathbf{x}) = \mathbf{h} - \mathbf{G}\mathbf{x}$  sends the polytope*

$$P_{\mathbf{h}} := \{\mathbf{x} \in \mathbb{R}^n \mid \mathbf{G}\mathbf{x} \leq \mathbf{h}\}$$

*to the polytope*

$$Q_{\mathbf{h}} := \{\mathbf{z} \in \mathbb{R}^N \mid \mathbf{K}\mathbf{z} = \mathbf{K}\mathbf{h} \text{ and } \mathbf{z} \geq 0\}.$$

*Proof.* This result is standard and is proved for instance in [DRS10, Coro. 9.5.7]. We include a short argument here for the convenience of the reader. For  $\mathbf{x}$  in  $P_{\mathbf{h}}$ , we have  $\Psi(\mathbf{x}) \geq 0$  by definition and  $\mathbf{K}\Psi(\mathbf{x}) = \mathbf{K}\mathbf{h} - \mathbf{K}\mathbf{G}\mathbf{x} = \mathbf{K}\mathbf{h}$  since  $\mathbf{K}$  is the left kernel of  $\mathbf{G}$ . Therefore  $\Psi(\mathbf{x}) \in Q_{\mathbf{h}}$ . Moreover, the map  $\Psi : P_{\mathbf{h}} \rightarrow Q_{\mathbf{h}}$  is:

- injective: Indeed,  $\Psi(\mathbf{x}) = \Psi(\mathbf{x}')$  implies  $\mathbf{G}(\mathbf{x} - \mathbf{x}') = 0$  and  $\mathbf{G}$  has full rank since  $\mathcal{F}$  is essential and complete.
- surjective: Indeed, for  $\mathbf{z} \in Q_{\mathbf{h}}$ , we have  $\mathbf{K}(\mathbf{h} - \mathbf{z}) = 0$  so that  $\mathbf{h} - \mathbf{z}$  belongs to the right kernel of  $\mathbf{K}$  which is the image of  $\mathbf{G}$ . Therefore, there exists  $\mathbf{x} \in \mathbb{R}^n$  such that  $\mathbf{h} - \mathbf{z} = \mathbf{G}\mathbf{x}$ . Therefore,  $\mathbf{z} = \Psi(\mathbf{x})$  and  $\mathbf{x} \in P_{\mathbf{h}}$  since  $\mathbf{h} - \mathbf{G}\mathbf{x} = \mathbf{z} \geq 0$ .  $\square$

**Corollary 1.11.** *Assume that the type cone  $\mathbb{T}\mathbb{C}(\mathcal{F})$  is simplicial and let  $\mathbf{K}$  be the  $(N - n) \times N$ -matrix whose rows are the inner normal vectors of the facets of  $\mathbb{T}\mathbb{C}(\mathcal{F})$ . Then the polytope*

$$R_{\boldsymbol{\ell}} := \{\mathbf{z} \in \mathbb{R}^N \mid \mathbf{K}\mathbf{z} = \boldsymbol{\ell} \text{ and } \mathbf{z} \geq 0\}$$

*is a realization of the fan  $\mathcal{F}$  for any positive vector  $\boldsymbol{\ell} \in \mathbb{R}_{>0}^{N-n}$ . Moreover, the polytopes  $R_{\boldsymbol{\ell}}$  for  $\boldsymbol{\ell} \in \mathbb{R}_{>0}^{N-n}$  describe all polytopal realizations of  $\mathcal{F}$ .*

*Proof.* Let  $\boldsymbol{\ell} \in \mathbb{R}_{>0}^{N-n}$ . Since  $\mathbf{K}$  has full rank there exists  $\mathbf{h} \in \mathbb{R}^N$  such that  $\mathbf{K}\mathbf{h} = \boldsymbol{\ell}$ . Since  $\mathbf{K}\mathbf{h} \geq 0$  and the rows of  $\mathbf{K}$  are precisely all inner normal vectors of the facets of the type cone  $\mathbb{T}\mathbb{C}(\mathcal{F})$ , we obtain that  $\mathbf{h}$  belongs to  $\mathbb{T}\mathbb{C}(\mathcal{F})$ . Since  $R_{\boldsymbol{\ell}} = Q_{\mathbf{h}} \sim P_{\mathbf{h}}$  by Proposition 1.10, we conclude that  $R_{\boldsymbol{\ell}}$  is a polytopal realization of  $\mathcal{F}$ . Since  $\mathbb{T}\mathbb{C}(\mathcal{F})$  is simplicial, we have  $\mathbf{K}\mathbb{T}\mathbb{C}(\mathcal{F}) = \mathbb{R}_{>0}^{N-n}$ , so that we obtain all polytopal realizations of  $\mathcal{F}$  in this way.  $\square$

**1.5. Faces of the type cone.** We now relate the faces of the closed type cone  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$  with the coarsenings of the fan  $\mathcal{F}$ .

**Theorem 1.12.** *Let  $\mathcal{F}$  be a polytopal fan. Then the relatively open faces of the closed type cone  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$  are the type cones of all (polytopal) coarsenings of  $\mathcal{F}$ .*

*Proof.* Let  $\mathcal{G}$  be a simplicial refinement of  $\mathcal{F}$ . By Proposition 1.7, the type cone of any coarsening of  $\mathcal{F}$  is a relatively open cell of the hyperplane arrangement defined by adjacent pairs of  $\mathcal{G}$ . The type cone of the coarsening is not empty whenever it is polytopal. When non-empty, distinct coarsenings give rise to distinct cells (one will have an equality that is a strict inequality in the other), and all lie in the closure of  $\mathbb{T}\mathbb{C}(\mathcal{F})$  (since they are all in the closure of all the defining half-spaces). Thus every coarsening describes a relatively open face of  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$ .

For the converse, observe that for  $\mathbf{h} \in \overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$ , the normal fan of  $P_{\mathbf{h}}$  is the polytopal complete fan obtained by merging all pairs of adjacent maximal cones  $\mathbb{R}_{\geq 0}\mathbf{R}$  and  $\mathbb{R}_{\geq 0}\mathbf{R}'$  of  $\mathcal{F}$  such that  $\sum_{s \in \mathbf{R} \cup \mathbf{R}'} \alpha_{\mathbf{R}, \mathbf{R}'}(\mathbf{s}) \mathbf{h}_s = 0$ .  $\square$

**Remark 1.13.** Some observations are in place:

- Note that any extremal adjacent pair  $\{\mathbb{R}_{\geq 0}\mathbf{R}, \mathbb{R}_{\geq 0}\mathbf{R}'\}$  of  $\mathcal{F}$  gives rise to a facet of  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$ , but that this pair might not be unique for this facet. There might be several extremal adjacent pairs giving rise to the same facet. This happens often when we have the unique exchange property and there are many pairs of maximal cones separating the same exchangeable rays.
- Mergings induced by extremal adjacent pairs are not the only ones that can take place in the boundary of  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$ . Indeed, if  $\mathcal{G}$  is the coarsening defining a lower-dimensional face  $\mathbb{T}\mathbb{C}(\mathcal{G})$  of  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$ , then to get  $\mathcal{F}$  we have to perform all the coarsenings given by facets of  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$  containing  $\mathbb{T}\mathbb{C}(\mathcal{G})$ . But we might have to perform more coarsenings arising from exchangeable pairs  $\{\mathbb{R}_{\geq 0}\mathbf{R}, \mathbb{R}_{\geq 0}\mathbf{R}'\}$  whose inequality is redundant for  $\overline{\mathbb{T}\mathbb{C}(\mathcal{F})}$  but tight for

- all points in  $\mathbb{TC}(\mathcal{G})$ . This situation arises when, in order to have a polytopal polyhedral fan, more pairs of adjacent cones must be merged.
- Even if  $\mathcal{F}$  is essential, not all its polytopal coarsenings need to be. Indeed, it can happen that there is a certain polytopal coarsening  $\mathcal{G}$  in which all the cells have a common linearity space. In this case,  $\mathcal{G}$  is the normal fan of a lower dimensional polytope (whose codimension is the dimension of the linearity space of  $\mathcal{G}$ ). For this to happen, it is necessary (but not sufficient) that there is a positive linear dependence between some rays of  $\mathcal{F}$ .

**Example 1.14.** Consider the 2-dimensional fan  $\mathcal{F}$  of Figure 1 (left) whose type cone has been described in Example 1.4 and represented in Figure 1 (right). The relative interior of the three facets of  $\overline{\mathbb{TC}}(\mathcal{F})$  are the type cones of three coarsenings of  $\mathcal{F}$ , obtained by merging certain adjacent maximal cones (those that are extremal). One of the rays generating  $\mathbf{K}\overline{\mathbb{TC}}(\mathcal{F})$  corresponds to a triangle, and its normal fan is obtained by merging two pairs of extremal adjacent maximal cones. The two remaining rays lie not only in hyperplanes  $H_{ij}$  defining facets of the type cone, but also in one extra such hyperplane. Their normal fans have only two cones, one arising as a merging of three cones and one arising as a merging of two cones. These fans are not essential, they have a one-dimensional linearity. Hence, the corresponding polytopes are not full-dimensional, they are of codimension 1.

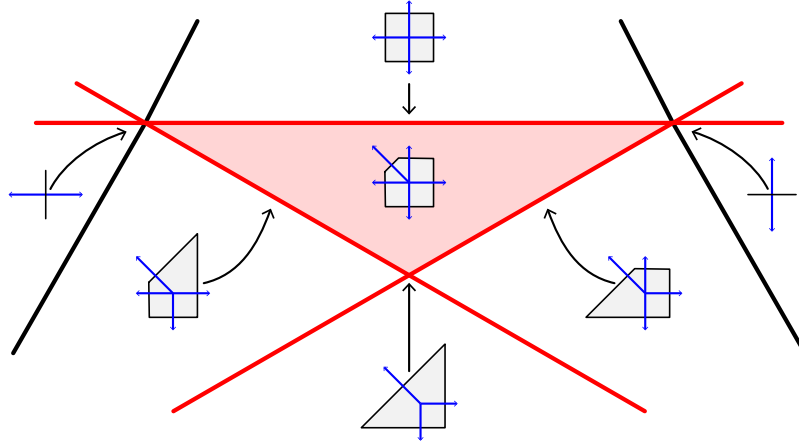


FIGURE 2. The type cone  $\overline{\mathbb{TC}}(\mathcal{F})$  of the fan  $\mathcal{F}$  of Figure 1 (left). On top of each face of  $\overline{\mathbb{TC}}(\mathcal{F})$ , we depict an example of polytope with the corresponding normal fan.

**1.6. Minkowski sums.** We now discuss the connection between convex combinations in the type cone and Minkowski sums of polytopes. Recall that the *Minkowski sum* of two polytopes  $P$  and  $Q$  is the polytope  $P + Q := \{p + q \mid p \in P \text{ and } q \in Q\}$ .

**Lemma 1.15.** For  $\mathbf{h}, \mathbf{h}' \in \mathbb{R}^N$ , the polytope  $P_{\mathbf{h}+\mathbf{h}'}$  is the Minkowski sum of the polytopes  $P_{\mathbf{h}}$  and  $P_{\mathbf{h}'}$ .

*Proof.* This follows from the definition of  $P_{\mathbf{h}}$  and of Minkowski sums:

$$\begin{aligned} P_{\mathbf{h}} + P_{\mathbf{h}'} &= \{\mathbf{x} + \mathbf{x}' \mid \mathbf{x} \in P_{\mathbf{h}} \text{ and } \mathbf{x}' \in P_{\mathbf{h}'}\} = \{\mathbf{x} + \mathbf{x}' \mid \mathbf{G}\mathbf{x} \leq \mathbf{h} \text{ and } \mathbf{G}\mathbf{x}' \leq \mathbf{h}'\} \\ &= \{\mathbf{y} \in \mathbb{R}^n \mid \mathbf{G}\mathbf{y} \leq \mathbf{h} + \mathbf{h}'\} = P_{\mathbf{h}+\mathbf{h}'}. \end{aligned} \quad \square$$

We say that  $P$  is a *Minkowski summand* of  $R$  if there is a polytope  $Q$  such that  $P+Q = R$ , and a *weak Minkowski summand* if there is a  $\lambda \geq 0$  and a polytope  $Q$  such that  $P + Q = \lambda R$ . Lemma 1.15 ensures that convex combinations in the type cone correspond to Minkowski combinations of polytopes. Actually, the set of weak Minkowski summands of a polytope  $P$  with normal fan  $\mathcal{F}$  is isomorphic to the closed type cone  $\overline{\mathbb{TC}}(\mathcal{F})$  modulo linearity (the cone of weak Minkowski summands was studied by W. Meyer in [Mey74], to see that it is equivalent to the type cone and other formulations, see for example the appendix of [PRW08]).

This provides natural Minkowski summands for all polytopal realizations of  $\mathcal{F}$ : the rays of the closed type cone. These correspond to indecomposable polytopes, see [Mey74] or [McM73]. A polytope  $P \subseteq \mathbb{R}^n$  is called *indecomposable* if all its weak Minkowski summands are of the form  $\lambda P + t$  for some  $\lambda \geq 0$  and  $t \in \mathbb{R}^n$ .

**Corollary 1.16.** *Any polytope in  $\overline{\text{TC}}(\mathcal{F})$  is the Minkowski sum of at most  $N - n$  indecomposable polytopes corresponding to some rays of  $\mathbf{K}\overline{\text{TC}}(\mathcal{F})$ .*

If  $P = Q + R$ , then we say that  $R$  is the *Minkowski difference* of  $P$  and  $Q$ , denoted  $R = P - Q$ . Note that this is only defined when  $Q$  is a Minkowski summand of  $P$ . For instance, we have  $P_{\mathbf{h}} - P_{\mathbf{h}'} = P_{\mathbf{h}-\mathbf{h}'}$  when  $P_{\mathbf{h}'}$  is a Minkowski summand of  $P_{\mathbf{h}}$ . There are two natural ways this construction generalizes to arbitrary pairs of polyhedra. On the one hand, one can consider that  $P - Q = \{x \in \mathbb{R}^n \mid x + Q \subseteq P\}$ . On the other hand, considering arbitrary differences of support functions gives rise to *virtual polyhedra*, which is the Grothendieck group of the semigroup of polytopes with Minkowski sums [PK92].

**Corollary 1.17.** *Let  $\mathbf{h}^{(1)}, \dots, \mathbf{h}^{(N-n)} \in \overline{\text{TC}}(\mathcal{F})$  form a basis of the left kernel of  $\mathbf{G}$ . Then for any  $\mathbf{h} \in \overline{\text{TC}}(\mathcal{F})$ , the polytope  $P_{\mathbf{h}}$  has a unique representation (up to translation) as a signed Minkowski sum of dilates of  $P_{\mathbf{h}^{(1)}}, \dots, P_{\mathbf{h}^{(N-n)}}$ .*

*Proof.* It suffices to express the projection of  $\mathbf{h}$  onto the left kernel of  $\mathbf{G}$  in terms of  $\mathbf{h}^{(1)}, \dots, \mathbf{h}^{(N-n)}$ , and to separate those terms with positive and negative coefficients to express Minkowski sums and differences.  $\square$

This is used in [ABD10] to show that every generalized permutahedron can be written uniquely as a signed Minkowski sum of simplices. In the particular case when the type cone is simplicial, then we can get rid of the Minkowski differences.

**Corollary 1.18.** *If the type cone  $\text{TC}(\mathcal{F})$  of  $\mathcal{F}$  is simplicial, then every  $P_{\mathbf{h}}$  with  $\mathbf{h} \in \text{TC}(\mathcal{F})$  (resp. with  $\mathbf{h} \in \overline{\text{TC}}(\mathcal{F})$ ) has a unique representation, up to translation, as a Minkowski sum of positive (resp. non-negative) dilates of the  $N - n$  indecomposable polytopes  $P_{\mathbf{h}^{(1)}}, \dots, P_{\mathbf{h}^{(N-n)}}$  arising from the rays  $\mathbf{h}^{(1)}, \dots, \mathbf{h}^{(N-n)}$  of  $\overline{\text{TC}}(\mathcal{F})$ .*

Note that such a family of polytopes giving rise to unique positive/non-negative representations only exists when the type cone is simplicial. We get unicity with any basis, but in general we cannot guarantee non-negativity unless we are in the simplicial cone they span. If we take all rays of the type cone, we get non-negativity, but the representation is not unique unless the cone is simplicial.

**Example 1.19.** Consider the 2-dimensional fan  $\mathcal{F}$  of Figure 1 (left) whose type cone has been described in Example 1.4 and represented in Figure 1 (right). As illustrated in Figure 2, the rays of the closed type cone  $\overline{\text{TC}}(\mathcal{F})$  are directed by the height vectors  $(1, 2, 1, 2, 1)$  (corresponding to a triangle),  $(0, 1, 1, 0, 1)$  (corresponding to a vertical segment) and  $(1, 0, 1, 1, 0)$  (corresponding to a horizontal segment). Therefore, any polytope in  $\overline{\text{TC}}(\mathcal{F})$  is (up to translation) a positive Minkowski combination of a triangle and two edges. Figure 3 illustrates this property for the polytope of Figure 1 (middle) corresponding to the height vector  $(\frac{1}{2}, \frac{3}{4}, \frac{5}{4}, 1, \frac{5}{4})$ . Note that  $\mathcal{F}$  is the normal fan of J.-L. Loday's 2-dimensional associahedron, whose realization as a Minkowski sum of faces of a simplex was given by A. Postnikov in [Pos09].

$$\left(\frac{1}{2}, \frac{3}{4}, \frac{5}{4}, 1, \frac{5}{4}\right) = \frac{1}{6}(1, 2, 1, 2, 1) + \frac{3}{4}(0, 1, 1, 0, 1) + \frac{1}{2}(1, 0, 1, 1, 0) - \frac{1}{6}(1, 0, -1, -1, 0) - \frac{1}{3}(0, 1, 1, 0, -1)$$

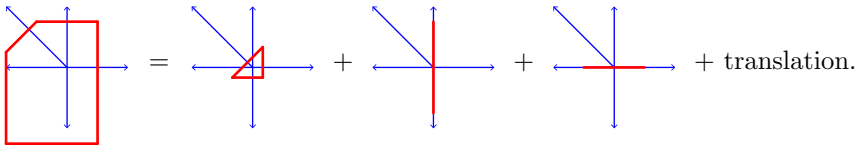


FIGURE 3. The polytope of Figure 1 (middle) is a Minkowski sum of a triangle and two edges.

2. APPLICATIONS TO THREE GENERALIZATIONS OF THE ASSOCIAHEDRON

In this section, we study the type cones of complete simplicial fans arising as normal fans of three families of generalizations of the associahedron: the generalized associahedra of finite type cluster algebras [FZ02, FZ03a, FZ07, HLT11, HPS18], the gentle associahedra [PPP17], and the graph associahedra [CD06, Pos09, FS05, Zel06]. All these families contain the classical associahedra  $\text{Asso}(n)$  constructed in [SS93, Lod04].

**2.1. Classical associahedra.** We first describe the associahedra of [SS93, Lod04] and their type cones as they are the prototypes of our constructions.

**2.1.1. Associahedra and their normal fans.** We quickly recall the combinatorics and the geometric construction of [SS93, Lod04] for the associahedron  $\text{Asso}(n)$ . The face lattice of  $\text{Asso}(n)$  is the reverse inclusion lattice of dissections (*i.e.* pairwise non-crossing subsets of diagonals) of a convex  $(n + 3)$ -gon. In particular, its vertices correspond to triangulations of the  $(n + 3)$ -gon and its facets correspond to internal diagonals of the  $(n + 3)$ -gon. Equivalently, its vertices correspond to rooted binary trees with  $(n + 1)$  internal nodes, and its facets correspond to proper intervals of  $[n + 1]$  (*i.e.* intervals distinct from  $\emptyset$  and  $[n + 1]$ ). These bijections become clear when the convex  $(n + 3)$ -gon is drawn with its vertices on a concave curve labeled by  $0, \dots, n + 2$ . The following statement provides three equivalent geometric constructions of  $\text{Asso}(n)$ .

**Theorem 2.1.** *The associahedron  $\text{Asso}(n)$  can be described equivalently as:*

- the convex hull of the points  $L(T) \in \mathbb{R}^{n+1}$  for all rooted binary trees  $T$  with  $n + 1$  internal nodes, where the  $i$ th coordinate of  $L(T)$  is the product of the number of leaves in the left subtree by the number of leaves in the right subtree of the  $i$ th node of  $T$  in inorder [Lod04],
- the intersection of the hyperplane  $\{\mathbf{x} \in \mathbb{R}^{n+1} \mid \sum_{\ell \in [n+1]} x_\ell = \binom{n+2}{2}\}$  with the halfspaces  $\{\mathbf{x} \in \mathbb{R}^{n+1} \mid \sum_{a < \ell < b} x_\ell \geq \binom{b-a+2}{2}\}$  for all internal diagonals  $(a, b)$  of the  $(n + 3)$ -gon [SS93],
- the Minkowski sum of the faces  $\Delta_{[i,j]}$  of the standard  $n$ -dimensional simplex  $\Delta_{[n+1]}$  corresponding to all proper intervals  $[i, j]$  of  $[n + 1]$ , [Pos09].

We now focus on the normal fan  $\mathcal{F}(n)$  of  $\text{Asso}(n)$ . Since  $\text{Asso}(n)$  lives in a hyperplane of  $\mathbb{R}^{n+1}$ , so does its normal fan. Let  $\mathbb{H} := \{\mathbf{x} \in \mathbb{R}^{n+1} \mid \sum_{\ell \in [n+1]} x_\ell = 0\}$  and  $\pi : \mathbb{R}^{n+1} \rightarrow \mathbb{H}$  denote the orthogonal projection. The following fans are illustrated in Figure 4 in dimension 2 and 3.

**Theorem 2.2.** *In the normal fan  $\mathcal{F}(n)$  of  $\text{Asso}(n)$ ,*

- the normal vector of the facet corresponding to an internal diagonal  $(a, b)$  of the  $(n + 3)$ -gon is the vector  $\mathfrak{g}(a, b) := \pi(\sum_{a < \ell < b} \mathbf{e}_\ell) = (n + 1) \sum_{a < \ell < b} \mathbf{e}_\ell - (b - a + 1) \sum_{1 \leq \ell \leq n+1} \mathbf{e}_\ell$ .
- the normal cone of the vertex corresponding to a rooted binary tree  $T$  is the incidence cone  $\{\mathbf{x} \in \mathbb{H} \mid x_i \leq x_j \text{ for all edges } i \rightarrow j \text{ in } T\}$ .

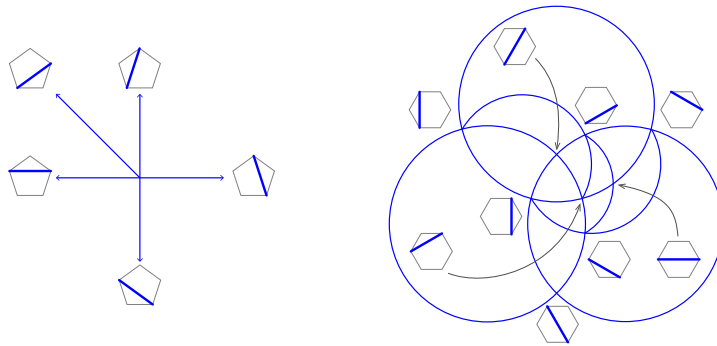


FIGURE 4. The normal fans  $\mathcal{F}(2)$  and  $\mathcal{F}(3)$  of J.-L. Loday's associahedra. As the rightmost fan is 3-dimensional, we intersect it with the sphere and stereographically project it from the direction  $(-1, -1, -1)$ .

Let us also recall the linear dependencies in this fan and observe that it has the unique exchange property discussed in Section 1.3. From now on, we use the convention that  $\mathbf{g}(a, b) = 0$  when  $(a, b)$  is a boundary edge of the  $(n + 3)$ -gon.

**Proposition 2.3.** *Let  $(a, b)$  and  $(a', b')$  be two crossing diagonals with  $0 \leq a < a' < b < b' \leq n + 2$ , and let  $T$  and  $T'$  be any two triangulations such that  $T \setminus \{(a, b)\} = T' \setminus \{(a', b')\}$ . Then both triangulations  $T$  and  $T'$  contain the square  $aa'bb'$ , and the linear dependence between the  $\mathbf{g}$ -vectors of  $T \cup T'$  is given by*

$$\mathbf{g}(a, b) + \mathbf{g}(a', b') = \mathbf{g}(a, b') + \mathbf{g}(a', b).$$

In particular, the fan  $\mathcal{F}(n)$  has the unique exchange property.

2.1.2. *Type cones of associahedra.* From the linear dependencies of Proposition 2.3, we obtain a redundant description of the type cone of the fan  $\mathcal{F}(n)$ .

**Corollary 2.4.** *Let  $n \in \mathbb{N}$  and  $X(n) := \{(a, b) \mid 0 \leq a < b \leq n + 2\}$ . Then the type cone of the normal fan  $\mathcal{F}(n)$  of  $\text{Asso}(n)$  is given by*

$$\text{TC}(\mathcal{F}(n)) = \left\{ \mathbf{h} \in \mathbb{R}^{X(n)} \mid \begin{array}{l} \mathbf{h}_{(0, n+2)} = 0, \quad \text{and} \quad \mathbf{h}_{(a, a+1)} = 0 \text{ for all } 0 \leq a \leq n+1 \\ \mathbf{h}_{(a, b)} + \mathbf{h}_{(a', b')} > \mathbf{h}_{(a, b')} + \mathbf{h}_{(a', b)} \text{ for all } 0 \leq a < a' < b < b' \leq n+2 \end{array} \right\}.$$

**Example 2.5.** Consider the fan  $\mathcal{F}(2)$  and  $\mathcal{F}(3)$  illustrated in Figure 4. The type cone of  $\mathcal{F}(2)$  lives in  $\mathbb{R}^5$  and has a linearity space of dimension 2 (this is the type cone studied in Examples 1.4, 1.14 and 1.19). It has 3 facet-defining inequalities (given below), which correspond to the flips described in Proposition 2.6 and illustrated in Figure 5 (left).

diagonals						
$\mathbf{g}$ -vectors	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	
facet defining inequalities	1 0 0	-1 1 0	1 -1 1	0 1 -1	0 0 1	Ⓐ Ⓑ <sup>ⓐ</sup> Ⓒ <sup>ⓐ</sup>

In all our tables, we just record the coefficients of the inequalities, which are then easily reconstructed. For instance, the inequality Ⓐ above is given by  $\mathbf{h}_{\triangleleft} + \mathbf{h}_{\triangle} > \mathbf{h}_{\triangleleft}$ .

The type cone of  $\mathcal{F}(2)$  lives in  $\mathbb{R}^9$  and has a linearity space of dimension 3. It has 6 facet-defining inequalities (given below), which correspond to the flips described in Proposition 2.6 and illustrated in Figure 5 (right).

diagonals										
$\mathbf{g}$ -vectors	$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$	
facet defining inequalities	1 0 0 0 0 0	-1 1 0 0 0 0	0 -1 1 0 0 0	1 -1 -1 1 0 0	0 1 -1 -1 1 0	0 0 0 1 -1 1	0 0 1 0 -1 0	0 0 0 0 1 -1	0 0 0 0 1 -1	Ⓐ <sup>ⓐ</sup> Ⓑ <sup>ⓐ</sup> Ⓒ <sup>ⓐ</sup> Ⓓ <sup>ⓐ</sup> Ⓔ <sup>ⓐ</sup> Ⓕ <sup>ⓐ</sup>

Motivated by Example 2.5, we now describe the facets of this type cone  $\text{TC}(\mathcal{F}(n))$ .

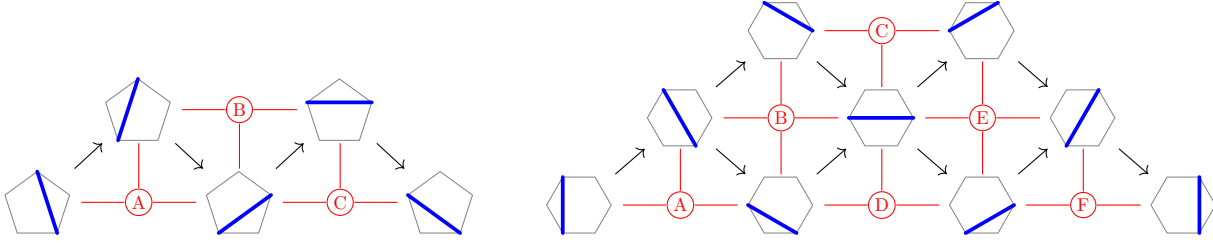


FIGURE 5. The facet-defining inequalities of the type cone  $\mathbb{TC}(\mathcal{F}(n))$  correspond to the flips described in Proposition 2.6. See Sections 2.2 and 3 for a representation theoretic interpretation.

**Proposition 2.6.** *Two internal diagonals  $(a, b)$  and  $(a', b')$  of the  $(n + 3)$ -gon form an extremal exchangeable pair for the fan  $\mathcal{F}(n)$  if and only if  $a = a' + 1$  and  $b = b' + 1$ , or the opposite.*

*Proof.* Let  $(\mathbf{f}_{(a,b)})_{0 \leq a < b \leq n+2}$  be the canonical basis of  $\mathbb{R}^{\binom{n+3}{2}}$ . Consider two crossing internal diagonals  $(a, b)$  and  $(a', b')$  with  $0 \leq a < a' < b < b' \leq n + 2$ . By Proposition 2.3, the linear dependence between the corresponding  $\mathbf{g}$ -vectors is given by

$$\mathbf{g}(a, b) + \mathbf{g}(a', b') = \mathbf{g}(a, b') + \mathbf{g}(a', b).$$

Therefore, the inner normal vector of the corresponding inequality of the type cone  $\mathbb{TC}(\mathcal{F}(n))$  is

$$\mathbf{n}(a, b, a', b') := \mathbf{f}_{(a,b)} + \mathbf{f}_{(a',b')} - \mathbf{f}_{(a,b')} - \mathbf{f}_{(a',b)}.$$

Denoting

$$\mathbf{m}(c, d) := \mathbf{n}(c, d - 1, c + 1, d) = \mathbf{f}_{(c,d-1)} + \mathbf{f}_{(c+1,d)} - \mathbf{f}_{(c,d)} - \mathbf{f}_{(c+1,d-1)},$$

we obtain that

$$\mathbf{n}(a, b, a', b') = \sum_{\substack{c \in [a, a'[ \\ d \in ]b, b']}} \mathbf{m}(c, d).$$

Indeed, on the right hand side, the basis vector  $\mathbf{f}_{(c,d)}$  appears with a positive sign in  $\mathbf{m}(c, d + 1)$  for  $(c, d) \in [a, a'[ \times ]b, b'[$  and in  $\mathbf{m}(c - 1, d)$  for  $(c, d) \in ]a, a' \times ]b, b']$ , and with a negative sign in  $\mathbf{m}(c, d)$  for  $(c, d) \in [a, a'[ \times ]b, b']$  and in  $\mathbf{m}(c - 1, d + 1)$  for  $(c, d) \in ]a, a' \times ]b, b'[$ . Therefore, these contributions all vanish except when  $(c, d)$  is one of the diagonals  $(a, b)$ ,  $(a', b')$ ,  $(a, b')$  or  $(a', b)$ . This shows that any exchange relation is a positive linear combination of the exchange relations corresponding to all pairs of diagonals  $(a, b)$  and  $(a', b')$  of the  $(n + 3)$ -gon such that  $a = a' + 1$  and  $b = b' + 1$  or the opposite.

Conversely, since  $\mathcal{F}(n)$  has dimension  $n$  and  $n(n + 3)/2$  rays (corresponding to the internal diagonals of the  $(n + 3)$ -gon), we know from Remark 1.6 that there are at least  $n(n + 1)/2$  extremal exchangeable pairs. We thus conclude that all exchangeable pairs of diagonals  $\{(a, b - 1), (a + 1, b)\}$  for  $1 \leq a < b - 2 \leq n$  are extremal.  $\square$

Our next statement follows from the end of the previous proof.

**Corollary 2.7.** *The type cone  $\mathbb{TC}(\mathcal{F}(n))$  is simplicial.*

Combining Corollary 1.11, Corollary 2.7 and Proposition 2.6, we derive the following description of all polytopal realizations of the fan  $\mathcal{F}(n)$ , recovering all associahedra of [AHBHY18, Sect. 3.2]. Note that the arguments of [AHBHY18, Sect. 3.2] were quite different from the present approach.

**Corollary 2.8** ([AHBHY18, Sect. 3.2]). *For  $n \in \mathbb{N}$ , define  $X(n) := \{(a, b) \mid 0 \leq a < b \leq n + 2\}$  and  $Y(n) := \{(a, b) \mid 0 \leq a < b - 2 \leq n\}$ . Then for any  $\ell \in \mathbb{R}_{>0}^{Y(n)}$ , the polytope*

$$R_\ell(n) := \left\{ \mathbf{z} \in \mathbb{R}^{X(n)} \mid \begin{array}{l} \mathbf{z} \geq 0, \quad \mathbf{z}_{(0,n+2)} = 0 \quad \text{and} \quad \mathbf{z}_{(a,a+1)} = 0 \text{ for all } 0 \leq a \leq n + 1 \\ \mathbf{z}_{(a,b-1)} + \mathbf{z}_{(a+1,b)} - \mathbf{z}_{(a,b)} - \mathbf{z}_{(a+1,b-1)} = \ell_{(a,b)} \text{ for all } (a, b) \in Y(n) \end{array} \right\}$$

*is an  $n$ -dimensional associahedron, whose normal fan is  $\mathcal{F}(n)$ . Moreover, the polytopes  $R_\ell(n)$  for  $\ell \in \mathbb{R}_{>0}^{Y(n)}$  describe all polytopal realizations of the fan  $\mathcal{F}(n)$ .*

**2.2. Finite type cluster complexes and generalized associahedra.** Cluster algebras were introduced by S. Fomin and A. Zelevinsky [FZ02] with motivation coming from total positivity and canonical bases. Here, we will focus on finite type cluster algebras [FZ03a] and more specifically on properties of their  $\mathbf{g}$ -vectors [FZ07]. These  $\mathbf{g}$ -vectors support a complete simplicial fan, which is called  $\mathbf{g}$ -vector fan or cluster fan. It is known to be the normal fan of a polytope called generalized associahedron. These polytopal realizations were first constructed for bipartite initial seeds by F. Chapoton, S. Fomin and A. Zelevinsky [CFZ02] using the  $\mathbf{d}$ -vector fans of [FZ03b], then for acyclic initial seeds by C. Hohlweg, C. Lange and H. Thomas [HLT11] using Cambrian lattices and fans of N. Reading and D. Speyer [Rea06, RS09], then revisited by S. Stella [Ste13], and by V. Pilaud and C. Stump [PS15] via brick polytopes, and finally for arbitrary initial seeds by C. Hohlweg, V. Pilaud and S. Stella [HPS18]. More recently in [BMDM<sup>+</sup>18], V. Bazier-Matte, G. Douville, K. Mousavand, H. Thomas and E. Yildirim extended the construction of associahedra of [AHBHY18, Sect. 3.2] to acyclic seeds of simply-laced finite type cluster algebras. Here, we extend the construction of [AHBHY18, Sect. 3.2] to any finite type (simply-laced or not) cluster algebra with respect to any seed (acyclic or not) by providing a direct proof that the type cone of the cluster fan of any finite type cluster algebra with respect to any initial seed is simplicial.

**2.2.1. Cluster algebras and cluster fans.** We present some definitions and properties of finite type cluster algebras and their cluster fans, following the presentation of [HPS18].

*Cluster algebras.* Let  $\mathbb{Q}(x_1, \dots, x_n, p_1, \dots, p_m)$  be the field of rational expressions in  $n + m$  variables with rational coefficients, and  $\mathbb{P}_m$  denote its abelian multiplicative subgroup generated by  $\{p_i\}_{i \in [m]}$ . For  $p = \prod_{i \in [m]} p_i^{a_i} \in \mathbb{P}_m$ , define  $\{p\}_+ := \prod_{i \in [m]} p_i^{\max(a_i, 0)}$  and  $\{p\}_- := \prod_{i \in [m]} p_i^{-\min(a_i, 0)}$ .

A *seed*  $\Sigma$  is a triple  $(B, P, X)$  where

- the *exchange matrix*  $B$  is an integer  $n \times n$  skew-symmetrizable matrix, *i.e.* such that there exists a diagonal matrix  $D$  with  $-BD = (BD)^T$ ,
- the *coefficient tuple*  $P$  is any subset of  $n$  elements of  $\mathbb{P}_m$ ,
- the *cluster*  $X$  is a set of  $n$  *cluster variables* in  $\mathbb{Q}(x_1, \dots, x_n, p_1, \dots, p_m)$  algebraically independent over  $\mathbb{Q}(p_1, \dots, p_m)$ .

To simplify our notations, we use the convention to label  $B = (b_{xy})_{x, y \in X}$  and  $P = \{p_x\}_{x \in X}$  by the cluster variables of  $X$ .

For a seed  $\Sigma = (B, P, X)$  and a cluster variable  $x \in X$ , the *mutation* in direction  $x$  creates a new seed  $\mu_x(\Sigma) = \Sigma' = (B', P', X')$  where:

- the new cluster  $X'$  is obtained from  $X$  by replacing  $x$  with the cluster variable  $x'$  defined by the following *exchange relation*:

$$xx' = \{p_x\}_+ \prod_{y \in X, b_{xy} > 0} y^{b_{xy}} + \{p_x\}_- \prod_{y \in X, b_{xy} < 0} y^{-b_{xy}}$$

and leaving the remaining cluster variables unchanged so that  $X \setminus \{x\} = X' \setminus \{x'\}$ .

- the row (resp. column) of  $B'$  indexed by  $x'$  is the negative of the row (resp. column) of  $B$  indexed by  $x$ , while all other entries satisfy  $b'_{yz} = b_{yz} + \frac{1}{2}(|b_{yx}|b_{xz} + b_{yx}|b_{xz}|)$ ,
- the elements of the new coefficient tuple  $P'$  are

$$p'_y = \begin{cases} p_x^{-1} & \text{if } y = x', \\ p_y \{p_x\}_-^{b_{xy}} & \text{if } y \neq x' \text{ and } b_{xy} \leq 0, \\ p_y \{p_x\}_+^{b_{xy}} & \text{if } y \neq x' \text{ and } b_{xy} > 0. \end{cases}$$

An important point is that mutations are involutions:  $\mu_{x'}(\mu_x(\Sigma)) = \Sigma$ . We say that two seeds are *mutationally equivalent* when they can be obtained from each other by a sequence of mutations (we also use the same terminology for exchange matrices). We denote by  $\mathcal{V}(B_\circ, P_\circ)$  the collection of all cluster variables in the seeds mutationally equivalent to an initial seed  $\Sigma_\circ = (B_\circ, P_\circ, X_\circ)$  with cluster variables  $X_\circ = \{x_1, \dots, x_n\}$ . The (geometric type) *cluster algebra*  $\mathcal{A}(B_\circ, P_\circ)$  is the  $\mathbb{Z}\mathbb{P}_m$ -subring of  $\mathbb{Q}(x_1, \dots, x_n, p_1, \dots, p_m)$  generated by the cluster variables in  $\mathcal{V}(B_\circ, P_\circ)$ . The



*cluster complex* of  $\mathcal{A}(B_\circ, P_\circ)$  is the simplicial complex whose vertices are the cluster variables of  $\mathcal{A}(B_\circ, P_\circ)$  and whose facets are the clusters of  $\mathcal{A}(B_\circ, P_\circ)$ .

*Finite type.* In this paper, we only consider *finite type* cluster algebras, *i.e.* those with a finite number  $N$  of cluster variables. It turns out that these finite type cluster algebras were classified by S. Fomin and A. Zelevinsky [FZ03a] using the Cartan-killing classification for crystallographic root systems. Define the *Cartan companion* of an exchange matrix  $B$  as the matrix  $A(B)$  given by  $a_{xy} = 2$  if  $x = y$  and  $a_{xy} = -|b_{xy}|$  otherwise.

**Theorem 2.9** ([FZ03a, Thm. 1.4]). *The cluster algebra  $\mathcal{A}(B_\circ, P_\circ)$  is of finite type if and only if  $B_\circ$  is mutationally equivalent to a matrix  $B$  whose Cartan companion  $A(B)$  is a Cartan matrix of finite type. Moreover the type of  $A(B)$  is determined by  $B_\circ$ .*

A finite type exchange matrix  $B_\circ$  is *acyclic* if  $A(B_\circ)$  is already a Cartan matrix, and *cyclic* otherwise. An acyclic exchange matrix  $B_\circ$  is *bipartite* if each row of  $B_\circ$  consists either of non-positive or non-negative entries. We use the same terminology for the seed  $\Sigma_\circ$ .

From now on, we fix a finite type cluster algebra  $\mathcal{A}(B_\circ, P_\circ)$  and we consider the root system of type  $A(B_\circ)$  (again, this root system is finite only when the initial seed  $B_\circ$  is acyclic). We use the following classical bases of the underlying vector spaces:

- the simple roots  $\{\alpha_x\}_{x \in X_\circ}$  and the fundamental weights  $\{\omega_x\}_{x \in X_\circ}$  are two bases of the same vector space  $V$  related by the Cartan matrix  $A(B_\circ)$ ,
- the simple coroots  $\{\alpha_x^\vee\}_{x \in X_\circ}$  and the fundamental coweights  $\{\omega_x^\vee\}_{x \in X_\circ}$  are two basis of the dual space  $V^\vee$  related by the transpose of the Cartan matrix  $A(B_\circ)^T$ ,

and the basis of simple roots is dual to the basis of fundamental coweights, while the basis of fundamental weights is dual to the basis of simple coroots.

The cluster complex of a finite type cluster algebra  $\mathcal{A}(B_\circ, P_\circ)$  is independent of the choice of coefficients and of the choice of the initial seed (as long as it remains in the same mutation class), and therefore only depends on the cluster type of  $\mathcal{A}(B_\circ, P_\circ)$  (*i.e.* the Cartan type of  $A(B)$  in Theorem 2.9). Moreover, for  $B_\circ^\vee := -B_\circ^T$ , then the map sending a cluster variable  $x$  in a seed  $\Sigma$  of  $\mathcal{A}(B_\circ, P_\circ)$  to the cluster variable  $x^\vee$  in the seed  $\Sigma^\vee$  of  $\mathcal{A}(B_\circ^\vee, P_\circ)$  obtained by the same sequence of mutations defines a natural isomorphism between the cluster complexes of  $\mathcal{A}(B_\circ, P_\circ)$  and  $\mathcal{A}(B_\circ^\vee, P_\circ)$ .

*Principal coefficients and  $\mathfrak{g}$ - and  $\mathfrak{c}$ -vectors.* We now consider principal coefficients to define the  $\mathfrak{g}$ - and  $\mathfrak{c}$ -vectors. As defined in [FZ07, Def. 3.1], the cluster algebra with *principal coefficients* at  $B_\circ$  is the cluster algebra  $\mathcal{A}(B_\circ, P_\circ)$  in  $\mathbb{Q}(x_1, \dots, x_n, p_1, \dots, p_n)$ , where  $P_\circ = \{p_x\}_{x \in X_\circ}$  are precisely the generators  $p_1, \dots, p_n$  of  $\mathbb{P}_n$  relabeled by  $X_\circ$ . For simplicity, we drop the mention of the coefficients for principal cluster algebras in the notations for seeds  $\Sigma = (B, X)$ , for cluster algebras  $\mathcal{A}(B_\circ)$  and for variables  $\mathcal{V}(B_\circ)$ . Principal coefficients cluster algebras are  $\mathbb{Z}^n$ -graded (in the fundamental weight basis  $\{\omega_x\}_{x \in X_\circ}$  of  $V$ ) for the degree function  $\deg(B_\circ, \cdot)$  on  $\mathcal{A}(B_\circ)$  obtained by setting  $\deg(B_\circ, x) := \omega_x$  and  $\deg(B_\circ, p_x) := \sum_{y \in X_\circ} -b_{yx} \omega_y$  for any  $x \in X_\circ$ .

**Definition 2.10** ([FZ07]). The  *$\mathfrak{g}$ -vector*  $\mathfrak{g}(x) = \mathfrak{g}(B_\circ, x)$  of a cluster variable  $x \in \mathcal{A}(B_\circ)$  is its degree. We denote by  $\mathfrak{g}(\Sigma) = \mathfrak{g}(B_\circ, \Sigma) := \{\mathfrak{g}(B_\circ, x) \mid x \in \Sigma\}$  the set of  $\mathfrak{g}$ -vectors of a seed  $\Sigma$ .

The next definition gives another family of integer vectors, introduced implicitly in [FZ07], that are relevant in the structure of  $\mathcal{A}(B_\circ)$ .

**Definition 2.11.** The  *$\mathfrak{c}$ -vector* of a cluster variable  $x$  in a seed  $\Sigma$  of  $\mathcal{A}(B_\circ)$  is the vector  $\mathfrak{c}(x \in \Sigma) = \mathfrak{c}(B_\circ, x \in \Sigma) := \sum_{y \in X_\circ} c_{yx} \alpha_y$  of exponents of  $p_x = \prod_{y \in X_\circ} (p_y)^{c_{yx}}$ . We denote by  $\mathfrak{c}(\Sigma) = \mathfrak{c}(B_\circ, \Sigma) := \{\mathfrak{c}(B_\circ, x \in \Sigma) \mid x \in \Sigma\}$  the set of  $\mathfrak{c}$ -vectors of a seed  $\Sigma$ .

These two families of vectors are connected via the isomorphism  $x \mapsto x^\vee$  between the cluster complexes of  $\mathcal{A}(B_\circ)$  and  $\mathcal{A}(B_\circ^\vee)$  described above.

**Theorem 2.12** ([NZ12, Thm 1.2]). *For any seed  $\Sigma$  of  $\mathcal{A}(B_\circ)$ , let  $\Sigma^\vee$  be its dual in  $\mathcal{A}(B_\circ^\vee)$ . Then the set of  $\mathfrak{g}$ -vectors  $\mathfrak{g}(B_\circ, \Sigma)$  and the set of  $\mathfrak{c}$ -vectors  $\mathfrak{c}(B_\circ^\vee, \Sigma^\vee)$  form dual bases, that is  $\langle \mathfrak{g}(B_\circ, x) \mid \mathfrak{c}(B_\circ^\vee, y^\vee \in \Sigma^\vee) \rangle = \delta_{x=y}$  for any two cluster variables  $x, y \in \Sigma$ .*

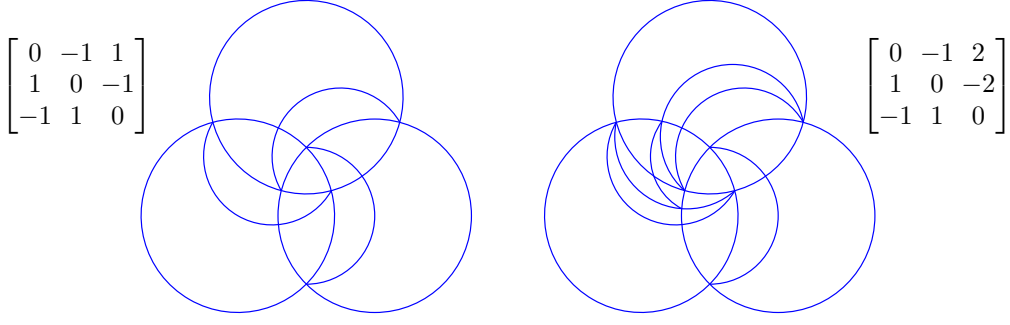


FIGURE 6. Two cluster fans  $\mathcal{F}(\mathbb{B}_\circ)$  for the type  $A_3$  (left) and type  $C_3$  (right) cyclic initial exchange matrices. As the fans are 3-dimensional, we intersect them with the sphere and stereographically project them from the direction  $(-1, -1, -1)$ . Illustration from [HPS18].

*Cluster fan and generalized associahedron.* The following statement is well known and admits several possible proofs as discussed in [HPS18, Sect. 4]. Examples are illustrated in Figure 6.

**Theorem 2.13.** *For any finite type exchange matrix  $\mathbb{B}_\circ$ , the collection of cones*

$$\{\mathbb{R}_{\geq 0} \mathbf{g}(\mathbb{B}_\circ, \Sigma) \mid \Sigma \text{ seed of } \mathcal{A}(\mathbb{B}_\circ)\},$$

*together with all their faces, forms a complete simplicial fan  $\mathcal{F}(\mathbb{B}_\circ)$ , called the **g-vector fan** or **cluster fan** of  $\mathbb{B}_\circ$ .*

Moreover, this fan is known to be polytopal. More precisely, consider a vector  $\mathbf{h} \in \mathbb{R}^{\mathcal{V}(\mathbb{B}_\circ)}$  such that

$$\mathbf{h}_x + \mathbf{h}_{x'} > \max \left( \sum_{y \in X \cap X', b_{xy} < 0} -b_{xy} \mathbf{h}_y, \sum_{y \in X \cap X', b_{xy} > 0} b_{xy} \mathbf{h}_y \right).$$

for any adjacent seeds  $(\mathbb{B}, X)$  and  $(\mathbb{B}', X')$  with  $X \setminus \{x\} = X' \setminus \{x'\}$ . Such a vector  $\mathbf{h}$  exists, see the discussion in [HPS18, Prop. 28].

**Theorem 2.14** ([HPS18, Thm. 26]). *For any finite type exchange matrix  $\mathbb{B}_\circ$ , the cluster fan  $\mathcal{F}(\mathbb{B}_\circ)$  is the normal fan of the  $\mathbb{B}_\circ$ -associahedron  $\text{Asso}(\mathbb{B}_\circ, \mathbf{h})$  defined equivalently as*

- (i) *the convex hull of the points  $\sum_{x \in \Sigma} \mathbf{h}_x \mathbf{c}(\mathbb{B}_\circ^\vee, x^\vee \in \Sigma^\vee)$  for all seeds  $\Sigma$  of  $\mathcal{A}(\mathbb{B}_\circ)$ , or*
- (ii) *the intersection of the halfspaces  $\{\mathbf{v} \in V^\vee \mid \langle \mathbf{g}(\mathbb{B}_\circ, x) \mid \mathbf{v} \rangle \leq \mathbf{h}_x\}$  for all cluster variables  $x$  of  $\mathcal{A}(\mathbb{B}_\circ)$ .*

*Mutations in the cluster fan.* We now discuss the linear dependences between  $\mathbf{g}$ -vectors of adjacent seeds. The following lemma was stated in [HPS18, Lem. 19].

**Lemma 2.15.** *For any finite type exchange matrix  $\mathbb{B}_\circ$  and any adjacent seeds  $(\mathbb{B}, X)$  and  $(\mathbb{B}', X')$  in  $\mathcal{A}(\mathbb{B}_\circ)$  with  $X \setminus \{x\} = X' \setminus \{x'\}$ , the  $\mathbf{g}$ -vectors of  $X \cup X'$  with respect to  $\mathbb{B}_\circ$  satisfy precisely one of the following two linear dependences*

$$\mathbf{g}(\mathbb{B}_\circ, x) + \mathbf{g}(\mathbb{B}_\circ, x') = \sum_{\substack{y \in X \cap X' \\ b_{xy} < 0}} -b_{xy} \mathbf{g}(\mathbb{B}_\circ, y) \quad \text{or} \quad \mathbf{g}(\mathbb{B}_\circ, x) + \mathbf{g}(\mathbb{B}_\circ, x') = \sum_{\substack{y \in X \cap X' \\ b_{xy} > 0}} b_{xy} \mathbf{g}(\mathbb{B}_\circ, y).$$

Note that Lemma 2.15 implies Theorem 2.14 since it ensures that the type cone  $\mathbb{TC}(\mathcal{F}(\mathbb{B}_\circ))$  of the cluster fan contains the cone of height vectors  $\mathbf{h} \in \mathbb{R}^{\mathcal{V}(\mathbb{B}_\circ)}$  such that  $\mathbf{h}_x + \mathbf{h}_{x'} > \sum_{y \in X \cap X', b_{xy} < 0} -b_{xy} \mathbf{h}_y$  and  $\mathbf{h}_x + \mathbf{h}_{x'} > \sum_{y \in X \cap X', b_{xy} > 0} b_{xy} \mathbf{h}_y$  for any seeds  $(\mathbb{B}, X)$  and  $(\mathbb{B}', X')$  with  $X \setminus \{x\} = X' \setminus \{x'\}$ .

Unfortunately, Lemma 2.15 is less precise than Proposition 2.3. Indeed, which of the two possible linear dependences is satisfied by the  $\mathbf{g}$ -vectors of  $X \cup X'$  depends on the initial exchange matrix  $\mathbb{B}_\circ$ . However, for cluster algebras of finite type, this linear dependence is independent of the choice of a seed containing  $x$  and  $x'$ . As explained in Corollary 3.30, this statement follows from [BMR<sup>+</sup>06, Thm. 7.5]. We state it here for future reference. Note that the corresponding statement for cluster variables, instead of  $\mathbf{g}$ -vectors, holds by [FZ03a, Thm. 1.11].

**Proposition 2.16.** *For any finite type exchange matrix  $B_\circ$ , the cluster fan has the unique exchange relation property.*

2.2.2. *Type cone of finite type cluster fans.* The linear dependences of Lemma 2.15 provide a redundant description of the type cone of the cluster fan  $\mathcal{F}(B_\circ)$ . We denote by  $\mathbf{n}(B_\circ, x, x')$  the normal vector of the inequality of the type cone corresponding to two exchangeable cluster variables  $x$  to  $x'$  (it is well defined by Proposition 2.16). In other words, depending on which of the two linear dependences of Lemma 2.15 holds, we have

$$\mathbf{n}(B_\circ, x, x') := \mathbf{f}_x + \mathbf{f}_{x'} - \sum_{\substack{y \in X \cap X' \\ b_{xy} < 0}} -b_{xy} \mathbf{f}_y \quad \text{or} \quad \mathbf{n}(B_\circ, x, x') := \mathbf{f}_x + \mathbf{f}_{x'} - \sum_{\substack{y \in X \cap X' \\ b_{xy} > 0}} b_{xy} \mathbf{f}_y,$$

where  $(\mathbf{f}_x)_{x \in \mathcal{V}(B_\circ)}$  denotes the canonical basis of  $\mathbb{R}^{\mathcal{V}(B_\circ)}$ . We obtain the following statement.

**Corollary 2.17.** *For any finite type exchange matrix  $B_\circ$ , the type cone of the cluster fan  $\mathcal{F}(B_\circ)$  is given by*

$$\text{TC}(\mathcal{F}(B_\circ)) = \left\{ \mathbf{h} \in \mathbb{R}^{\mathcal{V}(B_\circ)} \mid \langle \mathbf{n}(B_\circ, x, x'), \mathbf{h} \rangle > 0 \text{ for all exchangeable cluster variables } x, x' \right\}.$$

**Example 2.18.** Consider the cluster fans illustrated in Figure 6. The type cone of the left fan of Figure 6 lives in  $\mathbb{R}^9$  and has a linearity space of dimension 3. It has 6 facet-defining inequalities (given below), which correspond to the mesh mutations of Theorem 2.23 as illustrated in Figure 7.

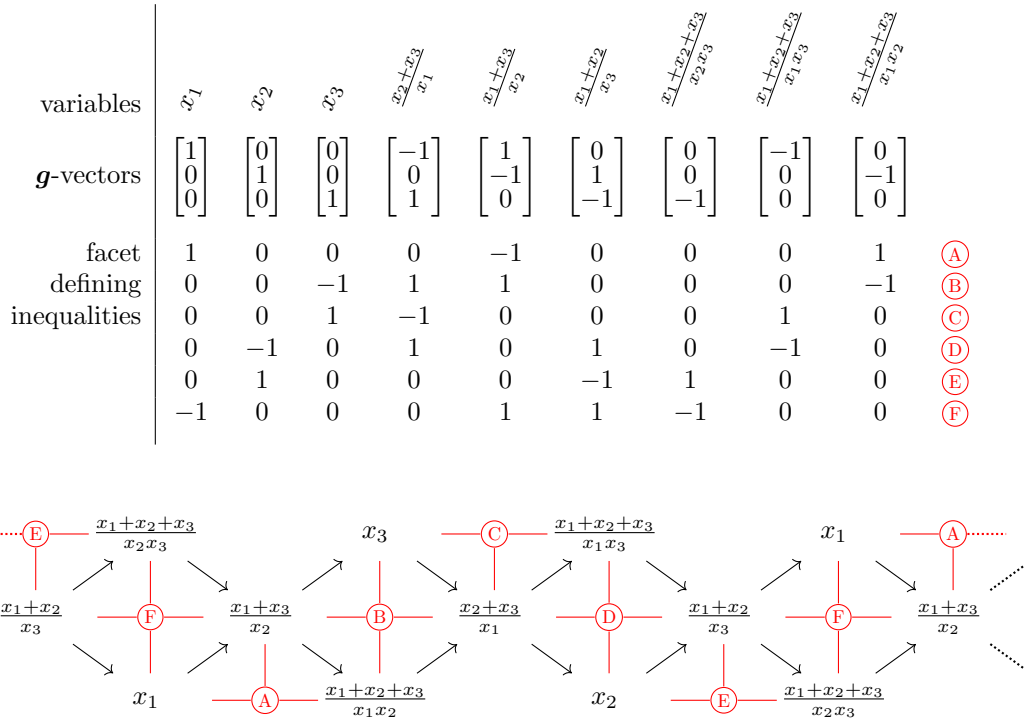


FIGURE 7. The facet-defining inequalities of the type cone  $\text{TC}(\mathcal{F}(B_\circ))$  of the cluster fan correspond to the mesh mutations described in Theorem 2.23. See Section 3 for a representation theoretic interpretation.

The type cone of the right fan of Figure 6 lives in  $\mathbb{R}^{12}$  and has a linearity space of dimension 3. It has 9 facet-defining inequalities (given below), which correspond to the mesh mutations of Theorem 2.23 as illustrated in Figure 8.

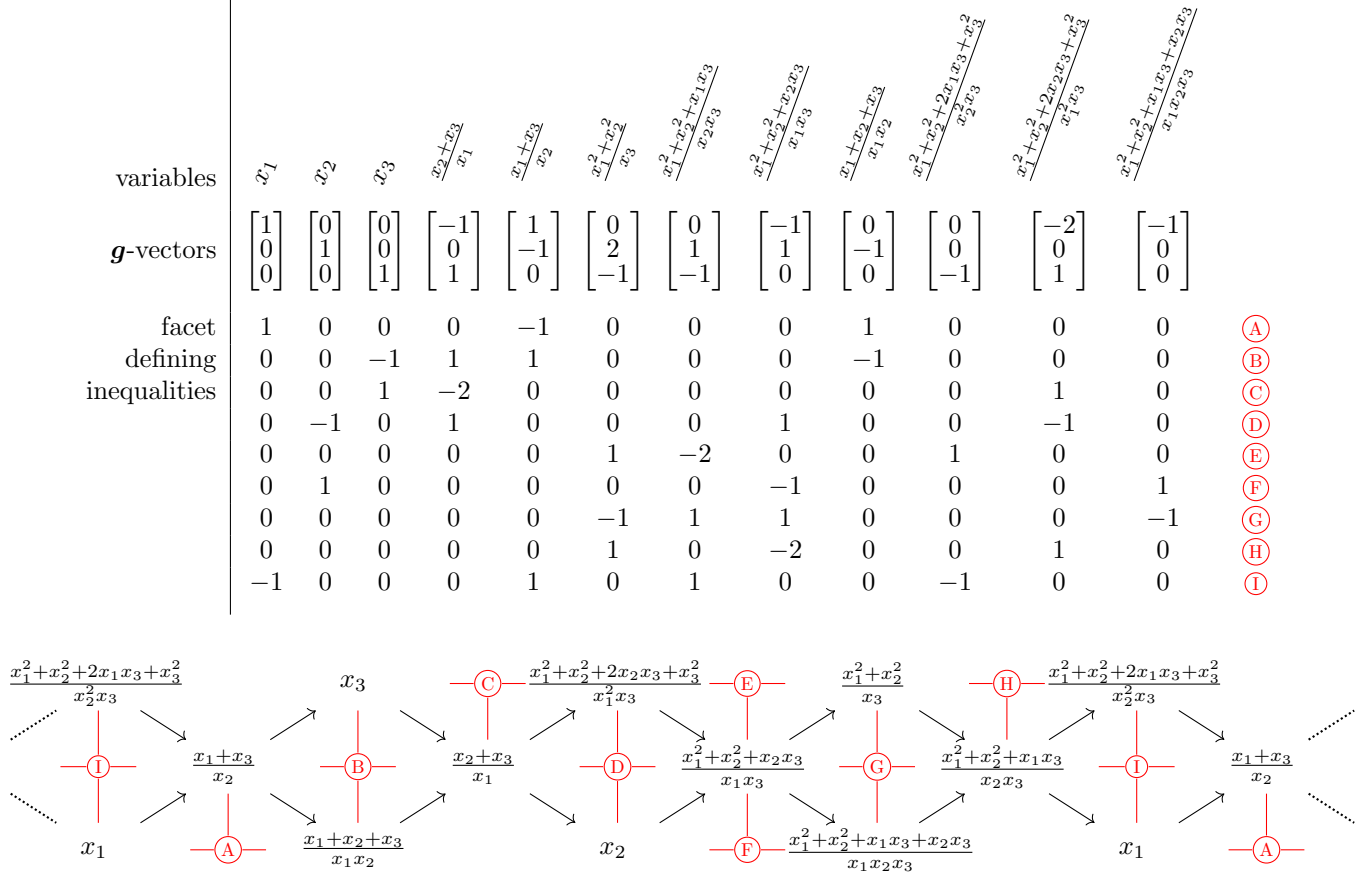


FIGURE 8. The facet-defining inequalities of the type cone  $\mathbb{TC}(\mathcal{F}(\mathcal{B}_\circ))$  of the cluster fan correspond to the mesh mutations described in Theorem 2.23. See Section 3 for a representation theoretic interpretation.

In order to describe the facets of this type cone, we need the following special mutations.

**Definition 2.19.** The mutation of a seed  $\Sigma = (\mathcal{B}, \mathcal{X})$  in the direction of a cluster variable  $x \in \mathcal{X}$  is a *mesh mutation* that *starts* (resp. *ends*) at  $x$  if the entries  $b_{xy}$  for  $y \in \mathcal{X}$  are all non-negative (resp. all non-positive). A mesh mutation is *initial* if it ends at a cluster variable of an initial seed. We denote by  $\mathcal{M}(\mathcal{B}_\circ)$  the set of all pairs  $\{x, x'\}$  where  $x$  and  $x'$  are two cluster variables of  $\mathcal{A}(\mathcal{B}_\circ)$  which are exchangeable via a non-initial mesh mutation.

The following statement is proved in Corollary 3.27.

**Lemma 2.20.** *We have that  $|\mathcal{V}(\mathcal{B}_\circ)| = |\mathcal{M}(\mathcal{B}_\circ)| + n$ .*

The following statement describes the linear dependence in the mesh mutations. It follows from Lemma 2.15 and Definition 2.19.

**Lemma 2.21.** *Consider two adjacent seeds  $(\mathcal{B}, \mathcal{X})$  and  $(\mathcal{B}', \mathcal{X}')$  with  $\mathcal{X} \setminus \{x\} = \mathcal{X}' \setminus \{x'\}$  connected by a mesh mutation. If the mesh mutation is initial, then*

$$\mathbf{g}(\mathcal{B}_\circ, x) + \mathbf{g}(\mathcal{B}_\circ, x') = 0.$$

*Otherwise, the  $\mathbf{g}$ -vectors of  $\mathcal{X} \cup \mathcal{X}'$  with respect to  $\mathcal{B}_\circ$  satisfy the linear dependence*

$$\mathbf{g}(\mathcal{B}_\circ, x) + \mathbf{g}(\mathcal{B}_\circ, x') = \sum_{y \in \mathcal{X} \cap \mathcal{X}'} |b_{xy}| \mathbf{g}(\mathcal{B}_\circ, y).$$

For  $\{x, x'\} \in \mathcal{M}(\mathbf{B}_\circ)$  and  $y \in \mathcal{V}(\mathbf{B}_\circ)$ , we denote by  $\alpha_{x, x', y}$  the coefficient of  $\mathbf{g}(\mathbf{B}_\circ, y)$  in the linear dependence between the  $\mathbf{g}$ -vectors  $\mathbf{g}(\mathbf{B}_\circ, x)$  and  $\mathbf{g}(\mathbf{B}_\circ, x')$ . In other words, according to Lemma 2.21, if  $(\mathbf{B}, X)$  and  $(\mathbf{B}', X')$  are two adjacent seeds with  $X \setminus \{x\} = X' \setminus \{x'\}$ , we have  $\alpha_{x, x', y} = |b_{xy}|$  for  $y \in X \cap X'$  and  $\alpha_{x, x', y} = 0$  otherwise. The following statement will be shown in Corollary 3.29.

**Proposition 2.22.** *For any finite type exchange matrix  $\mathbf{B}_\circ$  (acyclic or not, simply-laced or not), the linear dependence between the  $\mathbf{g}$ -vectors of any mutation can be decomposed into positive combinations of linear dependences between  $\mathbf{g}$ -vectors of non-initial mesh mutations.*

We derive from Proposition 2.22 the following description of the facets of the type cone of the cluster fan.

**Theorem 2.23.** *For any finite type exchange matrix  $\mathbf{B}_\circ$  (acyclic or not, simply-laced or not), the non-initial mesh mutations precisely correspond to the extremal exchangeable pairs of the cluster fan  $\mathcal{F}(\mathbf{B}_\circ)$ .*

*Proof.* Since  $\mathcal{F}(\mathbf{B}_\circ)$  has dimension  $n$  and  $|\mathcal{V}(\mathbf{B}_\circ)|$  rays (corresponding to the cluster variables), we know from Remark 1.6 that there are at least  $|\mathcal{V}(\mathbf{B}_\circ)| - n$  extremal exchangeable pairs. Moreover, Proposition 2.22 and Lemma 2.20 ensure that there are at most  $|\mathcal{M}(\mathbf{B}_\circ)| = |\mathcal{V}(\mathbf{B}_\circ)| - n$  extremal exchangeable pairs (corresponding to the non-initial mesh mutations). We conclude that all non-initial mesh mutations are extremal exchangeable pairs.  $\square$

Our next statement follows from the end of the previous proof.

**Corollary 2.24.** *The type cone  $\text{TC}(\mathcal{F}(n))$  is simplicial.*

As a follow-up to Theorem 2.23, we conjecture the following surprising property.

**Conjecture 2.25.** *Any positive dual  $\mathbf{c}$ -vector supports exactly one extremal exchangeable pair.*

Combining Corollaries 1.11 and 2.24 and Theorem 2.23, we derive the following description of all polytopal realizations of the cluster fan  $\mathcal{F}(\mathbf{B}_\circ)$ . This result was stated in [BMDM<sup>+</sup>18] in the special situation of acyclic seeds in simply-laced types. Note that our proof is quite different from [BMDM<sup>+</sup>18] as it relies on our type cone approach.

**Theorem 2.26.** *For any finite type exchange matrix  $\mathbf{B}_\circ$  (acyclic or not, simply-laced or not), and for any  $\ell \in \mathbb{R}_{>0}^{\mathcal{M}(\mathbf{B}_\circ)}$ , the polytope*

$$R_\ell(\mathbf{B}_\circ) := \left\{ \mathbf{z} \in \mathbb{R}^{\mathcal{V}(\mathbf{B}_\circ)} \mid \mathbf{z} \geq 0 \text{ and } \mathbf{z}_x + \mathbf{z}_{x'} - \sum_{y \in \mathcal{V}(\mathbf{B}_\circ)} \alpha_{x, x', y} \mathbf{z}_y = \ell_{\{x, x'\}} \text{ for all } \{x, x'\} \in \mathcal{M}(\mathbf{B}_\circ) \right\}$$

*is a generalized associahedron, whose normal fan is the cluster fan  $\mathcal{F}(\mathbf{B}_\circ)$ . Moreover, the polytopes  $R_\ell(\mathbf{B}_\circ)$  for  $\ell \in \mathbb{R}_{>0}^{\mathcal{M}(\mathbf{B}_\circ)}$  describe all polytopal realizations of  $\mathcal{F}(\mathbf{B}_\circ)$ .*

**Example 2.27.** To complement Section 2.1, let us translate to diagonals and triangulations the result of Theorem 2.26 in type  $A$ . Let  $n \geq 3$ . Consider a convex  $(n+3)$ -gon whose vertices are labeled modulo  $n+3$  and whose internal and boundary diagonals are denoted by  $\Delta(n) := \binom{\mathbb{Z}/(n+3)\mathbb{Z}}{2}$ . Consider a triangulation  $T$  of this polygon, formed by the  $n+3$  boundary edges and  $n$  internal diagonals of the  $(n+3)$ -gon. Then for any  $\ell \in \mathbb{R}_{>0}^{\Delta(n) \setminus T}$ , the polytope

$$R_\ell(T) := \left\{ \mathbf{z} \in \mathbb{R}^{\Delta(n)} \mid \begin{array}{l} \mathbf{z} \geq 0 \quad \text{and} \quad \mathbf{z}_{(a,b)} = 0 \text{ for all } (a,b) \in T \quad \text{and} \\ \mathbf{z}_{(a,b)} + \mathbf{z}_{(a-1,b-1)} - \mathbf{z}_{(a,b-1)} - \mathbf{z}_{(a-1,b)} = \ell_{(a,b)} \text{ for all } (a,b) \notin T \end{array} \right\}$$

is an associahedron whose normal fan is the  $\mathbf{g}$ -vector fan  $\mathcal{F}(T)$  with respect to the triangulation  $T$ . Moreover, the polytopes  $R_\ell(T)$  for  $\ell \in \mathbb{R}_{>0}^{\Delta(n) \setminus T}$  describe all polytopal realizations of  $\mathcal{F}(T)$ .

**2.3. Non-kissing complexes and gentle associahedra.** Gentle associahedra were constructed by Y. Palu, V. Pilaud and P.-G. Plamondon [PPP17] in the context of support  $\tau$ -tilting for gentle algebras. For a given  $\tau$ -tilting finite gentle quiver  $\bar{Q}$  (defined in the next section), the  $\bar{Q}$ -associahedron  $\text{Asso}(\bar{Q})$  is a simple polytope which encodes certain representations of  $\bar{Q}$  and their  $\tau$ -tilting relations. Combinatorially, the  $\bar{Q}$ -associahedron is a polytopal realization of the non-kissing complex of  $\bar{Q}$ , defined as the simplicial complex of all collections of walks on the blossoming quiver  $\bar{Q}^*$  which are pairwise non-kissing. The non-kissing complex encompasses two families of simplicial complexes studied independently in the literature: on the one hand the grid associahedra introduced by T. K. Petersen, P. Pylyavskyy and D. Speyer in [PPS10] for a staircase shape, studied by F. Santos, C. Stump and V. Welker [SSW17] for rectangular shapes, and extended by T. McConville in [McC17] for arbitrary grid shapes; and on the other hand the Stokes polytopes and accordion associahedra studied by Y. Baryshnikov [Bar01], F. Chapoton [Cha16], A. Garver and T. McConville [GM18] and T. Manneville and V. Pilaud [MP19]. These two families naturally extend the classical associahedron, obtained from a line quiver. Non-kissing complexes are geometrically realized by polytopes called gentle associahedra, whose normal fan is called the non-kissing fan: its rays correspond to walks in the quiver and its cones are generated by the non-kissing walks. In this section, we describe the type cone of the non-kissing fan of a quiver  $\bar{Q}$  with no self-kissing walks.

**2.3.1. Non-kissing complex and non-kissing fan of a gentle quiver.** We present the definitions and properties of the non-kissing complex of a gentle quiver, following the presentation of [PPP17]. See also [BDM<sup>+</sup>17] for an alternative presentation.

*Gentle quivers.* Consider a *bound quiver*  $\bar{Q} = (Q, I)$ , formed by a finite quiver  $Q = (Q_0, Q_1, s, t)$  and an ideal  $I$  of the path algebra  $kQ$  (the  $k$ -vector space generated by all paths in  $Q$ , including vertices as paths of length zero, with multiplication induced by concatenation of paths) such that  $I$  is generated by linear combinations of paths of length at least two, and  $I$  contains all sufficiently large paths. See [ASS06] for background.

Following M. Butler and C. Ringel [BR87], we say that  $\bar{Q}$  is a *gentle bound quiver* when

- (i) each vertex  $a \in Q_0$  has at most two incoming and two outgoing arrows,
- (ii) the ideal  $I$  is generated by paths of length exactly two,
- (iii) for any arrow  $\beta \in Q_1$ , there is at most one arrow  $\alpha \in Q_1$  such that  $t(\alpha) = s(\beta)$  and  $\alpha\beta \notin I$  (resp.  $\alpha\beta \in I$ ) and at most one arrow  $\gamma \in Q_1$  such that  $t(\beta) = s(\gamma)$  and  $\beta\gamma \notin I$  (resp.  $\beta\gamma \in I$ ).

The algebra  $kQ/I$  is called a *gentle algebra*.

The *blossoming quiver*  $\bar{Q}^*$  of a gentle quiver is the gentle quiver obtained by completing all vertices of  $\bar{Q}$  with additional incoming or outgoing *blossoms* such that all vertices of  $\bar{Q}$  become 4-valent. For instance, Figure 9, (left) shows a blossoming quiver: the vertices of  $\bar{Q}$  appear in black, while the blossom vertices of  $\bar{Q}^*$  appear in white. We now always assume that  $\bar{Q}$  is a gentle quiver with blossoming quiver  $\bar{Q}^*$ .

*Strings and walks.* A *string* in  $\bar{Q} = (Q, I)$  is a word of the form  $\rho = \alpha_1^{\varepsilon_1} \alpha_2^{\varepsilon_2} \cdots \alpha_\ell^{\varepsilon_\ell}$ , where

- (i)  $\alpha_i \in Q_1$  and  $\varepsilon_i \in \{-1, 1\}$  for all  $i \in [\ell]$ ,
- (ii)  $t(\alpha_i^{\varepsilon_i}) = s(\alpha_{i+1}^{\varepsilon_{i+1}})$  for all  $i \in [\ell - 1]$ ,
- (iii) there is no path  $\pi \in I$  such that  $\pi$  or  $\pi^{-1}$  appears as a factor of  $\rho$ , and
- (iv)  $\rho$  is reduced, in the sense that no factor  $\alpha\alpha^{-1}$  or  $\alpha^{-1}\alpha$  appears in  $\rho$ , for  $\alpha \in Q_1$ .

The integer  $\ell$  is called the *length* of the string  $\rho$ . For each vertex  $a \in Q_0$ , there is also a *string of length zero*, denoted by  $\varepsilon_a$ , that starts and ends at  $a$ . We implicitly identify the two inverse strings  $\rho$  and  $\rho^{-1}$ , and call it an *undirected string* of  $\bar{Q}$ . Let  $\mathcal{S}(\bar{Q})$  denote the set of strings of  $\bar{Q}$ .

A *walk* of  $\bar{Q}$  is a maximal string of its blossoming quiver  $\bar{Q}^*$  (meaning that each endpoint is a blossom). As for strings, we implicitly identify the two inverse walks  $\omega$  and  $\omega^{-1}$ , and call it an *undirected walk* of  $\bar{Q}$ . Let  $\mathcal{W}(\bar{Q})$  denote the set of walks of  $\bar{Q}$ .

A *substring* of a walk  $\omega = \alpha_1^{\varepsilon_1} \cdots \alpha_\ell^{\varepsilon_\ell}$  of  $\bar{Q}$  is a string  $\sigma = \alpha_{i+1}^{\varepsilon_{i+1}} \cdots \alpha_{j-1}^{\varepsilon_{j-1}}$  of  $\bar{Q}$  for some indices  $1 \leq i < j \leq \ell$ . Note that by definition,

- the endpoints of  $\sigma$  are not allowed to be blossom endpoints of  $\omega$ ,

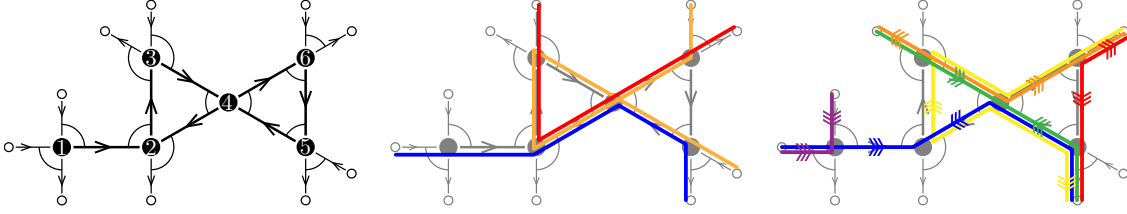


FIGURE 9. A blossoming quiver (left), three pairwise kissing walks (middle), and a non-kissing facet (right). Illustration from [PPP17].

- the position of  $\sigma$  as a factor of  $\omega$  matters (the same string at a different position is considered a different substring).
- the string  $\varepsilon_a$  is a substring of  $\omega$  for each occurrence of  $a$  as a vertex of  $\omega$  (take  $j = i + 1$ ).

We denote by  $\Sigma(\omega)$  the set of substrings of  $\omega$ . We say that the substring  $\sigma = \alpha_{i+1}^{\varepsilon_{i+1}} \cdots \alpha_{j-1}^{\varepsilon_{j-1}}$  is *at the bottom* (resp. *on top*) of the walk  $\omega = \alpha_1^{\varepsilon_1} \cdots \alpha_\ell^{\varepsilon_\ell}$  if  $\varepsilon_i = 1$  and  $\varepsilon_j = -1$  (resp. if  $\varepsilon_i = -1$  and  $\varepsilon_j = 1$ ). In other words the two arrows of  $\omega$  incident to the endpoints of  $\sigma$  point towards  $\sigma$  (resp. outwards from  $\sigma$ ). We denote by  $\Sigma_{\text{bot}}(\omega)$  and  $\Sigma_{\text{top}}(\omega)$  the sets of bottom and top substrings of  $\omega$  respectively. We use the same notation for undirected walks (of course, substrings of an undirected walk are undirected).

A *peak* (resp. *deep*) of a walk  $\omega$  is a substring of  $\omega$  of length zero which is on top (resp. at the bottom of  $\omega$ ). A walk  $\omega$  is *straight* if it has no peak or deep (*i.e.* if  $\omega$  or  $\omega^{-1}$  is a path in  $\bar{Q}^*$ ), and *bending* otherwise. We denote by  $\text{peaks}(\omega)$  (resp.  $\text{deeps}(\omega)$ ) the multisets of vertices of peaks (resp. deeps) of  $\omega$ .

*Non-kissing complex.* Let  $\omega$  and  $\omega'$  be two undirected walks on  $\bar{Q}$ . We say that  $\omega$  *kisses*  $\omega'$  if  $\Sigma_{\text{top}}(\omega) \cap \Sigma_{\text{bot}}(\omega') \neq \emptyset$ . In other words,  $\omega$  and  $\omega'$  share a common substring  $\sigma$ , and both arrows of  $\omega$  (resp. of  $\omega'$ ) incident to the endpoints of  $\sigma$  but not in  $\sigma$  are outgoing (resp. incoming) at the endpoints of  $\sigma$ . See Figure 10 for a schematic representation and Figure 9 (middle) where the three walks are pairwise kissing. We say that  $\omega$  and  $\omega'$  are *kissing* if  $\omega$  kisses  $\omega'$  or  $\omega'$  kisses  $\omega$  (or both). Note that we authorize the situation where the common finite substring is reduced to a vertex  $a$ , that  $\omega$  can kiss  $\omega'$  several times, that  $\omega$  and  $\omega'$  can mutually kiss, and that  $\omega$  can kiss itself. For example, the orange walk in Figure 9 (middle) is self-kissing (at its self-intersection). We say that a walk is *proper* if it is not straight nor self-kissing. We denote by  $\mathcal{W}_{\text{prop}}(\bar{Q})$  the set of all proper walks of  $\bar{Q}$ .



FIGURE 10. A schematic representation of kissing and non-kissing walks. The walks  $\omega$  and  $\omega'$  kiss (left) while the walks  $\mu$  and  $\nu$  share a common substring but do not kiss (right). Illustration from [PPP17].

The (reduced) *non-kissing complex* of  $\bar{Q}$  is the simplicial complex  $\mathcal{NK}(\bar{Q})$  whose faces are the collections of pairwise non-kissing proper walks of  $\bar{Q}$ . For example, Figure 9 (right) represents a non-kissing facet. As shown in [PPP17, Thm. 2.46], the non-kissing complex is a combinatorial model for the support  $\tau$ -tilting complex on  $\tau$ -rigid modules over  $kQ/I$ . The quiver  $\bar{Q}$  is called  *$\tau$ -tilting finite* or *non-kissing finite* when this complex is finite (in other words,  $\bar{Q}$  has finitely many non-kissing walks).

***g-* and *c*-vectors.** We now define two families of vectors associated to walks in the non-kissing complex. Let  $(e_v)_{v \in Q_0}$  denote the canonical basis of  $\mathbb{R}^{Q_0}$ . For a multiset  $V = \{\{v_1, \dots, v_k\}\}$  of  $Q_0$ , we denote by  $\mathbf{m}_V := \sum_{i \in [k]} e_{v_i}$ .

**Definition 2.28** ([PPP17, Def. 4.8]). The ***g*-vector** of a walk  $\omega$  is  $\mathbf{g}(\omega) := \mathbf{m}_{\text{peaks}(\omega)} - \mathbf{m}_{\text{deeps}(\omega)}$ . We set  $\mathbf{g}(F) := \{\mathbf{g}(\omega) \mid \omega \in F\}$  for a non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$ .

For example, the ***g*-vectors** of the blue, green, and yellow walks of Figure 9 (right) are respectively  $(0, -1, 0, 0, 1, 0)$ ,  $(0, 0, 1, -1, 1, 0)$  and  $(0, 0, 0, 0, 1, 0)$ . Note that by definition, the  $\mathbf{g}(\omega) = 0$  for a straight walk  $\omega$ .

To define the other family of vectors, we need to recall the notion of distinguished substring of a walk defined in [PPP17, Def. 2.25]. Consider an arrow  $\alpha \in Q_1$  contained in two distinct walks  $\omega, \omega'$  of a non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$ , and let  $\sigma$  denote the common substring of  $\omega$  and  $\omega'$ . We write  $\omega \prec_\alpha \omega'$  if  $\omega$  enters and/or exits  $\sigma$  with arrows in the direction pointed by  $\alpha$ , while  $\omega'$  enters and/or exits  $\sigma$  with arrows in the direction opposite to  $\alpha$ . For example, in Figure 10, we have  $\mu \prec_\gamma \nu$  but  $\nu \prec_\delta \mu$ . The ***distinguished walk*** of the non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$  at the arrow  $\alpha$  is the maximum walk of  $F$  for  $\prec_\alpha$ . The ***distinguished arrows*** of the walk  $\omega$  in the non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$  are the arrows where  $\omega$  is the distinguished walk. It is shown in [PPP17, Prop. 2.28] that each bending walk in a non-kissing facet has precisely two distinguished arrows, pointing in opposite directions. For example, we have marked in Figure 9 (right) the two distinguished arrows on each walk by triple arrows. The ***distinguished substring***  $\text{ds}(\omega, F)$  of the walk  $\omega$  in the non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$  is the substring located between its two distinguished arrows.

**Definition 2.29** ([PPP17, Def. 4.11]). The ***c*-vector** of a walk  $\omega$  in a non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$  is  $\mathbf{c}(\omega \in F) := \varepsilon(\omega, F) \mathbf{m}_{\text{ds}(\omega, F)}$ , where  $\varepsilon(\omega, F) \in \{-1, 1\}$  is positive if  $\text{ds}(\omega, F) \in \Sigma_{\text{top}}(\omega)$  and negative if  $\text{ds}(\omega, F) \in \Sigma_{\text{bot}}(\omega)$ . We set  $\mathbf{c}(F) := \{\mathbf{c}(\omega \in F) \mid \omega \in F\}$  for a non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$ .

For example, the ***g*-vectors** of the blue, green, and yellow walks in the non-kissing facet of Figure 9 (right) are respectively  $(0, -1, 0, 0, 0, 0)$ ,  $(0, 0, 0, -1, 0, 0)$  and  $(0, 1, 0, 1, 1, 0)$ . As the reader can observe on the example of Figure 9 (right), the ***g*-** and ***c*-vectors** also form dual bases.

**Proposition 2.30.** *For any non-kissing facet  $F \in \mathcal{NK}(\bar{Q})$ , the set of ***g*-vectors**  $\mathbf{g}(F)$  and the set of ***c*-vectors**  $\mathbf{c}(F)$  form dual bases, that is  $\langle \mathbf{g}(\omega) \mid \mathbf{c}(\omega' \in F) \rangle = \delta_{\omega=\omega'}$  for any two walks  $\omega, \omega' \in F$ .*

The following result will also be essential in our discussion. We say that a string  $\sigma$  is ***distinguishable*** if it is the distinguished substring of a walk in a non-kissing facet, and we denote by  $\mathcal{S}_{\text{dist}}(\bar{Q})$  the set of distinguishable strings of  $\bar{Q}$ .

**Proposition 2.31** ([PPP17, Prop. 3.68]). *The number of distinguishable strings  $\mathcal{S}_{\text{dist}}(\bar{Q})$  and proper walks  $\mathcal{W}_{\text{prop}}(\bar{Q})$  of the quiver  $\bar{Q}$  are related by*

$$|\mathcal{S}_{\text{dist}}(\bar{Q})| + |Q_0| = |\mathcal{W}_{\text{prop}}(\bar{Q})|.$$

***Non-kissing fan and gentle associahedron.*** The ***g*-vectors** support a complete simplicial fan realization of the non-kissing complex  $\mathcal{NK}(\bar{Q})$ . Examples are illustrated in Figure 11.

**Theorem 2.32** ([PPP17, Thm. 4.17]). *For any non-kissing finite gentle quiver  $\bar{Q}$ , the set of cones*

$$\mathcal{F}(\bar{Q}) := \{\mathbb{R}_{\geq 0} \mathbf{g}(F) \mid F \text{ non-kissing face of } \mathcal{NK}(\bar{Q})\}$$

*is a complete simplicial fan of  $\mathbb{R}^{Q_0}$ , called ***non-kissing fan*** of  $\bar{Q}$ , which realizes the non-kissing complex  $\mathcal{NK}(\bar{Q})$ .*

It is proved in [PPP17, Thm. 4.27] that the non-kissing fan comes from a polytope. For a walk  $\omega$ , denote by  $\text{KN}(\omega)$  the sum over all other walks  $\omega'$  of the number of kisses between  $\omega$  and  $\omega'$ .

**Theorem 2.33** ([PPP17, Thm. 4.27]). *For any non-kissing finite gentle quiver  $\bar{Q}$ , the non-kissing fan  $\mathcal{F}(\bar{Q})$  is the normal fan of the ***gentle associahedron***  $\text{Asso}(\bar{Q})$  defined equivalently as:*

- (i) *the convex hull of the points  $\sum_{\omega \in F} \text{KN}(\omega) \mathbf{c}(\omega \in F)$  for all facets  $F \in \mathcal{NK}(\bar{Q})$ , or*
- (ii) *the intersection of the halfspaces  $\{\mathbf{x} \in \mathbb{R}^{Q_0} \mid \langle \mathbf{g}(\omega) \mid \mathbf{x} \rangle \leq \text{KN}(\omega)\}$  for all walks  $\omega$  on  $\bar{Q}$ .*



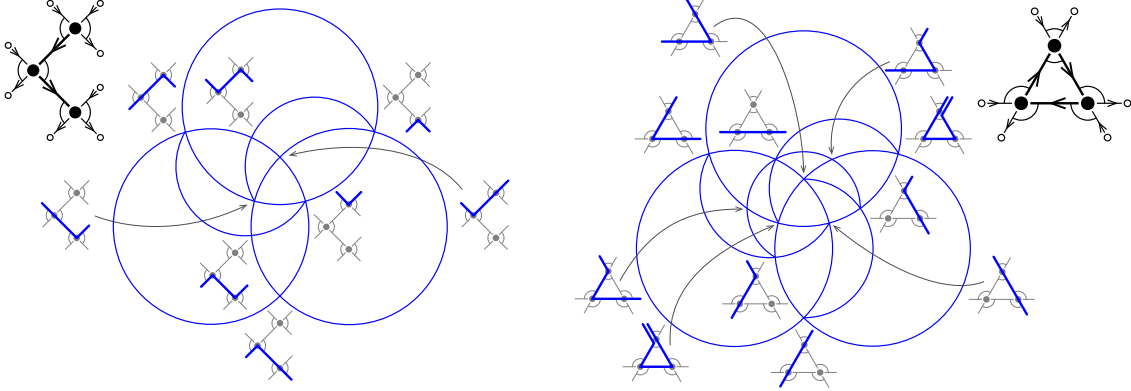


FIGURE 11. Two non-kissing fans. As the fans are 3-dimensional, we intersect them with the sphere and stereographically project them from the direction  $(-1, -1, -1)$ . Illustration from [PPP17].

*Flips in the non-kissing fan.* Although we lack a characterization of the exchangeable pairs of the non-kissing complex (see Remark 2.35), we can still describe the linear dependence among the  $\mathbf{g}$ -vectors involved in a flip. The following statement is partially proved in [PPP17, Thm. 4.17]. The notations are illustrated in Figure 12.

**Proposition 2.34.** *Let  $\omega, \omega'$  be two exchangeable walks on  $\bar{Q}$ . Then:*

- (i) *For any non-kissing facets  $F, F'$  of  $\mathcal{NK}(\bar{Q})$  with  $F \setminus \{\omega\} = F' \setminus \{\omega'\}$ , the distinguished substrings of  $\omega$  in  $F$  and of  $\omega'$  in  $F'$  coincide to a string  $\sigma$ . Moreover, if we decompose  $\omega = \rho\sigma\tau$  and  $\omega' = \rho'\sigma\tau'$ , then the facets  $F$  and  $F'$  both contain the walks  $\mu := \rho'\sigma\tau$  and  $\nu := \rho\sigma\tau'$ .*
- (ii) *The substring  $\sigma$  and thus the walks  $\mu$  and  $\nu$  only depend on the exchangeable walks  $\omega$  and  $\omega'$ , and not on the adjacent non-kissing facet  $F$  and  $F'$ .*
- (iii) *The linear dependence between the  $\mathbf{g}$ -vectors of  $F \cup F'$  is given by*

$$\mathbf{g}(\omega) + \mathbf{g}(\omega') = \mathbf{g}(\mu) + \mathbf{g}(\nu).$$

*In other words, the non-kissing fan of  $\bar{Q}$  has the unique exchange relation property.*

- (iv) *The  $\mathbf{c}$ -vector orthogonal to all  $\mathbf{g}$ -vectors  $\mathbf{g}(\lambda)$  for  $\lambda \in F \cap F'$  is the multiplicity vector  $\mathbf{m}_\sigma$  of the vertices of the substring  $\sigma$  of  $\omega$  and  $\omega'$ .*

*Proof.* Points (i), (iii) and (iv) were shown in [PPP17, Prop. 2.33, Thm. 4.17 & Prop 4.16]. We postpone the proof of point (ii) until Corollary 4.45.  $\square$

**Remark 2.35.** In view of Proposition 2.34, it is tempting to look for a characterization of the exchangeable pairs  $\omega, \omega'$  using the kisses between  $\omega$  and  $\omega'$ . This question was discussed in [BDM<sup>+</sup>17, Sect. 9]. However, as illustrated for instance in the non-kissing complex of Figure 11 (right),

- two exchangeable walks may kiss along more than one string (only one is distinguished),
- two non-exchangeable walks can kiss along more than one distinguishable string,
- two walks that kiss along a single distinguishable string are not always exchangeable,
- not all strings are distinguishable.

In Section 2.3.3, we will restrict to a situation that avoids all these pathologies.

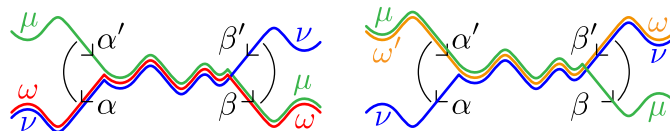


FIGURE 12. A schematic representation of a flip. Illustration from [PPP17].

*Two families of examples: gentle grid and dissection quivers.* The initial motivation for non-kissing complexes came from two families of examples, illustrated in Figure 13:

- (1) **Grid quivers:** Consider the infinite grid quiver  $\bar{Q}_{\mathbb{Z}^2}$ , whose vertices are all integer points of  $\mathbb{Z}^2$ , whose arrows are  $(i, j) \rightarrow (i, j + 1)$  and  $(i, j) \rightarrow (i + 1, j)$  for any  $(i, j) \in \mathbb{Z}^2$ , and whose relations are  $(i - 1, j) \rightarrow (i, j) \rightarrow (i, j + 1)$  and  $(i, j - 1) \rightarrow (i, j) \rightarrow (i + 1, j)$  for any  $(i, j) \in \mathbb{Z}^2$ . A *gentle grid quiver* is any subquiver  $\bar{Q}_A$  of  $\bar{Q}_{\mathbb{Z}^2}$  induced by a finite subset  $A \subset \mathbb{Z}^2$  of the integer grid. See Figure 13. The non-kissing complex of gentle grid quivers were introduced in [McC17] with motivation coming from [PPS10] and [SSW17].
- (2) **Dissection quivers:** Consider a dissection  $D$  of a convex polygon  $P$  (that is a crossing-free set of diagonals of  $P$ ) and its *gentle dissection quiver*  $\bar{Q}_D$ , whose vertices are the internal diagonals of  $D$ , whose arrows connect pairs of consecutive internal diagonals along the boundary of a face of  $D$ , and whose relations correspond to triples of consecutive internal diagonals along the boundary of a face of  $D$ . See Figure 13. The non-kissing complex of  $\bar{Q}_D$  then corresponds to non-crossing sets of accordions of  $D$ , where an accordion is a segment connecting the middles of two boundary edges of  $P$  and crossing a connected set of diagonals of  $D$ . This accordion complex was studied in [GM18] and [MP19] with motivation coming from [Bar01], and [Cha16].

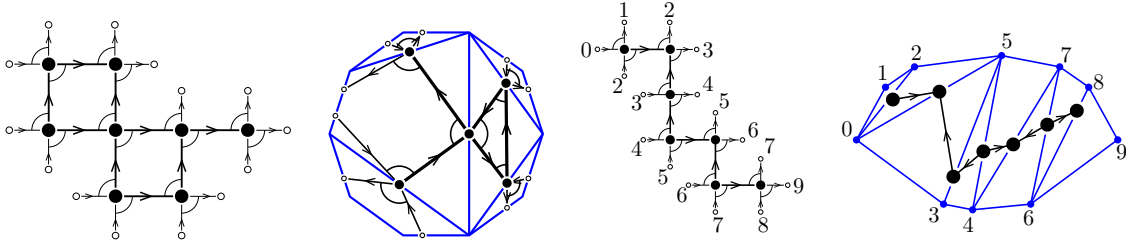


FIGURE 13. A gentle grid quiver (left), a gentle dissection quiver (middle left), and a path quiver which is both the gentle grid quiver of a ribbon (middle right) and the dissection quiver of a triangulation (right). Illustration from [PPP17].

These two families of non-kissing complexes are well-behaved as they avoid all pathologies of Remark 2.35. However, they still provide good examples of non-kissing complexes. In particular, both families contain the classical associahedron. Namely, the gentle associahedron  $\text{Asso}(\bar{Q})$  is the classical associahedron of [SS93, Lod04] presented in Theorem 2.1 when  $\bar{Q} = \bar{Q}_A$  for the path  $A = \{(0, j) \mid j \in [n]\}$  or equivalently  $\bar{Q} = \bar{Q}_D$  for the fan triangulation  $D$  (where all internal diagonals are incident to the same point). More generally,  $\text{Asso}(\bar{Q})$  is an associahedron of [HL07] when  $\bar{Q} = \bar{Q}_A$  for a ribbon  $A$  or equivalently  $\bar{Q} = \bar{Q}_D$  for a triangulation  $D$ . See Figure 13.

Note that, it was shown in [PPP18] that the accordion complexes can be extended to dissections of arbitrary orientable surfaces with marked points and then provide a geometric model for all non-kissing complexes of gentle quivers.

2.3.2. *Type cones of non-kissing fans.* We now discuss the type cones of the non-kissing fans defined in Theorem 2.32. We obtain from Proposition 2.34 the following redundant description.

**Corollary 2.36.** *For any non-kissing finite gentle quiver  $\bar{Q}$ , the type cone of the non-kissing fan  $\mathcal{F}(\bar{Q})$  is given by*

$$\text{TC}(\mathcal{F}(\bar{Q})) = \left\{ \mathbf{h} \in \mathbb{R}^{\mathcal{W}(\bar{Q})} \mid \begin{array}{l} \mathbf{h}_\omega = 0 \text{ for any improper walk } \omega \\ \mathbf{h}_\omega + \mathbf{h}_{\omega'} > \mathbf{h}_\mu + \mathbf{h}_\nu \text{ for any exchangeable walks } \omega, \omega' \end{array} \right\},$$

where the walks  $\mu$  and  $\nu$  for two exchangeable walks  $\omega, \omega'$  are defined in Proposition 2.34.

**Example 2.37.** Consider the non-kissing fans illustrated in Figure 11. The type cone of the left fan of Figure 11 lives in  $\mathbb{R}^8$  and has a linearity space of dimension 3. It has 5 facet-defining inequalities (given below), which correspond to the flips described in Propositions 2.41 and 2.42 and illustrated in Figure 14 (left).

walks									
$g$ -vectors	$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$	
facet defining inequalities	0	-1	1	0	1	0	0	0	(A)
	0	1	0	0	-1	0	0	1	(B)
	-1	0	0	1	1	0	0	-1	(C)
	1	0	0	-1	0	0	1	0	(D)
	0	0	0	1	0	1	-1	0	(E)

The type cone of the right fan of Figure 11 lives in  $\mathbb{R}^{11}$  and has a linearity space of dimension 3. It has 9 facet-defining inequalities (given below), which correspond to the flips illustrated in Figure 14 (right). In particular, it is not simplicial.

walks												
$g$ -vectors	$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$	
facet defining inequalities	-1	1	0	0	1	0	-1	0	0	0	0	(A)
	1	0	0	0	-1	0	0	0	0	0	1	(B)
	0	0	0	1	-1	0	1	0	0	0	0	(C)
	1	0	-1	-1	0	1	0	0	0	0	0	(D)
	0	0	0	-1	1	0	0	0	0	1	-1	(E)
	0	0	1	0	0	-1	0	0	0	1	0	(F)
	0	0	0	1	0	-1	0	1	0	0	0	(G)
	0	0	0	0	0	1	0	-1	1	-1	0	(H)
	0	-1	0	0	0	0	1	1	-1	0	0	(K)

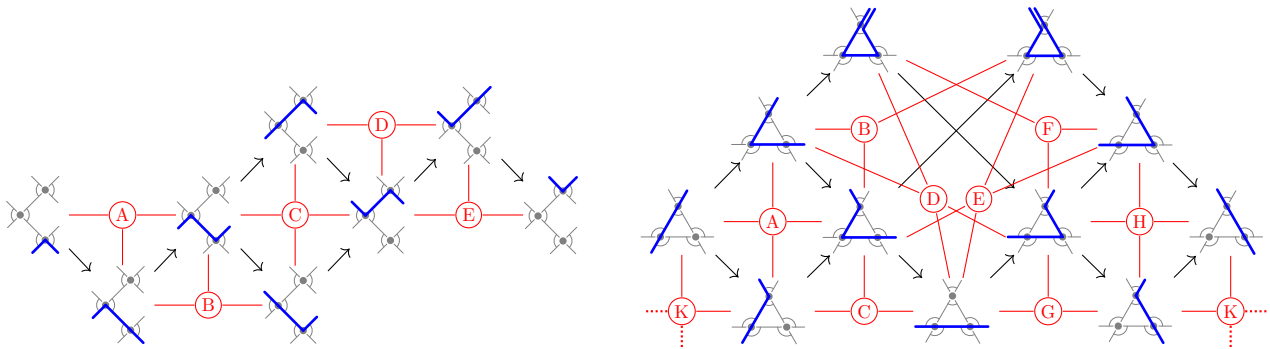


FIGURE 14. The facet-defining inequalities of the type cone  $\text{TC}(\mathcal{F}(\bar{Q}))$  of the non-kissing fan, represented on the Auslander Reiten quiver of the gentle algebra of  $\bar{Q}$ . While they correspond to meshes on the left, they are not as clear in the general case as on the right. See also Section 4.

As illustrated in Example 2.37, the type cone of the non-kissing fan is not always simplicial and we do not always understand its extremal exchangeable pairs. In the next section section, we will explore a special family of gentle quivers for which we can completely describe the type cone. The combination of this special family with computer experiments in the general case supports the following conjecture.

**Conjecture 2.38.** *Consider a distinguishable string  $\sigma \in \mathcal{S}_{\text{dist}}(\bar{Q})$ , and let  $\omega$  (resp.  $\omega'$ ) be the walk obtained from  $\sigma$  by adding two hooks (resp. two cohooks) at the endpoints of  $\sigma$ . Then*

- (1) *The  $\mathbf{c}$ -vector  $\mathbf{m}_\sigma$  is the direction of at least one extremal exchangeable pair.*
- (2) *If the walks  $\omega$  and  $\omega'$  are non-self-kissing and exchangeable, then they form the unique extremal exchangeable pair directed by  $\sigma$ . These extremal exchangeable pairs correspond to meshes of the Auslander-Reiten quiver.*

2.3.3. *Simplicial type cones for brick and 2-acyclic gentle bound quivers.* The following family of gentle quivers was considered in [GMM18, Sect. 4].

**Proposition 2.39.** *The following conditions are equivalent for a gentle quiver  $\bar{Q}$ .*

- (i) *any (non necessarily oriented) cycle of  $\bar{Q}$  contains at least two relations in  $I$ ,*
- (ii) *any string of  $\bar{Q}$  is distinguishable,*
- (iii) *no walk on  $\bar{Q}$  is self-kissing.*

In this section, we will restrict our attention to the following family of quivers.

**Definition 2.40.** A gentle quiver  $\bar{Q}$  is called:

- **brick** if it satisfies the three equivalent conditions of Proposition 2.39,
- **2-acyclic** if it contains no cycle of length 2.

Note that the family of brick and 2-acyclic gentle quivers already contains a lot of relevant examples, including the gentle grid and dissection quivers discussed in Section 2.3.1. In particular, the classical associahedron is the gentle associahedron of a brick and 2-acyclic gentle quiver. We will see in Corollary 2.43 that the type cone of the non-kissing fan  $\mathcal{F}(\bar{Q})$  of a brick and 2-acyclic gentle quiver  $\bar{Q}$  happens to be simplicial, and we will derive in Corollary 2.44 a simple description of all polytopal realizations of  $\mathcal{F}(\bar{Q})$ .

For a string  $\sigma$  of  $\bar{Q}$ , we denote by  $\sigma^\wedge$  (resp.  $\sigma^\vee$ ) the unique string of the blossoming quiver  $\bar{Q}^*$  of the form  $\sigma^\wedge = \sigma\alpha_1^{-1}\alpha_2 \dots \alpha_\ell$  (resp.  $\sigma^\vee = \sigma\alpha_1\alpha_2^{-1} \dots \alpha_\ell^{-1}$ ) with  $\ell \geq 1$  and  $\alpha_1, \dots, \alpha_\ell \in Q_1$  and such that  $t(\alpha_\ell)$  (resp.  $s(\alpha_\ell)$ ) is a blossom of  $\bar{Q}^*$ . These notations are motivated by the representation of strings used in [BR87, PPP17], and the terminology usually says that  $\sigma^\wedge$  (resp.  $\sigma^\vee$ ) is obtained by adding a *hook* (resp. a *cohook*) to  $\sigma$ . We define similarly  $\wedge\sigma$  (resp.  $\vee\sigma$ ). The walk  $\wedge(\sigma^\wedge) = (\wedge\sigma)^\wedge$  of  $\bar{Q}$  is simply denoted by  $\wedge\sigma^\wedge$ , and we define similarly  $\vee\sigma^\vee$ ,  $\wedge\sigma^\vee$  and  $\vee\sigma^\wedge$ .

**Proposition 2.41.** *For any brick and 2-acyclic gentle quiver  $\bar{Q}$  and any string  $\sigma \in \mathcal{S}(\bar{Q})$ , the walks  $\vee\sigma^\vee$  and  $\wedge\sigma^\wedge$  are exchangeable with distinguished substring  $\sigma$ .*

*Proof.* We fix some notations similar to that of Figure 12. Let  $\omega := \vee\sigma^\vee$ ,  $\omega' := \wedge\sigma^\wedge$ ,  $\mu := \wedge\sigma^\vee$  and  $\nu := \vee\sigma^\wedge$ . See Figure 12.

Since  $\bar{Q}$  is brick, these walks are not self-kissing by Proposition 2.39 and since they are bending, they are proper walks. We want to show that there are non-kissing facets  $F, F'$  of the non-kissing complex  $\mathcal{NK}(\bar{Q})$  containing both  $\mu$  and  $\nu$  and such that  $F \setminus \{\omega\} = F' \setminus \{\omega'\}$ .

We first show that  $\mu$  and  $\nu$  are compatible. Let  $\tau$  be a maximal common substring of  $\mu$  and  $\nu$ . If  $\sigma$  and  $\tau$  are not disjoint, then  $\sigma = \tau$  and  $\mu$  and  $\nu$  are not kissing at  $\tau$ . We can therefore assume that  $\tau$  appears completely before or completely after  $\sigma$  in both  $\mu$  and  $\nu$ . We distinguish two different cases:

- If  $\tau$  appears before  $\sigma$  in both  $\mu$  and  $\nu$ , then  $\alpha\tau\alpha'$  forms a cycle in  $\bar{Q}$ . If  $\tau$  is reduced to a vertex, then we have a 2-cycle. Otherwise, since  $\alpha\tau$  is a substring of  $\nu$  and  $\alpha'\tau$  is a substring of  $\mu$ , the cycle  $\alpha\tau\alpha'$  contains a unique relation  $\alpha'\alpha$ . This rules out this case under the assumption that  $\bar{Q}$  is brick and 2-acyclic. The case when  $\tau$  appears after  $\sigma$  in both  $\mu$  and  $\nu$  is symmetric.

- If  $\tau$  appears before  $\sigma$  in  $\mu$  and after  $\sigma$  in  $\nu$ , then  $\omega$ ,  $\mu$  and  $\nu$  finish at the same blossom so that  $\mu$  and  $\nu$  are not kissing at  $\tau$ . The case when  $\tau$  appears after  $\sigma$  in  $\mu$  and before  $\sigma$  in  $\nu$  is symmetric.

We conclude that  $\mu$  and  $\nu$  are non-kissing, which also implies that  $\{\mu, \nu, \omega\}$  and  $\{\mu, \nu, \omega'\}$  are non-kissing faces of  $\mathcal{NK}(\bar{Q})$ . We can therefore consider a non-kissing facet  $F$  containing  $\{\mu, \nu, \omega\}$ .

We claim that  $\omega$  is distinguished at  $\alpha$  and  $\beta$  in  $F$ , that  $\mu$  is distinguished at  $\alpha'$  in  $F$  and that  $\nu$  is distinguished at  $\beta'$  in  $F$ . Let us just prove that  $\mu$  is distinguished at  $\alpha'$ , the other statements being similar. Consider any walk  $\lambda$  of  $F$  containing  $\alpha'$ , and let  $\tau$  be the maximal common substring of  $\omega$  and  $\lambda$ . Note that  $\omega$  has the outgoing arrow  $\alpha$  while  $\lambda$  has the incoming arrow  $\alpha'$  at one end of  $\tau$ . Since  $\omega$  and  $\lambda$  are compatible, it ensures that either  $\tau$  ends at a blossom, or  $\lambda$  has an outgoing arrow at the other end of  $\tau$ . This shows that  $\lambda \prec_{\alpha'} \mu$  since  $\lambda$  separates from  $\mu$  with an arrow in the same direction as  $\alpha'$ .

Since this precisely coincides with the description of the flip in the non-kissing complex (see Proposition 2.34 (i) or [PPP17, Prop. 2.31] for an alternative presentation), we conclude that the flip of  $\omega$  in  $F$  creates a facet  $F'$  containing  $\omega'$ . Therefore,  $\omega$  and  $\omega'$  are exchangeable with distinguished substring  $\sigma$ .  $\square$

The following statement describes the type cone of the non-kissing fan of a brick and 2-acyclic gentle quiver. We provide here an elementary combinatorial proof, a more general representation theoretic perspective is discussed in Theorem 4.46.

**Proposition 2.42.** *For any brick and 2-acyclic gentle quiver  $\bar{Q}$ , the extremal exchangeable pairs for the non-kissing fan of  $\bar{Q}$  are precisely the pairs  $\{\searrow\sigma\swarrow, \swarrow\sigma\searrow\}$  for all strings  $\sigma \in \mathcal{S}(\bar{Q})$ .*

*Proof.* Let  $(\mathbf{f}_\omega)_{\omega \in \mathcal{W}(\bar{Q})}$  be the canonical basis of  $\mathbb{R}^{\mathcal{W}(\bar{Q})}$ . Consider two exchangeable walks  $\omega$  and  $\omega'$  with distinguished substring  $\sigma \in \Sigma_{\text{top}}(\omega) \cap \Sigma_{\text{bot}}(\omega')$ . Decompose  $\omega = \rho\sigma\tau$  and  $\omega' = \rho'\sigma\tau'$  and define  $\mu := \rho'\sigma\tau$  and  $\nu := \rho\sigma\tau'$  as in Proposition 2.34 (i). Proposition 2.34 (iii) ensures that the linear dependence between the corresponding  $\mathfrak{g}$ -vectors is given by

$$\mathbf{g}(\omega) + \mathbf{g}(\omega') = \mathbf{g}(\mu) + \mathbf{g}(\nu).$$

Therefore, the inner normal vector of the corresponding inequality of the type cone  $\mathbb{TC}(\mathcal{F}(\bar{Q}))$  is

$$\mathbf{n}(\omega, \omega') := \mathbf{f}_\omega + \mathbf{f}_{\omega'} - \mathbf{f}_\mu - \mathbf{f}_\nu.$$

We claim that this normal vector is always a positive linear combination of the normal vectors  $\mathbf{m}(\sigma) := \mathbf{n}(\searrow\sigma\swarrow, \swarrow\sigma\searrow) = \mathbf{f}_{\searrow\sigma\swarrow} + \mathbf{f}_{\swarrow\sigma\searrow} - \mathbf{f}_{\swarrow\sigma\swarrow} - \mathbf{f}_{\searrow\sigma\searrow}$  for all strings  $\sigma \in \mathcal{S}(\bar{Q})$ . Our proof works by descending induction on the length  $\lambda(\omega, \omega') := \ell(\sigma)$  of the common substring of  $\omega$  and  $\omega'$ . If  $\lambda(\omega, \omega')$  is big enough, then the walk  $\omega$  (resp.  $\omega'$ ) is just obtained by adding two outgoing (resp. incoming) blossoms at the end of  $\sigma$ , thus  $\omega = \searrow\sigma\swarrow$  (resp.  $\omega' = \swarrow\sigma\searrow$ ), and there is nothing to prove. Assume now that  $\omega \neq \swarrow\sigma\searrow$  (the situation where  $\omega' \neq \searrow\sigma\swarrow$  is symmetric). If  $\rho \neq \searrow$ , observe that

- $\omega$  and  $\searrow\sigma\tau'$  are exchangeable with  $\mathbf{n}(\omega, \searrow\sigma\tau') = \mathbf{f}_\omega + \mathbf{f}_{\searrow\sigma\tau'} - \mathbf{f}_{\searrow\sigma\tau} - \mathbf{f}_\nu$ , and
- $\searrow\sigma\tau$  and  $\omega'$  are exchangeable with  $\mathbf{n}(\searrow\sigma\tau, \omega') = \mathbf{f}_{\searrow\sigma\tau} + \mathbf{f}_{\omega'} - \mathbf{f}_{\searrow\sigma\tau'} - \mathbf{f}_\mu$ .

We derive that

$$\mathbf{n}(\omega, \omega') = \mathbf{n}(\omega, \searrow\sigma\tau') + \mathbf{n}(\searrow\sigma\tau, \omega').$$

Observe moreover that since  $\omega$  has outgoing arrows at the endpoints of  $\sigma$ , the common substring of  $\omega$  and  $\searrow\sigma\tau'$  strictly contains  $\sigma$  so that  $\lambda(\omega, \searrow\sigma\tau') > \lambda(\omega, \omega')$ . By induction,  $\mathbf{n}(\omega, \searrow\sigma\tau')$  is thus a positive linear combination of  $\mathbf{m}(\sigma)$  for  $\sigma \in \mathcal{S}(\bar{Q})$ . By symmetry, we obtain the four equalities

$$\mathbf{n}(\omega, \omega') = \begin{cases} \mathbf{n}(\omega, \searrow\sigma\tau') + \mathbf{n}(\searrow\sigma\tau, \omega') & \text{if } \rho \neq \searrow, \\ \mathbf{n}(\omega, \rho'\sigma\swarrow) + \mathbf{n}(\rho\sigma\swarrow, \omega') & \text{if } \tau \neq \swarrow, \\ \mathbf{n}(\omega, \swarrow\sigma\tau') + \mathbf{n}(\swarrow\sigma\tau, \omega') & \text{if } \rho' \neq \swarrow, \\ \mathbf{n}(\omega, \rho'\sigma\searrow) + \mathbf{n}(\rho\sigma\searrow, \omega') & \text{if } \tau' \neq \searrow. \end{cases}$$

These four equalities are illustrated on Figure 15. Moreover  $\mathbf{n}(\omega, \searrow\sigma\tau')$ ,  $\mathbf{n}(\searrow\sigma\tau, \swarrow\sigma\swarrow)$ ,  $\mathbf{n}(\searrow\sigma\searrow, \swarrow\sigma\tau')$

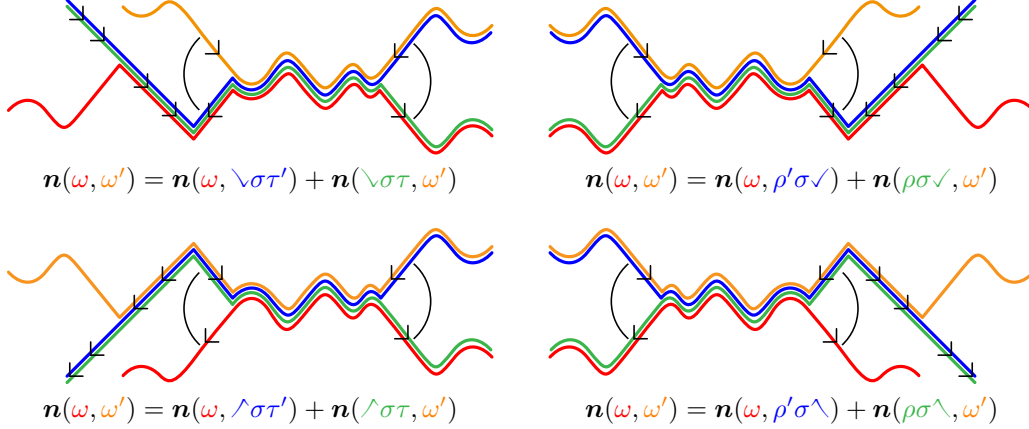


FIGURE 15. Schematic representation of the four equalities in the proof of Proposition 2.42.

and  $n(\nearrow\sigma\tau, \omega')$  are all positive combinations of  $\mathbf{m}(\sigma)$  for  $\sigma \in \mathcal{S}(\bar{Q})$  by induction hypothesis. Applying these equalities one after the other, we obtain

$$\begin{aligned}
& \frac{\mathbf{n}(\omega, \omega')}{=} \frac{\mathbf{n}(\omega, \searrow\sigma\tau') + \mathbf{n}(\searrow\sigma\tau, \omega')}{\text{Equality 1}} \\
& = \mathbf{n}(\omega, \searrow\sigma\tau') + \frac{\mathbf{n}(\searrow\sigma\tau, \nearrow\sigma\tau')}{\text{Equality 2}} + \mathbf{n}(\nearrow\sigma\tau, \omega') \\
& = \mathbf{n}(\omega, \searrow\sigma\tau') + \mathbf{n}(\searrow\sigma\tau, \nearrow\sigma\checkmark) + \frac{\mathbf{n}(\searrow\sigma\checkmark, \nearrow\sigma\tau')}{\text{Equality 3}} + \mathbf{n}(\nearrow\sigma\tau, \omega') \\
& = \mathbf{n}(\omega, \searrow\sigma\tau') + \mathbf{n}(\searrow\sigma\tau, \nearrow\sigma\checkmark) + \mathbf{n}(\searrow\sigma\checkmark, \nearrow\sigma\wedge) + \mathbf{n}(\searrow\sigma\wedge, \nearrow\sigma\tau') + \mathbf{n}(\nearrow\sigma\tau, \omega') \\
& = \mathbf{n}(\omega, \searrow\sigma\tau') + \mathbf{n}(\searrow\sigma\tau, \nearrow\sigma\checkmark) + \mathbf{m}(\sigma) + \mathbf{n}(\searrow\sigma\wedge, \nearrow\sigma\tau') + \mathbf{n}(\nearrow\sigma\tau, \omega')
\end{aligned}$$

where we fix the convention  $\mathbf{n}(\lambda, \lambda) = 0$  in case  $\rho = \nearrow$ ,  $\rho' = \searrow$ ,  $\tau = \wedge$  or  $\tau' = \checkmark$ . We conclude that  $\mathbf{n}(\omega, \omega')$  is a positive combination of  $\mathbf{m}(\sigma)$  for  $\sigma \in \mathcal{S}(\bar{Q})$ , since  $\mathbf{n}(\omega, \searrow\sigma\tau')$ ,  $\mathbf{n}(\searrow\sigma\tau, \nearrow\sigma\checkmark)$ ,  $\mathbf{n}(\searrow\sigma\wedge, \nearrow\sigma\tau')$  and  $\mathbf{n}(\nearrow\sigma\tau, \omega')$  are. This shows that all extremal exchangeable pairs are of the form  $\{\searrow\sigma\checkmark, \nearrow\sigma\wedge\}$  for  $\sigma \in \mathcal{S}(\bar{Q})$ .

Conversely, we know from Remark 1.6 that there are at least  $|\mathcal{W}_{\text{prop}}(\bar{Q})| - |Q_0|$  extremal exchangeable pairs. Since  $|\mathcal{S}(\bar{Q})| = |\mathcal{S}_{\text{dist}}(\bar{Q})| = |\mathcal{W}_{\text{prop}}(\bar{Q})| - |Q_0|$  by Proposition 2.31, we conclude that all exchangeable pairs  $\{\searrow\sigma\checkmark, \nearrow\sigma\wedge\}$  for  $\sigma \in \mathcal{S}(\bar{Q})$  are extremal.  $\square$

Our next statement follows from the end of the previous proof. See also Corollary 4.49.

**Corollary 2.43.** *For any brick and 2-acyclic gentle quiver  $\bar{Q}$ , the type cone  $\text{TC}(\mathcal{F}(\bar{Q}))$  of the non-kissing fan  $\bar{Q}$  is simplicial.*

Combining Corollaries 1.11 and 2.43 and Proposition 2.42, we derive the following description of all polytopal realizations of the non-kissing fan  $\mathcal{F}(\bar{Q})$  of a brick and 2-acyclic quiver  $\bar{Q}$ .

**Corollary 2.44.** *For any brick and 2-acyclic gentle quiver  $\bar{Q}$  and any  $\ell \in \mathbb{R}_{>0}^{\mathcal{S}(\bar{Q})}$ , the polytope*

$$R_{\ell}(\bar{Q}) := \left\{ \mathbf{z} \in \mathbb{R}^{\mathcal{W}(\bar{Q})} \mid \begin{array}{l} \mathbf{z} \geq 0 \quad \text{and} \quad \mathbf{z}_{\omega} = 0 \text{ for any improper walk } \omega \\ \mathbf{z}_{\searrow\sigma\checkmark} + \mathbf{z}_{\nearrow\sigma\wedge} - \mathbf{z}_{\nearrow\sigma\checkmark} - \mathbf{z}_{\searrow\sigma\wedge} = \ell_{\sigma} \text{ for all } \sigma \in \mathcal{S}(\bar{Q}) \end{array} \right\}$$

*is a realization of the non-kissing fan  $\mathcal{F}(\bar{Q})$ . Moreover, the polytopes  $R_{\ell}(\bar{Q})$  for  $\ell \in \mathbb{R}_{>0}^{\mathcal{S}(\bar{Q})}$  describe all polytopal realizations of  $\mathcal{F}(\bar{Q})$ .*

We also obtain from Proposition 2.42 the following surprising property.

**Corollary 2.45.** *Any c-vector supports exactly one extremal exchangeable pair.*

**Remark 2.46.** Although not needed in the proof of Proposition 2.42, we note that the extremal exchangeable pairs  $\{\searrow\sigma\checkmark, \nearrow\sigma\wedge\}$  and their linear dependencies  $\mathbf{g}(\searrow\sigma\checkmark) + \mathbf{g}(\nearrow\sigma\wedge) - \mathbf{g}(\nearrow\sigma\checkmark) - \mathbf{g}(\searrow\sigma\wedge)$  precisely correspond to the meshes of the Auslander-Reiten quiver of  $\bar{Q}$ .

**Remark 2.47.** Note that Propositions 2.41 and 2.42 and therefore Corollaries 2.43 and 2.44 fail when the quiver is not brick or 2-cyclic. The smallest examples are the 2-cycles whose non-kissing fans are represented in Figure 16. The left one is not brick: it has a non-distinguishable string and a self-kissing walk. The right one is brick but is 2-cyclic.

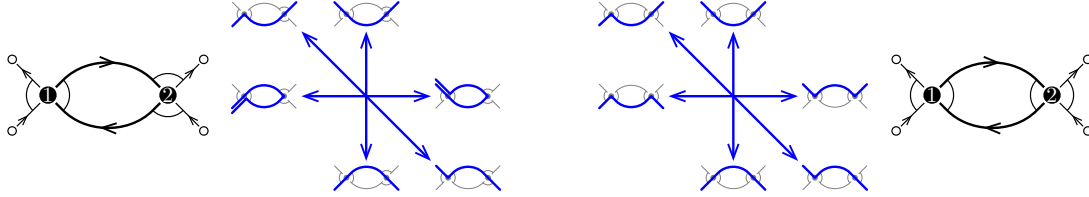


FIGURE 16. The non-kissing fans of two 2-cyclic gentle quivers. Illustration from [PPP17].

In both cases, Proposition 2.41 fails for the string  $\sigma$  of length 0 at vertex 1 (resp. 2) as the resulting walks  $\setminus\sigma\swarrow$  and  $\wedge\sigma\wedge$  have  $g$ -vectors  $g(\setminus\sigma\swarrow) = (1, -1)$  and  $g(\wedge\sigma\wedge) = (-1, 1)$  (resp.  $g(\setminus\sigma\swarrow) = (-1, 1)$  and  $g(\wedge\sigma\wedge) = (1, -1)$ ), and are therefore not exchangeable. Proposition 2.42 also fails as the type cone has dimension 4 and the following 5 inequalities:

walks						
$g$ -vectors	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ -1 \end{bmatrix}$
facet	1	-1	1	0	0	0
defining	0	1	-1	1	0	0
inequalities	0	0	1	-1	1	0
	0	0	0	1	-1	1
	1	0	0	0	1	-1

(since the fans are the same, the type cones are the same and we therefore present them together). Figure 11 (right) gives another example of brick but 2-cyclic gentle quiver for which Propositions 2.41 and 2.42 fail.

**2.4. Graphical nested complexes and graph associahedra.** Graph associahedra were defined by M. Carr and S. Devadoss [CD06] in connection to C. De Concini and C. Procesi’s wonderful arrangements [DCP95]. For a given graph  $G$ , the  $G$ -associahedron  $\text{Asso}(G)$  is a simple polytope whose combinatorial structure encodes the connected subgraphs of  $G$  and their nested structure. More precisely, the  $G$ -associahedron is a polytopal realization of the nested complex of  $G$ , defined as the simplicial complex of all collections of tubes (connected induced subgraphs) of  $G$  which are pairwise compatible (either nested, or disjoint and non-adjacent). As illustrated in Figure 17, the graph associahedra of certain special families of graphs coincide with well-known families of polytopes: complete graph associahedra are permutahedra, path associahedra are classical associahedra, cycle associahedra are cyclohedra, and star associahedra are stellohedra. The graph associahedra were extended to the *nestohedra*, which are simple polytopes realizing the nested complex of arbitrary building sets [Pos09, FS05]. Graph associahedra and nestohedra have been geometrically realized in different ways: by successive truncations of faces of the standard simplex [CD06], as Minkowski sums of faces of the standard simplex [Pos09, FS05], or from their normal fans by exhibiting explicit inequality descriptions [Dev09, Zel06]. For a given graph  $G$ , the resulting polytopes all have the same normal fan, called nested fan of  $G$ : its rays are the characteristic vectors of the tubes, and its cones are generated by characteristic vectors of compatible tubes. In this section, we describe the type cone of the nested fan of any graph  $G$ .

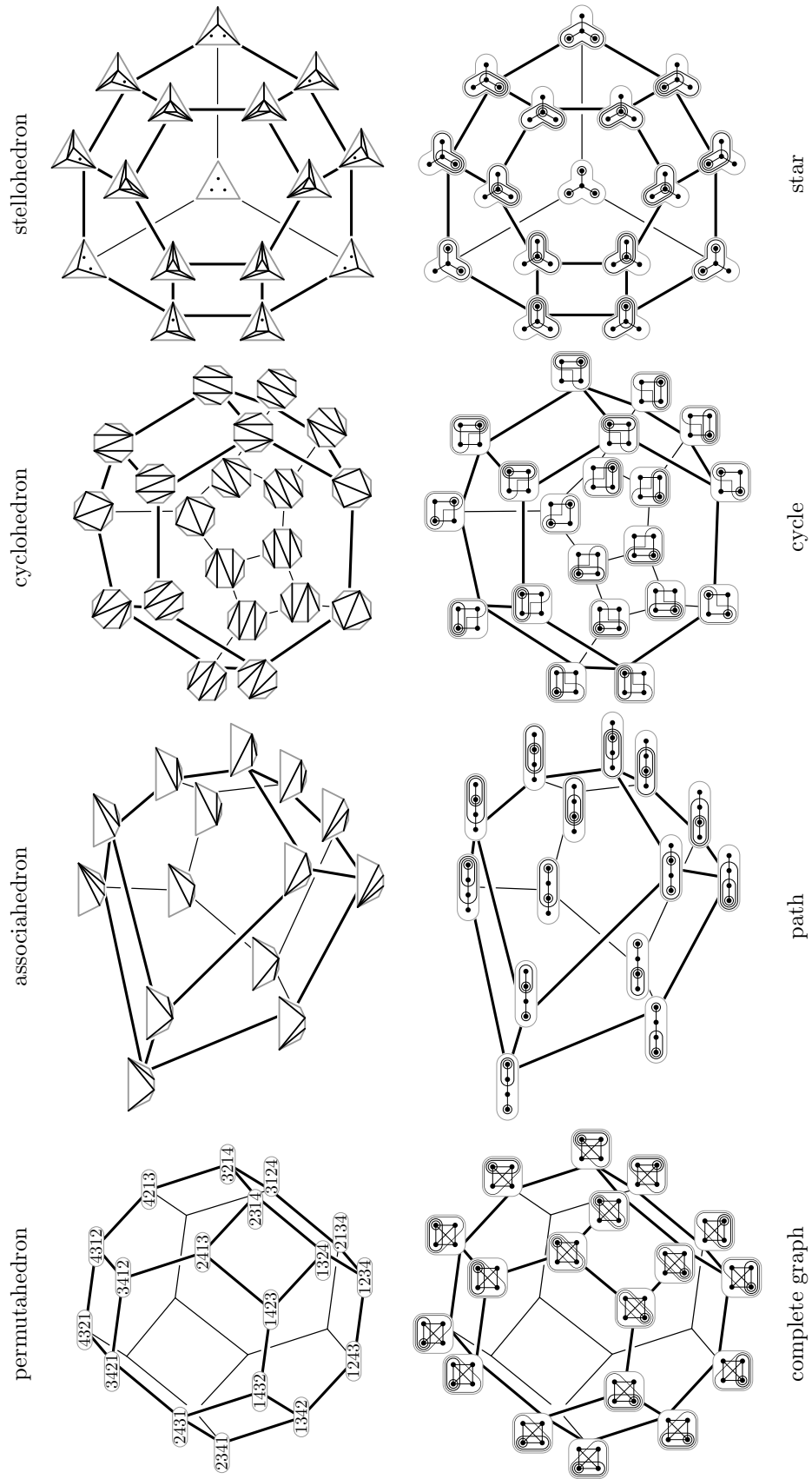


FIGURE 17. Some classical families of polytopes as graph associahedra. Illustration from [MP17].



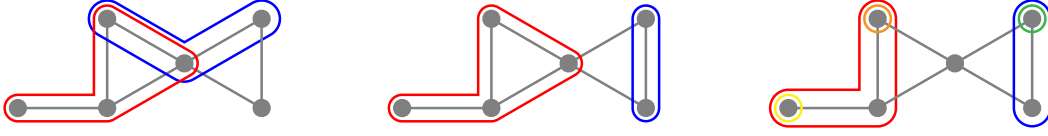


FIGURE 18. Some incompatible tubes (left and middle), and a maximal tubing (right).

2.4.1. *Nested complex and nested fan of a graph.* We present the definitions and properties of the nested complex of a graph, following ideas from [CD06, Pos09, FS05, Zel06].

*Nested complex.* Let  $G$  be a graph with vertex set  $V$ . Let  $\kappa(G)$  denote the set of connected components of  $G$  and define  $n := |V| - |\kappa(G)|$ . A *tube* of  $G$  is a connected induced subgraph of  $G$ . The set of tubes of  $G$  is denoted by  $\mathcal{T}(G)$ . The inclusion maximal tubes of  $G$  are its connected components  $\kappa(G)$ . The tubes which are neither empty nor maximal are called *proper*. Two tubes  $t, t'$  of  $G$  are *compatible* if they are either nested (*i.e.*  $t \subseteq t'$  or  $t' \subseteq t$ ), or disjoint and non-adjacent (*i.e.*  $t \cup t'$  is not a tube of  $G$ ). A *tubing* on  $G$  is a set  $\mathbb{T}$  of pairwise compatible proper tubes of  $G$ . See Figure 18. The *nested complex* of  $G$  is the simplicial complex  $\mathcal{N}(G)$  of all tubings on  $G$ .

*Nested fan and graph associahedron.* Let  $(e_v)_{v \in V}$  be the canonical basis of  $\mathbb{R}^V$ . We consider the hyperplane  $\mathbb{H} := \{x \in \mathbb{R}^V \mid \sum_{w \in W} x_w = 0 \text{ for all } W \in \kappa(G)\}$  and let  $\pi : \mathbb{R}^V \rightarrow \mathbb{H}$  denote the orthogonal projection on  $\mathbb{H}$ .

**Definition 2.48.** The  *$\mathbf{g}$ -vector* of a tube  $t$  of  $G$  is the projection  $\mathbf{g}(t) := \pi(\sum_{v \in t} e_v)$  of the characteristic vector of  $t$ . We set  $\mathbf{g}(\mathbb{T}) := \{\mathbf{g}(t) \mid t \in \mathbb{T}\}$  for a tubing  $\mathbb{T}$  on  $G$ .

Note that by definition,  $\mathbf{g}(\emptyset) = 0$  and  $\mathbf{g}(W) = 0$  for all connected components  $W \in \kappa(G)$ . These vectors support a complete simplicial fan realization of the nested complex. Examples are illustrated in Figure 19.

**Theorem 2.49** ([CD06, Pos09, FS05, Zel06]). *For any graph  $G$ , the set of cones*

$$\mathcal{F}(G) := \{\mathbb{R}_{\geq 0} \mathbf{g}(\mathbb{T}) \mid \mathbb{T} \text{ tubing on } G\}$$

*is a complete simplicial fan of  $\mathbb{H}$ , called **nested fan** of  $G$ , which realizes the nested complex  $\mathcal{N}(G)$ .*

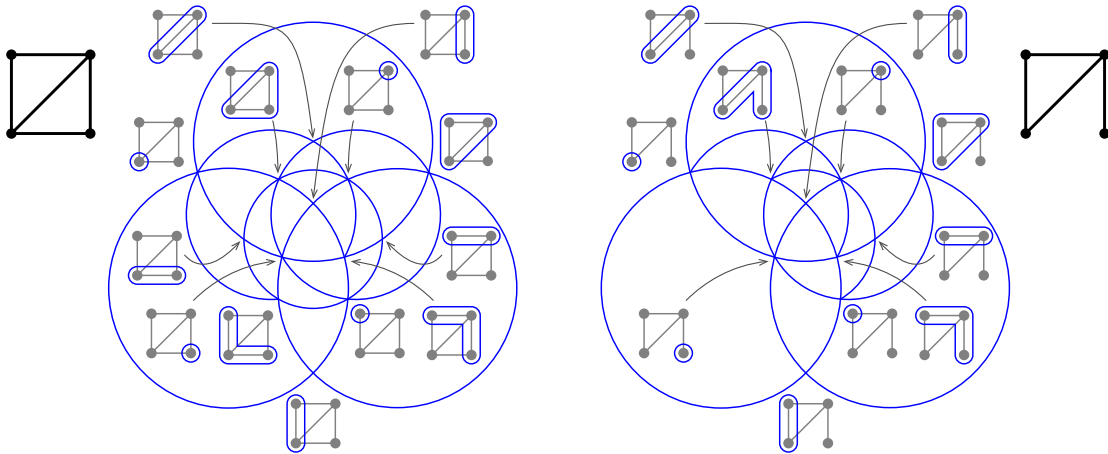


FIGURE 19. Two nested fans. As the fans are 3-dimensional, we intersect them with the sphere and stereographically project them from the direction  $(-1, -1, -1)$ .

It is proved in [CD06, Dev09, Pos09, FS05, Zel06] that the nested fan comes from a polytope. For any subset  $U \subseteq V$ , denote by  $\Delta_U := \text{conv}\{e_u \mid u \in U\}$  the face of the standard simplex  $\Delta_V$  corresponding to  $U$ .

**Theorem 2.50** ([CD06, Dev09, Pos09, FS05, Zel06]). *For any graph  $G$ , the nested fan  $\mathcal{F}(G)$  is the normal fan of the graph associahedron  $\text{Asso}(G)$ . It can be constructed as*

- the intersection of  $\mathbb{H}$  with the hyperplanes  $\langle \mathbf{g}(\mathfrak{t}) \mid \mathbf{x} \rangle \leq 3^{|\mathfrak{t}|-2}$  for all tubes  $\mathfrak{t} \in \mathcal{T}(G)$  [Dev09],
- the Minkowski sum  $\sum_{\mathfrak{t} \in \mathcal{T}(G)} \Delta_{\mathfrak{t}}$  of the faces of the standard simplex corresponding to all tubes of  $G$  [Pos09].

Flips in the nested fan. The following statement follows from [MP17, Zel06].

**Proposition 2.51.** *Let  $\mathfrak{t}, \mathfrak{t}'$  be two tubes of  $G$ . Then*

- The tubes  $\mathfrak{t}$  and  $\mathfrak{t}'$  are exchangeable if and only if  $\mathfrak{t}'$  has a unique neighbor  $v$  in  $\mathfrak{t} \setminus \mathfrak{t}'$  and  $\mathfrak{t}$  has a unique neighbor  $v'$  in  $\mathfrak{t}' \setminus \mathfrak{t}$ .
- For any maximal tubings  $\mathbb{T}, \mathbb{T}'$  on  $G$  with  $\mathbb{T} \setminus \{\mathfrak{t}\} = \mathbb{T}' \setminus \{\mathfrak{t}'\}$ , both  $\mathbb{T} \cup \kappa(G)$  and  $\mathbb{T}' \cup \kappa(G)$  contain the tube  $\mathfrak{t} \cup \mathfrak{t}'$  and the connected components of  $\mathfrak{t} \cap \mathfrak{t}'$ .
- The linear dependence between the  $\mathbf{g}$ -vectors of  $\mathbb{T} \cup \mathbb{T}'$  is given by

$$\mathbf{g}(\mathfrak{t}) + \mathbf{g}(\mathfrak{t}') = \mathbf{g}(\mathfrak{t} \cup \mathfrak{t}') + \sum_{\mathfrak{s} \in \kappa(\mathfrak{t} \cap \mathfrak{t}')} \mathbf{g}(\mathfrak{s}).$$

In other words, the nested fan of  $G$  has the unique exchange relation property.

- The  $\mathbf{c}$ -vector orthogonal to all  $\mathbf{g}$ -vectors  $\mathbf{g}(\mathfrak{s})$  for  $\mathfrak{s} \in \mathbb{T} \cap \mathbb{T}'$  is  $\mathbf{e}_v - \mathbf{e}_{v'}$ .

*Proof.* Points (i) and (ii) was proved in [MP17]. Point (iii) follows from the fact that

$$\sum_{v \in \mathfrak{t}} \mathbf{e}_v + \sum_{v \in \mathfrak{t}'} \mathbf{e}_v = \sum_{v \in \mathfrak{t} \cup \mathfrak{t}'} \mathbf{e}_v + \sum_{v \in \mathfrak{t} \cap \mathfrak{t}'} \mathbf{e}_v = \sum_{v \in \mathfrak{t} \cup \mathfrak{t}'} \mathbf{e}_v + \sum_{\substack{\mathfrak{s} \in \kappa(\mathfrak{t} \cap \mathfrak{t}') \\ v \in \mathfrak{s}}} \mathbf{e}_v.$$

Finally for (iv), any tube  $\mathfrak{s} \in \mathbb{T} \cap \mathbb{T}'$  that contains  $v$  or  $v'$  actually contains both (to be compatible with  $\mathfrak{t}$  and  $\mathfrak{t}'$ ). Therefore,  $\mathbf{g}(\mathfrak{s})$  is orthogonal to  $\mathbf{e}_v - \mathbf{e}_{v'}$  for any tube  $\mathfrak{s} \in \mathbb{T} \cap \mathbb{T}'$ .  $\square$

2.4.2. *Type cones of graphical nested fans.* We now discuss the type cones of the graphical nested fans defined in Theorem 2.49. We first obtain from Proposition 2.51 the following redundant description.

**Corollary 2.52.** *For any graph  $G$ , the type cone of the nested fan  $\mathcal{F}(G)$  is given by*

$$\text{TC}(\mathcal{F}(G)) = \left\{ \mathbf{h} \in \mathbb{R}^{\mathcal{T}(G)} \mid \begin{array}{l} \mathbf{h}_{\mathfrak{t}} = 0 \text{ for any improper tube } \mathfrak{t} \\ \mathbf{h}_{\mathfrak{t}} + \mathbf{h}_{\mathfrak{t}'} > \mathbf{h}_{\mathfrak{t} \cup \mathfrak{t}'} + \sum_{\mathfrak{s} \in \kappa(\mathfrak{t} \cap \mathfrak{t}')} \mathbf{h}_{\mathfrak{s}} \text{ for any exchangeable tubes } \mathfrak{t}, \mathfrak{t}' \end{array} \right\}.$$

**Example 2.53.** For the complete graph  $K_n$ , the admissible height vectors are precisely the submodular functions, *i.e.* the functions  $\mathbf{h} : 2^{[n]} \rightarrow \mathbb{R}$  such that  $\mathbf{h}_{\emptyset} = 0$  and  $\mathbf{h}_A + \mathbf{h}_B > \mathbf{h}_{A \cap B} + \mathbf{h}_{A \cup B}$  for any  $A, B \subseteq [n]$ . This is precisely the description of the generalized permutahedra introduced by A. Postnikov in [Pos09] and E.-M. Feichtner and B. Sturmfels in [FS05].

**Example 2.54.** Consider the nested fans illustrated in Figure 19. The type cone of the left fan lives in  $\mathbb{R}^{13}$ , has a linearity space of dimension 3 and 19 facet-defining inequalities (given below). In particular, it is not simplicial.

tubes														
$g$ -vectors	$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 2 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ -2 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ -2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -2 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$	
facet defining inequalities	0	0	0	0	0	0	0	0	0	0	1	-1	1	
	0	0	0	0	0	1	0	0	0	1	0	-1	0	
	-1	1	0	-1	0	0	1	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	1	-1	-1	1	0	
	0	0	0	0	0	-1	1	0	0	0	0	1	-1	
	-1	1	-1	0	1	0	0	0	0	0	0	0	0	
	-1	0	0	0	1	-1	1	0	0	0	0	0	0	
	0	1	-1	0	0	0	0	-1	1	0	0	0	0	
	0	0	-1	0	1	0	0	0	1	0	-1	0	0	
	0	0	0	0	1	-1	0	0	0	0	-1	1	0	
	0	0	1	0	0	0	0	0	-1	1	0	0	0	
	0	0	1	0	-1	1	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	1	-1	0	1	0	0	
	1	0	0	0	0	0	-1	0	0	0	0	0	1	
	1	0	0	0	-1	0	0	0	0	0	1	0	0	
	1	-1	0	0	0	0	0	1	0	0	0	0	0	
	0	0	0	1	0	0	0	-1	0	1	0	0	-1	
	0	0	0	1	0	1	-1	0	0	0	0	0	0	
	0	-1	1	1	0	0	0	0	0	0	0	0	0	

The type cone of the right fan lives in  $\mathbb{R}^{11}$ , has a linearity space of dimension 3 and 12 facet-defining inequalities (given below). In particular, it is not simplicial.

tubes												
$g$ -vectors	$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ -2 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ -2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -2 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ -2 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$	
facet defining inequalities	-1	1	-1	1	0	0	0	0	0	0	0	
	1	-1	0	0	0	1	0	0	0	0	0	
	0	1	-1	0	0	-1	1	0	0	0	0	
	1	0	0	-1	0	0	0	0	1	0	0	
	0	0	-1	1	0	0	1	0	-1	0	0	
	0	0	0	1	-1	0	0	0	-1	1	0	
	0	0	0	0	0	1	-1	0	1	0	0	
	0	0	0	0	0	0	1	-1	-1	1	0	
	0	0	0	0	0	0	0	0	1	-1	1	
	0	0	0	0	1	0	0	1	0	-1	0	
	0	0	1	0	0	0	-1	1	0	0	0	
	0	0	1	-1	1	0	0	0	0	0	0	

In the remaining of this section, we describe the facet-defining inequalities of the type cone of the graphical nested fans. Observe first that we have already indirectly described this type cone when the graph is a path in Proposition 2.6. Recall that on the path with  $n + 1$  vertices, the tubes of the path are the intervals of  $[n + 1]$  and that two intervals  $[i, j]$  and  $[i', j']$  of  $[n + 1]$  are exchangeable if either  $i < i' \leq j + 1 < j' + 1$  or  $i' < i \leq j' + 1 < j + 1$ .

**Proposition 2.55.** *Two intervals  $[i, j]$  and  $[i', j']$  of  $[n + 1]$  form an extremal exchangeable pair for the nested fan of the path if and only if  $i = i' + 1$  and  $j = j' + 1$ , or the opposite.*

We now consider an arbitrary graph  $G$  and describe the type cone of its nested fan. We give a necessary condition for an exchangeable pair to be extremal in Lemma 2.56, exploit it in Example 2.57, and prove that it is actually a sufficient condition in Proposition 2.58

**Lemma 2.56.** *If two tubes  $\mathfrak{t}$  and  $\mathfrak{t}'$  of  $G$  form an extremal exchangeable pair for the nested fan of  $G$ , then  $\mathfrak{t} \setminus \{v\} = \mathfrak{t}' \setminus \{v'\}$  for some neighbor  $v$  of  $\mathfrak{t}'$  and some neighbor  $v'$  of  $\mathfrak{t}$ .*

*Proof.* Consider an exchangeable pair  $\{\mathfrak{t}, \mathfrak{t}'\}$  of tubes of  $G$ . The inner normal vector of the corresponding inequality of the type cone is

$$\mathbf{n}(\mathfrak{t}, \mathfrak{t}') := \mathbf{f}_{\mathfrak{t}} + \mathbf{f}_{\mathfrak{t}'} - \mathbf{f}_{\mathfrak{t} \cup \mathfrak{t}'} - \sum_{s \in \kappa(\mathfrak{t} \cap \mathfrak{t}')} \mathbf{f}_s.$$

By Proposition 2.51,  $\mathfrak{t}'$  has a unique neighbor  $v$  in  $\mathfrak{t} \setminus \mathfrak{t}'$  and  $\mathfrak{t}$  has a unique neighbor  $v'$  in  $\mathfrak{t}' \setminus \mathfrak{t}$ . Therefore,  $\mathfrak{t} \setminus \mathfrak{t}'$  and  $\mathfrak{t}' \setminus \mathfrak{t}$  are both connected. Assume that  $\mathfrak{t} \setminus \mathfrak{t}' \neq \{v\}$ , and let  $w \neq v$  be a non-disconnecting node of  $\mathfrak{t} \setminus \mathfrak{t}'$ . By Proposition 2.51,  $\tilde{\mathfrak{t}} := \mathfrak{t} \setminus \{w\}$  and  $\mathfrak{t}'$  are exchangeable, and  $\tilde{\mathfrak{t}}' := (\mathfrak{t} \cup \mathfrak{t}') \setminus \{w\}$  and  $\mathfrak{t}$  are exchangeable as well. Moreover, we have

$$\begin{aligned} \mathbf{n}(\tilde{\mathfrak{t}}, \mathfrak{t}') + \mathbf{n}(\mathfrak{t}, \tilde{\mathfrak{t}}') &= \left( \mathbf{f}_{\tilde{\mathfrak{t}}} + \mathbf{f}_{\mathfrak{t}'} - \mathbf{f}_{\tilde{\mathfrak{t}} \cup \mathfrak{t}'} - \sum_{s \in \kappa(\tilde{\mathfrak{t}} \cap \mathfrak{t}')} \mathbf{f}_s \right) + \left( \mathbf{f}_{\mathfrak{t}} + \mathbf{f}_{\tilde{\mathfrak{t}}'} - \mathbf{f}_{\mathfrak{t} \cup \tilde{\mathfrak{t}}'} - \sum_{s \in \kappa(\mathfrak{t} \cap \tilde{\mathfrak{t}}')} \mathbf{f}_s \right) \\ &= \mathbf{f}_{\mathfrak{t}} + \mathbf{f}_{\mathfrak{t}'} - \mathbf{f}_{\mathfrak{t} \cup \mathfrak{t}'} - \sum_{s \in \kappa(\mathfrak{t} \cap \mathfrak{t}')} \mathbf{f}_s = \mathbf{n}(\mathfrak{t}, \mathfrak{t}'), \end{aligned}$$

as  $\tilde{\mathfrak{t}} \cup \mathfrak{t}' = \tilde{\mathfrak{t}}'$ ,  $\tilde{\mathfrak{t}} \cap \mathfrak{t}' = \mathfrak{t} \cap \mathfrak{t}'$ ,  $\mathfrak{t} \cup \tilde{\mathfrak{t}}' = \mathfrak{t} \cup \mathfrak{t}'$  and  $\kappa(\mathfrak{t} \cap \tilde{\mathfrak{t}}') = \kappa(\tilde{\mathfrak{t}}) = \tilde{\mathfrak{t}}$ . Therefore  $\mathbf{n}(\mathfrak{t}, \mathfrak{t}')$  defines a redundant inequality and  $\{\mathfrak{t}, \mathfrak{t}'\}$  is not an extremal exchangeable pair. The proof is symmetric if  $\mathfrak{t}' \setminus \mathfrak{t} \neq \{v'\}$ .  $\square$

**Example 2.57.** We now exploit Lemma 2.56 to show that certain height functions belong to the type cone of  $\mathcal{F}(G)$  and recover the classical constructions of the graph associahedron.

- (1) Consider the height function  $\mathbf{h} \in \mathbb{R}^{\mathcal{T}(G)}$  given by  $\mathbf{h}_{\mathfrak{t}} := -|\{s \in \mathcal{T}(G) \mid s \subseteq \mathfrak{t}\}|$ . Then for any tubes  $\mathfrak{t}$  and  $\mathfrak{t}'$  such that  $\mathfrak{t} \setminus \{v\} = \mathfrak{t}' \setminus \{v'\}$  for some neighbor  $v$  of  $\mathfrak{t}'$  and some neighbor  $v'$  of  $\mathfrak{t}$ , we have

$$\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{h} \rangle = |\{s \in \mathcal{T}(G) \mid \mathfrak{t} \Delta \mathfrak{t}' \subseteq s \subseteq \mathfrak{t} \cup \mathfrak{t}'\}|,$$

where  $\mathfrak{t} \Delta \mathfrak{t}' = \{v, v'\}$  denotes the symmetric difference. This quantity is positive since at least  $\mathfrak{t} \cup \mathfrak{t}'$  fulfills the condition. Thus, the height function  $\mathbf{h}$  belongs to the type cone  $\mathbb{TC}(\mathcal{F}(G))$ . The polytope  $P_{\mathbf{h}} := \{\mathbf{x} \in \mathbb{R}^V \mid \langle \mathbf{g}(\mathfrak{t}) \mid \mathbf{x} \rangle \leq \mathbf{h}_{\mathfrak{t}} \text{ for any tube } \mathfrak{t} \in \mathcal{T}(G)\}$  is the graph associahedron constructed by A. Postnikov's in [Pos09].

- (2) Consider now the height function  $\mathbf{h} \in \mathbb{R}^{\mathcal{T}(G)}$  given by  $\mathbf{h}_{\mathfrak{t}} := -3^{|\mathfrak{t}|-2}$ . Then for any tubes  $\mathfrak{t}$  and  $\mathfrak{t}'$  such that  $\mathfrak{t} \setminus \{v\} = \mathfrak{t}' \setminus \{v'\}$  for some neighbor  $v$  of  $\mathfrak{t}'$  and some neighbor  $v'$  of  $\mathfrak{t}$ , we have

$$\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{h} \rangle = -3^{|\mathfrak{t}|-2} - 3^{|\mathfrak{t}'|-2} + 3^{|\mathfrak{t} \cup \mathfrak{t}'|-2} + \sum_{s \in \kappa(\mathfrak{t} \cap \mathfrak{t}')} 3^{|s|-2} \geq -2 \cdot 3^{|\mathfrak{t} \cup \mathfrak{t}'|-1} + 3^{|\mathfrak{t} \cup \mathfrak{t}'|} > 0.$$

Thus, the height function  $\mathbf{h}$  belongs to the type cone  $\mathbb{TC}(\mathcal{F}(G))$ . The corresponding polytope  $P_{\mathbf{h}}$  is the graph associahedron constructed by S. Devadoss's in [Dev09].

- (3) Finally, consider the height function  $\mathbf{h} \in \mathbb{R}^{\mathcal{T}(G)}$  given by  $\mathbf{h}_{\mathfrak{t}} := |\{s \in \mathcal{T}(G) \mid s \supseteq \mathfrak{t}\}|$ . Then for any tubes  $\mathfrak{t}$  and  $\mathfrak{t}'$  such that  $\mathfrak{t} \setminus \{v\} = \mathfrak{t}' \setminus \{v'\}$  for some neighbor  $v$  of  $\mathfrak{t}'$  and some neighbor  $v'$  of  $\mathfrak{t}$ , we have

$$\begin{aligned} \langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{h} \rangle &= |\{(r, s) \in \mathcal{T}(G) \times \kappa(\mathfrak{t} \cap \mathfrak{t}') \mid s \subseteq r \text{ and } \mathfrak{t}, \mathfrak{t}' \not\subseteq r\}| \\ &\quad + (|\kappa(\mathfrak{t} \cap \mathfrak{t}')| - 1) \cdot |\{r \in \mathcal{T}(G) \mid \mathfrak{t} \text{ or } \mathfrak{t}' \subseteq r\}|. \end{aligned}$$

Any connected component of  $\mathfrak{t} \cap \mathfrak{t}'$  certifies the positivity of this evaluation, showing that the height function  $\mathbf{h}$  belongs to  $\mathbb{TC}(\mathcal{F}(G))$ . The corresponding realization  $P_{\mathbf{h}}$  of the graph associahedron is new, to the best of our knowledge.

We now show that the condition of Lemma 2.56 actually characterizes the extremal exchangeable pairs of the nested fan  $\mathcal{F}(G)$ .

**Proposition 2.58.** *Two tubes  $\mathfrak{t}$  and  $\mathfrak{t}'$  of  $G$  form an extremal exchangeable pair for the nested fan of  $G$  if and only if  $\mathfrak{t} \setminus \{v\} = \mathfrak{t}' \setminus \{v'\}$  for some neighbor  $v$  of  $\mathfrak{t}'$  and some neighbor  $v'$  of  $\mathfrak{t}$ .*

*Proof.* By Lemma 2.56, an exchangeable pair  $\{\mathfrak{t}, \mathfrak{t}'\}$  is not extremal unless both  $\mathfrak{t} \setminus \mathfrak{t}'$  and  $\mathfrak{t}' \setminus \mathfrak{t}$  are singletons. We now need to show that all these pairs are extremal. Until we finish the proof, we will call such a pair a *suspected extremal pair*.

Let  $\{\mathfrak{t}, \mathfrak{t}'\}$  be a suspected extremal pair. To prove that it is extremal, we will construct a vector  $\mathbf{w} \in \mathbb{R}^{\mathcal{T}(G)}$  such that  $\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{w} \rangle < 0$ , but  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{w} \rangle > 0$  for any other suspected extremal pair  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\}$ . This will show that the inequality induced by  $\{\mathfrak{t}, \mathfrak{t}'\}$  is not redundant.

Define  $\alpha(\mathfrak{t}, \mathfrak{t}') := \{r \in \mathcal{T}(G) \mid \mathfrak{t} \Delta \mathfrak{t}' \subseteq r \subseteq \mathfrak{t} \cup \mathfrak{t}'\}$ , where  $\Delta$  denotes the symmetric difference, and define  $\mathbf{x} \in \mathbb{R}^{\mathcal{T}(G)}$  be such that

$$\mathbf{x}_s = -|\{r \in \mathcal{T}(G) \setminus \alpha(\mathfrak{t}, \mathfrak{t}') \mid r \subseteq s\}|$$

for each tube  $s \in \mathcal{T}(G)$ . For any suspected extremal pair  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\}$  we have

$$\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{x} \rangle = |\alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \setminus \alpha(\mathfrak{t}, \mathfrak{t}')| \geq 0.$$

Notice that  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{x} \rangle = 0$  if  $\alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \subseteq \alpha(\mathfrak{t}, \mathfrak{t}')$  and  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{x} \rangle \geq 1$  otherwise. In particular, if  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\} \neq \{\mathfrak{t}, \mathfrak{t}'\}$  then  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{x} \rangle \geq 1$  unless  $\tilde{\mathfrak{t}} \cup \tilde{\mathfrak{t}}' \subsetneq \mathfrak{t} \cup \mathfrak{t}'$  because  $\tilde{\mathfrak{t}} \cup \tilde{\mathfrak{t}}' \in \alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}')$ , and if  $\tilde{\mathfrak{t}} \cup \tilde{\mathfrak{t}}' = \mathfrak{t} \cup \mathfrak{t}'$  but  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\} \neq \{\mathfrak{t}, \mathfrak{t}'\}$ , then either  $\mathfrak{t}$  or  $\mathfrak{t}'$  will belong to  $\alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}')$ .

Now, define  $\mathbf{y} \in \mathbb{R}^{\mathcal{T}(G)}$  by

$$\mathbf{y}_s = \begin{cases} -1 & \text{if } |s| \geq |\mathfrak{t}|, \\ 0 & \text{otherwise,} \end{cases}$$

for each tube  $s \in \mathcal{T}(G)$ . We have  $\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{y} \rangle = -1$ . For any suspected extremal pair  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\}$  we have  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{y} \rangle \geq -1$ . If moreover  $\tilde{\mathfrak{t}} \cup \tilde{\mathfrak{t}}' \subsetneq \mathfrak{t} \cup \mathfrak{t}'$ , then we have  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{y} \rangle \geq 0$ .

Finally, consider  $\mathbf{z} \in \mathbb{R}^{\mathcal{T}(G)}$  given by

$$\mathbf{z}_s = -|\{r \in \alpha(\mathfrak{t}, \mathfrak{t}') \mid r \subseteq s\}|,$$

for each tube  $s \in \mathcal{T}(G)$ . It verifies  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{z} \rangle \geq 0$  for any suspected extremal pair  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\}$ , and  $\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{z} \rangle = |\alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}')| > 0$  if  $\alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \subseteq \alpha(\mathfrak{t}, \mathfrak{t}')$ .

For  $0 < \varepsilon < 1$ , and  $0 < \delta < \frac{\varepsilon}{|\alpha(\mathfrak{t}, \mathfrak{t}')|}$ , we claim that the vector  $\mathbf{w} := \mathbf{x} + \varepsilon \mathbf{y} + \delta \mathbf{z}$  fulfills the desired properties. Indeed, if  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\} \neq \{\mathfrak{t}, \mathfrak{t}'\}$  is a suspected extremal pair with  $\alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \not\subseteq \alpha(\mathfrak{t}, \mathfrak{t}')$ , then

$$\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{w} \rangle = \underbrace{\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{x} \rangle}_{\geq 1} + \varepsilon \underbrace{\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{y} \rangle}_{> -1} + \delta \underbrace{\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{z} \rangle}_{\geq 0} > 0.$$

If  $\{\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}'\} \neq \{\mathfrak{t}, \mathfrak{t}'\}$  is a suspected extremal pair with  $\alpha(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \subseteq \alpha(\mathfrak{t}, \mathfrak{t}')$ , then  $\tilde{\mathfrak{t}} \cup \tilde{\mathfrak{t}}' \subsetneq \mathfrak{t} \cup \mathfrak{t}'$  and

$$\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{w} \rangle = \underbrace{\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{x} \rangle}_{=0} + \varepsilon \underbrace{\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{y} \rangle}_{\geq 0} + \delta \underbrace{\langle \mathbf{n}(\tilde{\mathfrak{t}}, \tilde{\mathfrak{t}}') \mid \mathbf{z} \rangle}_{>0} > 0.$$

However,

$$\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{w} \rangle = \underbrace{\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{x} \rangle}_{=0} + \varepsilon \underbrace{\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{y} \rangle}_{=-\varepsilon} + \delta \underbrace{\langle \mathbf{n}(\mathfrak{t}, \mathfrak{t}') \mid \mathbf{z} \rangle}_{=\delta|\alpha(\mathfrak{t}, \mathfrak{t}')| < \varepsilon} < 0. \quad \square$$

The following statement reformulates Proposition 2.58.

**Corollary 2.59.** *The extremal exchangeable pairs for the nested fan of  $G$  are precisely the pairs of tubes  $s \setminus \{v'\}$  and  $s \setminus \{v\}$  for any tube  $s \in \mathcal{T}(G)$  and distinct non-disconnecting vertices  $v, v'$  of  $s$ .*

We derive from Proposition 2.58 and Corollary 2.59 all polytopal realizations of the nested fan.

**Corollary 2.60.** *Consider a graph  $G$  on  $V$  with tubes  $\mathcal{T}(G)$  and a height vector  $\mathbf{h} \in \mathbb{R}^{\mathcal{T}(G)}$  such that  $\mathbf{h}_\emptyset = \mathbf{h}_G = 0$  and satisfying  $\mathbf{h}_{\mathfrak{s} \setminus \{v'\}} + \mathbf{h}_{\mathfrak{s} \setminus \{v\}} > \mathbf{h}_\mathfrak{s} + \mathbf{h}_{\mathfrak{s} \setminus \{v, v'\}}$  for any tube  $\mathfrak{s} \in \mathcal{T}(G)$  and distinct non-disconnecting vertices  $v, v'$  of  $\mathfrak{s}$ . Then the nested fan  $\mathcal{F}(G)$  is the normal fan of the graph associahedron*

$$\{\mathbf{x} \in \mathbb{R}^V \mid \langle \mathbf{g}(\mathfrak{t}) \mid \mathbf{x} \rangle \leq \mathbf{h}_\mathfrak{t} \text{ for any tube } \mathfrak{t} \in \mathcal{T}(G)\}.$$

We also obtain from Proposition 2.58 the following surprising property.

**Corollary 2.61.** *Any  $\mathbf{c}$ -vector supports at least one extremal exchangeable pair.*

*Proof.* Consider a  $\mathbf{c}$ -vector  $\mathbf{e}_v - \mathbf{e}_{v'}$  for two distinct vertices  $v, v'$  in a common connected component of  $G$ . Let  $r$  be a path from  $v$  to  $v'$  in  $G$  and let  $\mathfrak{t} := r \cup \{v\}$  and  $\mathfrak{t}' := r \cup \{v'\}$ . Then  $\{\mathfrak{t}, \mathfrak{t}'\}$  is an extremal exchangeable pair with  $\mathbf{c}$ -vector  $\mathbf{e}_v - \mathbf{e}_{v'}$ .  $\square$

We derive from Corollary 2.59 the number of extremal exchangeable pairs of the nested fan. For a tube  $\mathfrak{t}$  of  $G$ , we denote by  $\text{nd}(\mathfrak{t})$  the number of non-disconnecting vertices of  $\mathfrak{t}$ . In other words,  $\text{nd}(\mathfrak{t})$  is the number of tubes covered by  $\mathfrak{t}$  in the inclusion poset of all tubes of  $G$ .

**Corollary 2.62.** *The nested fan  $\mathcal{F}(G)$  has  $\sum_{\mathfrak{s} \in \mathcal{T}(G)} \binom{\text{nd}(\mathfrak{s})}{2}$  extremal exchangeable pairs.*

The formula of Corollary 2.62 can be made more explicit for specific families of graph associahedra discussed in the introduction and illustrated in Figure 17.

**Proposition 2.63.** *The number of extremal exchangeable pairs of the nested fan  $\mathcal{F}(G)$  is:*

- $2^{n-2} \binom{n}{2}$  for the permutahedron (complete graph associahedron),
- $\binom{n}{2}$  for the associahedron (path associahedron),
- $3 \binom{n}{2} - n$  for the cyclohedron (cycle associahedron),
- $n - 1 + 2^{n-3} \binom{n-1}{2}$  for the stellohedron (star associahedron).

*Proof.* For the permutahedron, choose any two vertices  $v, v'$ , and complete them into a tube by selecting any subset of the  $n - 2$  remaining vertices. For the associahedron, choose any two vertices  $v, v'$ , and complete them into a tube by taking the path between them. For the cyclohedron, choose the two vertices  $v, v'$ , and complete them into a tube by taking either all the cycle, or one of the two paths between  $v$  and  $v'$  (this gives three options in general, but only two when  $v, v'$  are neighbors). For the stellohedron, choose either  $v$  as the center of the star and  $v'$  as one of the  $n - 1$  leaves, or  $v$  and  $v'$  as leaves of the star and complete them into a tube by taking the center and any subset of the  $n - 3$  remaining leaves.  $\square$

To conclude on graph associahedra, we characterize the graphs  $G$  whose nested fan has a simplicial type cone.

**Proposition 2.64.** *The type cone  $\text{TC}(\mathcal{F}(G))$  is simplicial if and only if  $G$  is a path.*

*Proof.* Note that any tube  $\mathfrak{t}$  with  $|\mathfrak{t}| \geq 2$  has two non-disconnecting vertices when it is a path, and at least three non-disconnecting vertices otherwise (the leaves of an arbitrary spanning tree of  $\mathfrak{t}$ , or any vertex if it is a cycle). Therefore, each tube of  $\mathcal{T}(G)$  which is not a singleton contributes to at least one extremal exchangeable pair. We conclude that the number of extremal exchangeable pairs is at least:

$$|\mathcal{T}(G)| - |V| = |\mathcal{T}(G) \setminus \{\emptyset, G\}| - (|V| - 1) = N - n,$$

with equality if and only if all tubes of  $G$  are paths, *i.e.* if and only if  $G$  is a path.  $\square$

## Part II. Grothendieck group and relations between $\mathfrak{g}$ -vectors

### 3. RELATIONS FOR $\mathfrak{g}$ -VECTORS IN FINITE TYPE CLUSTER ALGEBRAS VIA 2-CALABI–YAU TRIANGULATED CATEGORIES

In [Aus84], M. Auslander showed that the relations in the Grothendieck group of an Artin algebra are generated by the ones given by almost-split sequences precisely when the algebra is of finite representation type. Inspired by this result, we will show that a similar statement holds (see Theorem 3.8) for the  $\mathfrak{g}$ -vectors (or indices) of objects in a 2-Calabi–Yau triangulated category.

**3.1. Setting.** Let  $\mathbb{K}$  be a field. Let  $\mathcal{C}$  be a  $\mathbb{K}$ -linear triangulated category with suspension functor  $\Sigma$ . We fix a collection  $\text{ind}(\mathcal{C})$  of representatives of isomorphism classes of indecomposable objects of  $\mathcal{C}$ . We will assume the following:

- $\mathcal{C}$  is essentially small (in particular,  $\text{ind}(\mathcal{C})$  is a set);
- $\mathcal{C}$  is Hom-finite: for each pair of objects  $X$  and  $Y$ , the  $\mathbb{K}$ -vector space  $\mathcal{C}(X, Y)$  is finite-dimensional;
- $\mathcal{C}$  is Krull–Schmidt: the endomorphism algebra of any indecomposable object is local;
- $\mathcal{C}$  is 2-Calabi–Yau: for each pair of objects  $X$  and  $Y$ , there is an isomorphism of bifunctors

$$\mathcal{C}(X, \Sigma Y) \rightarrow D\mathcal{C}(Y, \Sigma X)$$

where  $D = \text{Hom}_{\mathbb{K}}(-, \mathbb{K})$  is the usual duality of vector spaces;

- $\mathcal{C}$  contains a basic cluster-tilting object  $T = \bigoplus_{i=1}^n T_i$ :

$$\text{for any object } X, \quad \mathcal{C}(T, \Sigma X) = 0 \quad \text{if and only if} \quad X \in \text{add}(T),$$

where  $\text{add}(T)$  is the smallest additive full subcategory of  $\mathcal{C}$  containing the  $T_i$ 's and closed under isomorphisms.

**3.2. Statement of the theorem.** We need to introduce some notations before stating the main result of this section. Let  $\Lambda := \text{End}_{\mathcal{C}}(T)$ , and let  $F$  be the functor

$$F = \mathcal{C}(T, -) : \mathcal{C} \rightarrow \text{mod } \Lambda.$$

**Proposition 3.1** ([BMR07, KR07]). *The functor  $F$  induces an equivalence of  $\mathbb{K}$ -linear categories*

$$F : \mathcal{C}/(\Sigma T) \rightarrow \text{mod } \Lambda,$$

where  $(\Sigma T)$  is the ideal of morphisms factoring through an object of  $\text{add}(\Sigma T)$  and  $\text{mod } \Lambda$  is the category of finite-dimensional right  $\Lambda$ -modules. This equivalence induces further equivalences between  $\text{add}(T)$  and the category of projective modules, and between  $\text{add}(\Sigma^2 T)$  and that of injective modules.

For categories with a cluster-tilting object, the 2-Calabi–Yau condition implies other duality results which we shall need.

**Proposition 3.2** ([Pal08]). *For any pair of objects  $X$  and  $Y$  in  $\mathcal{C}$ , there is an isomorphism of bifunctors*

$$(\Sigma T)\mathcal{C}(X, \Sigma Y) \xrightarrow{\cong} \mathcal{C}(Y, \Sigma X)/(\Sigma T),$$

where  $(\Sigma T)\mathcal{C}(X, \Sigma Y)$  is the space of morphisms from  $X$  to  $Y$  factoring through  $(\Sigma T)$ .

**Remark 3.3.** Although the field  $\mathbb{K}$  is assumed to be algebraically closed in [Pal08], this assumption is not needed in the proof, and the result is valid over any field.

Finally, we need the existence of almost-split triangles in  $\mathcal{C}$ . Recall that a triangle

$$X \xrightarrow{f} Y \xrightarrow{g} Z \xrightarrow{h} \Sigma X$$

in  $\mathcal{C}$  is *almost-split* if  $X$  and  $Z$  are indecomposable,  $h$  is non-zero, and any non-section  $X \rightarrow X'$  factors through  $f$  (or equivalently, any non-retraction  $Z' \rightarrow Z$  factors through  $g$ ). We say that a triangulated category *has almost-split triangles* if there is an almost-split triangle as above for any indecomposable object  $X$ .

**Proposition 3.4** ([RVdB02, Prop. I.2.3]). *Any triangulated category admitting a Serre functor has almost-split triangles. In particular, any 2-Calabi–Yau triangulated category has almost-split triangles.*

**Definition 3.5.** (1) Let  $K_0^{\text{sp}}(\mathcal{C})$  be the *split Grothendieck group* of  $\mathcal{C}$ , that is, the free abelian group generated by symbols  $[X]$ , where  $[X]$  denotes the isomorphism class of  $X$  in  $\mathcal{C}$ , modulo the following relations: for any objects  $Y$  and  $Z$ , we let  $[Y \oplus Z] = [Y] + [Z]$ .  
 (2) Let  $K_0(\mathcal{C}; T)$  be the quotient of  $K_0^{\text{sp}}(\mathcal{C})$  by the relations  $[X] + [Z] - [Y]$  for all triangles

$$X \rightarrow Y \rightarrow Z \xrightarrow{h} \Sigma X$$

with  $h \in (\Sigma T)$ . Denote by  $\mathbf{g} : K_0^{\text{sp}}(\mathcal{C}) \rightarrow K_0(\mathcal{C}; T)$  the canonical projection.

In particular,  $K_0^{\text{sp}}(\mathcal{C})$  is isomorphic to a free abelian group over the set  $\text{ind}(\mathcal{C})$ . Considering the modified group  $K_0(\mathcal{C}; T)$  instead of the usual Grothendieck group is motivated by Section 3.4, where we study relations between  $\mathbf{g}$ -vectors.

**Definition 3.6.** For any two objects  $X$  and  $Y$  of  $\mathcal{C}$ , define

$$\langle X, Y \rangle := \dim_{\mathbb{K}} \text{Hom}_{\Lambda}(FX, FY).$$

This defines a bilinear form

$$\langle -, - \rangle : K_0^{\text{sp}}(\mathcal{C}) \times K_0^{\text{sp}}(\mathcal{C}) \rightarrow \mathbb{Z}.$$

**Notation 3.7.** (1) For any indecomposable object  $X$  of  $\mathcal{C}$ , let

$$X \rightarrow E \rightarrow \Sigma^{-1}X \rightarrow \Sigma X$$

be an almost split triangle (unique up to isomorphism). We let

$$\ell_X := [X] + [\Sigma^{-1}X] - [E] \in K_0^{\text{sp}}(\mathcal{C}).$$

(2) For any indecomposable object  $Y$  of  $\mathcal{C}$ , let

$$\Sigma Y \rightarrow E' \rightarrow Y \rightarrow \Sigma^2 Y$$

be an almost split triangle (unique up to isomorphism). We let

$$r_Y := [Y] + [\Sigma Y] - [E'] \in K_0^{\text{sp}}(\mathcal{C}).$$

We can finally state the main theorem of this section, which is an analogue of the main result of [Aus84].

**Theorem 3.8.** *Let  $\mathcal{C}$  be a category satisfying the hypotheses of Section 3.1. Then  $\mathcal{C}$  has only finitely many isomorphism classes of indecomposable objects if and only if the set*

$$L := \{\ell_X \mid X \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)\}$$

*generates the kernel of  $\mathbf{g} : K_0^{\text{sp}}(\mathcal{C}) \rightarrow K_0(\mathcal{C}; T)$ . In this case, the set  $L$  is a basis of the kernel of  $\mathbf{g}$ , and for any  $x \in \ker(\mathbf{g})$ , we have that*

$$x = \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \frac{\langle x, A \rangle}{\langle \ell_A, A \rangle} \ell_A.$$

**Corollary 3.9.** *Assume that  $\text{ind}(\mathcal{C})$  is finite. Let  $X \rightarrow E \rightarrow Y \xrightarrow{h} \Sigma X$  be a triangle with  $h \in (\Sigma T)$ . Then the element  $x = [X] + [Y] - [E]$  of the kernel of  $\mathbf{g}$  is a non-negative linear combination of the  $\ell_A$ , with  $A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)$ .*

*Proof.* We know that  $x = \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \frac{\langle x, [A] \rangle}{\langle \ell_A, [A] \rangle} \ell_A$ ; since  $\langle \ell_A, [A] \rangle$  is positive by Lemma 3.16, we only need to show that each  $\langle x, [A] \rangle$  is non-negative. The functor  $F = \mathcal{C}(T, -)$  induces an exact sequence

$$FX \rightarrow FE \rightarrow FY \rightarrow 0,$$

which in turn induces an exact sequence

$$0 \rightarrow \text{Hom}_{\Lambda}(FY, FA) \rightarrow \text{Hom}_{\Lambda}(FE, FA) \xrightarrow{f} \text{Hom}_{\Lambda}(FX, FA) \rightarrow \text{coker}(f) \rightarrow 0.$$

Therefore  $\langle x, [A] \rangle = \dim_{\mathbb{K}} \text{coker}(f) \geq 0$ . □



**3.3. Proof of Theorem 3.8.** Before we can prove Theorem 3.8, we need to recall the following results and definition from [DK08, Pal08].

**Proposition 3.10.** *Let  $X$  be an object of  $\mathcal{C}$ . Then there exists a triangle*

$$T_1^X \rightarrow T_0^X \rightarrow X \rightarrow \Sigma T_1^X$$

with  $T_1^X$  and  $T_0^X$  in  $\text{add}(T)$ .

**Definition 3.11.** The *index* of an object  $X$  is the element

$$\text{ind}_T(X) := [T_0^X] - [T_1^X] \in K_0^{\text{sp}}(\text{add}(T)).$$

The notion of index is very close to the definition of the map  $\mathfrak{g} : K_0^{\text{sp}}(\mathcal{C}) \rightarrow K_0(\mathcal{C}; T)$  of Definition 3.5. The link is given by the following result.

**Proposition 3.12** ([Pal08]). *Let  $X \rightarrow Y \rightarrow Z \xrightarrow{h} \Sigma X$  be a triangle. Then*

$$\text{ind}_T(X) + \text{ind}_T(Z) - \text{ind}_T(Y) = 0$$

if and only if  $h \in (\Sigma T)$ .

**Corollary 3.13.** *There is an isomorphism  $\phi : K_0(\mathcal{C}; T) \rightarrow K_0^{\text{sp}}(\text{add}(T))$  such that  $\text{ind}_T = \phi \circ \mathfrak{g}$ . In particular,  $K_0(\mathcal{C}; T)$  is a free abelian group generated by the  $[T_i]$ .*

We can now begin the proof of Theorem 3.8

**Lemma 3.14.** *If  $X$  or  $Y$  lie in  $\text{add}(\Sigma T)$ , then  $\langle X, Y \rangle = 0$ .*

*Proof.* This is because  $F\Sigma T = 0$ . □

**Lemma 3.15.** *Let  $X \rightarrow Y \rightarrow \Sigma^{-1}X \xrightarrow{h} \Sigma X$  be an almost-split triangle. Then  $X \notin \text{add}(\Sigma T)$  if and only if  $h \in (\Sigma T)$ .*

*Proof.* If  $X \in \text{add}(\Sigma T)$ , then  $h$  cannot be in  $(\Sigma T)$ , otherwise it would be zero since  $\mathcal{C}(T, \Sigma T) = 0$ .

Assume now that  $X \notin \text{add}(\Sigma T)$ . Let  $\mathbb{K}_X$  be the residue field of the algebra  $\text{End}_{\mathcal{C}}(X)$ . By definition of an almost-split triangle,  $h$  is in the socle of the right  $\text{End}_{\mathcal{C}}(X)$ -module  $\mathcal{C}(\Sigma^{-1}X, \Sigma X)$ . Moreover, this socle is a one-dimensional  $\mathbb{K}_X$ -vector space; indeed, the 2-Calabi–Yau condition gives an isomorphism

$$\mathcal{C}(\Sigma^{-1}X, \Sigma X) \cong DC(X, X).$$

Thus the socle of the right module  $\mathcal{C}(\Sigma^{-1}X, \Sigma X)$  has the same  $\mathbb{K}_X$  dimension as the top of the left module  $\mathcal{C}(X, X)$ . Since  $X$  is indecomposable,  $\mathcal{C}(X, X)$  is local, and its top is one-dimensional over  $\mathbb{K}_X$ .

Now,  $(\Sigma T)\mathcal{C}(\Sigma^{-1}X, \Sigma X)$  is a sub-module of  $\mathcal{C}(\Sigma^{-1}X, \Sigma X)$ . Therefore, if  $(\Sigma T)\mathcal{C}(\Sigma^{-1}X, \Sigma X)$  is non-zero, then it contains the one-dimensional socle of  $\mathcal{C}(\Sigma^{-1}X, \Sigma X)$ , and thus contains  $h$ . By [Pal08],

$$(\Sigma T)\mathcal{C}(\Sigma^{-1}X, \Sigma X) \cong DC(X, X)/(\Sigma T).$$

The identity morphism of  $X$  is not in  $(\Sigma T)$ , since  $X$  is not in  $\text{add}(\Sigma T)$ . Thus the right-hand side is non-zero, and so neither is the left-hand side. By the above, this implies  $h \in (\Sigma T)\mathcal{C}(\Sigma^{-1}X, \Sigma X)$ , which finishes the proof. □

**Lemma 3.16.** *Let  $A$  and  $B$  be two indecomposable objects of  $\mathcal{C}$ .*

(1) *If  $A \notin \text{add}(\Sigma T)$ , then*

$$\langle \ell_A, B \rangle = \begin{cases} 0 & \text{if } A \not\cong B; \\ \dim_{\mathbb{K}} \mathbb{K}_A & \text{if } A \cong B. \end{cases}$$

(2) *If  $B \notin \text{add}(\Sigma T)$ , then*

$$\langle A, r_B \rangle = \begin{cases} 0 & \text{if } A \not\cong B; \\ \dim_{\mathbb{K}} \mathbb{K}_B & \text{if } A \cong B. \end{cases}$$

*Proof.* We only prove the first assertion; the second one is proved dually. Assume that  $A \notin \text{add}(\Sigma T)$ . Let

$$A \xrightarrow{f} E \rightarrow \Sigma^{-1}A \xrightarrow{h} \Sigma A$$

be an almost-split triangle. By Lemma 3.15, the morphism  $h$  is in  $(\Sigma T)$ . Applying the functor  $F = \mathcal{C}(T, -)$ , we get an exact sequence

$$FA \xrightarrow{Ff} FE \rightarrow F\Sigma^{-1}A \rightarrow 0.$$

Applying now the functors  $\mathcal{C}(-, B)$  and  $\text{Hom}_\Lambda(-, FB)$ , we get a commutative diagram whose rows are exact sequences and whose vertical maps are surjective by Proposition 3.1.

$$\begin{array}{ccccccccc} \mathcal{C}(\Sigma^{-1}A, B) & \longrightarrow & \mathcal{C}(E, B) & \xrightarrow{f^*} & \mathcal{C}(A, B) & \longrightarrow & \text{coker}(f^*) & \longrightarrow & 0 \\ \downarrow & & \downarrow & & \downarrow & & \downarrow & & \\ 0 \longrightarrow & \text{Hom}_\Lambda(F\Sigma^{-1}A, FB) & \longrightarrow & \text{Hom}_\Lambda(FE, FB) & \xrightarrow{Ff^*} & \text{Hom}_\Lambda(FA, FB) & \longrightarrow & \text{coker}(Ff^*) & \longrightarrow & 0. \end{array}$$

If  $B \not\cong A$ , then the definition of an almost-split triangle implies that  $f^*$  is surjective. Thus  $\text{coker}(f^*) = 0$ , so that  $\text{coker}(Ff^*) = 0$ , and by additivity of the dimension in exact sequences, we get that  $\langle \ell_A, B \rangle = 0$ .

If  $B \cong A$ , then  $\text{coker}(f^*)$  is isomorphic to the residue field  $\mathbb{K}_A$  of  $\mathcal{C}(A, A)$ . Since  $A$  is not in  $\text{add}(\Sigma T)$ , the ideal of endomorphisms of  $A$  factoring through an object of  $\text{add}(\Sigma T)$  is contained in the maximal ideal of  $\mathcal{C}(A, A)$ . Therefore, the rightmost morphism in the commutative diagram is an isomorphism, so  $\text{coker}(Ff^*)$  is isomorphic to  $\mathbb{K}_A$ .  $\square$

**Lemma 3.17.** *Let  $x \in K_0^{\text{sp}}(\mathcal{C})$ , and write*

$$x = \sum_{A \in \text{ind}(\mathcal{C})} \lambda_A [A].$$

*Then for any  $A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)$ , we have that*

$$\lambda_A = \frac{\langle \ell_A, x \rangle}{\langle \ell_A, A \rangle} = \frac{\langle x, r_A \rangle}{\langle A, r_A \rangle}.$$

*Proof.* Let  $B \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)$ . Applying Lemma 3.16, we get that

$$\langle \ell_B, x \rangle = \langle \ell_B, \sum_{A \in \text{ind}(\mathcal{C})} \lambda_A [A] \rangle = \sum_{A \in \text{ind}(\mathcal{C})} \lambda_A \langle \ell_B, [A] \rangle = \lambda_B \langle \ell_B, [B] \rangle.$$

The equality  $\lambda_A = \frac{\langle x, r_A \rangle}{\langle A, r_A \rangle}$  is proved in a similar way.  $\square$

**Corollary 3.18.** *Let  $x \in K_0^{\text{sp}}(\mathcal{C})$ . Then the following are equivalent.*

- (1)  $x \in K_0^{\text{sp}}(\text{add}(\Sigma T))$ ;
- (2)  $\langle x, [A] \rangle = 0$  for all  $A \in \text{ind}(\mathcal{C})$ ;
- (3)  $\langle [A], x \rangle = 0$  for all  $A \in \text{ind}(\mathcal{C})$ .

*Proof.* We will only prove that (1) is equivalent to (2); the proof that (1) is equivalent to (3) is similar.

Assume that (2) holds. Then, by Lemma 3.17, we have that

$$x = \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \frac{\langle \ell_A, x \rangle}{\langle \ell_A, A \rangle} [A] + \sum_{i=1}^n \lambda_{\Sigma T_i} [\Sigma T_i] = \sum_{i=1}^n \lambda_{\Sigma T_i} [\Sigma T_i].$$

Thus  $x \in K_0^{\text{sp}}(\text{add}(\Sigma T))$ , and (1) holds.

Assume now that (1) holds. Then  $\langle x, [A] \rangle = 0$  for any  $A$  by Lemma 3.14. Thus (2) holds.  $\square$

**Proposition 3.19.** (1) *The set  $\{[\ell_A] \mid A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)\} \cup \{[\Sigma T_i] \mid i \in [n]\}$  is free in  $K_0^{\text{sp}}(\mathcal{C})$ .*  
(2) *The set  $\{[r_A] \mid A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)\} \cup \{[\Sigma T_i] \mid i \in [n]\}$  is free in  $K_0^{\text{sp}}(\mathcal{C})$ .*

*Proof.* We only prove (1); the proof of (2) is similar. Assume that

$$x = \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \lambda_A \ell_A + \sum_{i=1}^n \lambda_i [\Sigma T_i] = 0.$$

Then  $\langle x, [A] \rangle = 0$  for all  $A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)$ . But  $\langle x, [A] \rangle = \lambda_A$  by Lemma 3.16. Thus

$$x = \sum_{i=1}^n \lambda_i [\Sigma T_i] = 0.$$

But the  $[\Sigma T_i]$  are linearly independent in  $K_0^{\text{sp}}(\mathcal{C})$ . Thus  $\lambda_i = 0$  for all  $i \in [n]$ . This finishes the proof.  $\square$

**Proposition 3.20.** *Assume that  $\text{ind}(\mathcal{C})$  is finite. Then the set  $\{[\ell_A] \mid A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)\}$  is a basis of the kernel of  $\mathfrak{g} : K_0^{\text{sp}}(\mathcal{C}) \rightarrow K_0(\mathcal{C}; T)$ . Moreover, for any  $x \in \ker \mathfrak{g}$ , we have that*

$$x = \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \frac{\langle x, A \rangle}{\langle \ell_A, A \rangle} \ell_A.$$

*Proof.* By Proposition 3.19, the set is free. Let  $x \in \ker \mathfrak{g}$ . Consider the element

$$z = x - \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \frac{\langle x, A \rangle}{\langle \ell_A, A \rangle} \ell_A.$$

Then for any  $B \in \text{ind} \mathcal{C}$ , we have that

$$\langle z, [B] \rangle = \left\langle x - \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \frac{\langle x, A \rangle}{\langle \ell_A, A \rangle} \ell_A, [B] \right\rangle = \langle x, [B] \rangle - \langle x, [B] \rangle = 0,$$

where the second equality is obtained by using Lemma 3.16. By Corollary 3.18, this implies that  $z \in K_0^{\text{sp}}(\text{add}(\Sigma T))$ . Since  $z \in \ker(\mathfrak{g})$  and since  $\mathfrak{g}$  is injective on  $K_0^{\text{sp}}(\text{add}(\Sigma T))$  by Corollary 3.13, we get that  $z = 0$ . This finishes the proof.  $\square$

**Corollary 3.21.** *If  $\text{ind}(\mathcal{C})$  is finite, then the set*

$$\{[\ell_A] \mid A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)\} \cup \{[\Sigma T_i] \mid i \in [n]\}$$

*is a basis of  $K_0^{\text{sp}}(\mathcal{C})$ .*

*Proof.* By Proposition 3.19, the set is free. It suffices to prove that it generates  $K_0^{\text{sp}}(\mathcal{C})$ . Let  $x \in K_0^{\text{sp}}(\mathcal{C})$ . Consider

$$z = x - \sum_{A \in \text{ind} \mathcal{C}} \frac{\langle x, A \rangle}{\langle \ell_A, A \rangle} \ell_A.$$

Then for any  $B \in \text{ind}(\mathcal{C})$ , we have that  $\langle z, [B] \rangle = 0$ . By Corollary 3.18, this implies that  $z \in K_0^{\text{sp}}(\text{add}(\Sigma T))$ , and finishes the proof.  $\square$

All that remains is to prove the converse in the statement of Theorem 3.8.

**Proposition 3.22.** *Assume that the set  $\{[\ell_A] \mid A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)\}$  is a basis of the kernel of  $\mathfrak{g}$ . Then  $\text{ind}(\mathcal{C})$  is finite.*

*Proof.* Let  $x \in \ker \mathfrak{g}$ , and write  $x = \sum_{[A] \in \text{ind}(\mathcal{C})} \lambda_A [A]$ , where the sum has finite support. For any  $B$  not in the support of the sum, we have that  $\langle x, [B] \rangle = 0$ .

Now,  $[T] + [\Sigma T]$  is in the kernel of  $\mathfrak{g}$ , but  $\langle [T] + [\Sigma T], [B] \rangle = \langle [T], [B] \rangle = 0$  if and only if  $B \in \text{add}(\Sigma T)$ . Thus  $\text{ind}(\mathcal{C})$  has to be finite.  $\square$

**3.4. Application to  $\mathbf{g}$ -vectors of cluster algebras of finite type.** In this section, we apply the results of Section 3.2 in order to prove Propositions 2.16 and 2.22 of Section 2.2.

We first recall the results on categorification of cluster algebras that we will use in the proofs.

**Theorem 3.23.** *Let  $\mathcal{C}$  be the cluster category of a valued quiver of Dynkin type  $A, B, C, D, E, F$  or  $G$ . Let  $T$  be a basic cluster-tilting object in  $\mathcal{C}$ , and let  $Q$  be the valued Gabriel quiver of  $\text{End}_{\mathcal{C}}(T)$ . Then there is a bijection*

$$\phi : \text{ind}(\mathcal{C}) \rightarrow \{\text{cluster variables in the cluster algebra of } Q\},$$

expressing cluster variables as Laurent polynomials in the variables of the cluster  $\phi(T)$  and which has the following properties.

- (i) ([BMR<sup>+</sup>06, Prop. 3.2]) For any  $X, Y \in \text{ind}(\mathcal{C})$ ,  $\phi(X)$  and  $\phi(Y)$  are compatible if and only if  $\mathcal{C}(X, \Sigma Y) = 0$ .
- (ii) ([FK10, Prop. 4.3] and [Pal08, Prop. 2.2], where the proofs also work over an arbitrary base field) For any  $X \in \text{ind}(\mathcal{C})$ , the  $\mathbf{g}$ -vector of  $\phi(X)$  is  $\mathbf{g}([X])$ , where we identify  $\mathbb{Z}^n$  and  $K_0(\mathcal{C}; T)$  via the isomorphism sending  $(a_1, \dots, a_n)$  to  $\sum_{i=1}^n a_i [T_i]$ .
- (iii) ([BMR<sup>+</sup>06, Thm. 7.5]) For any  $X, Y \in \text{ind}(\mathcal{C})$ ,  $\phi(X)$  and  $\phi(Y)$  are exchangeable if and only if  $\dim_{\mathbb{K}_X} \mathcal{C}(X, \Sigma Y) = \dim_{\mathbb{K}_Y} \mathcal{C}(X, \Sigma Y) = 1$ .
- (iv) ([BIRS09] and [BMR08, Thm. 5.1], adapted to the cluster categories of species of Dynkin type) Let  $T'$  be any basic cluster-tilting object of  $\mathcal{C}$ . Then the matrix  $B'$  of the associated seed  $(\phi(T'), B')$  is given by the multiplicities of the middle terms of the exchange triangles.

The following definition is a cluster-tilting version of the positive mutation for  $\tau$ -tilting modules, or for 2-term silted complexes.

**Definition 3.24.** Let  $x \in X$  be a cluster variable in a given cluster and let  $x' \in X'$  be obtained by mutating  $X$  at  $x$ . The pair  $(x, x')$  is said to be a **positive mutation** with respect to some initial cluster  $X_{\circ}$  if there are  $X, Y \in \text{ind}(\mathcal{C})$  such that  $\phi(X) = x$ ,  $\phi(Y) = x'$ ,  $\dim_{\mathbb{K}_X} \mathcal{C}(X, \Sigma Y) = \dim_{\mathbb{K}_Y} \mathcal{C}(X, \Sigma Y) = 1$  and, for any non-split triangle

$$X \rightarrow E \rightarrow Y \xrightarrow{h} \Sigma X$$

(this triangle is unique up to isomorphism) we have  $h \in (\Sigma T)$ , where  $T \in \mathcal{C}$  is any basic cluster-tilting object such that  $\phi(T) = X_{\circ}$ .

The mutation is a **mesh mutation** if the triangle can be chosen to be an almost-split triangle (with no assumption on  $h$ ).

**Lemma 3.25.** *For every non-initial cluster variable, there exists precisely one pair  $(x, x')$  such that there exists a positive mesh mutation changing  $x$  into  $x'$ .*

*Proof.* Up to isomorphism, there is precisely one almost-split triangle of  $\mathcal{C}$  starting in  $X$ , where  $X$  is the object such that  $\phi(X) = x$ . Thus there is precisely one mesh relation. By Lemma 3.15, the pair  $(x, x')$  is a positive mutation if and only if  $X \notin \text{add}(\Sigma T)$ , that is, if and only if  $x$  is not an initial variable.  $\square$

**Lemma 3.26.** *The set of positive mesh mutations  $(x, x')$  of Definition 3.24 is in bijection with the set  $\mathcal{M}(B_{\circ})$  of Definition 3.24.*

*Proof.* If  $(x, x')$  is a positive mesh mutation, then  $\{x, x'\}$  is in  $\mathcal{M}(B_{\circ})$ . Indeed, if  $X$  and  $X'$  are the corresponding objects in  $\mathcal{C}$ , then there is an almost-split triangle

$$X \rightarrow E \rightarrow X' \rightarrow \Sigma E,$$

so that  $X' = \tau^{-1}X$ . Moreover, there is a slice of the Auslander–Reiten quiver of  $\mathcal{C}$  containing  $X$  and all indecomposable direct factors of  $E$ . The direct sum of indecomposable objects in this slice is a cluster-tilting object in which  $X$  is a source, and mutation at  $X$  gives  $X'$ . Thus  $\{x, x'\}$  is in  $\mathcal{M}(B_{\circ})$ . This gives an injective map from the set of positive mesh mutations to  $\mathcal{M}(B_{\circ})$ .

Next, assume that  $\{x, x'\} \in \mathcal{M}(B_{\circ})$  starts in  $x$ . Then there is a cluster-tilting object  $T$  in  $\mathcal{C}$  having  $X$  as a direct factor, and such that  $X$  is a source in  $T$  and mutation at  $X$  yields  $X'$ . Since  $X$  is a source, the mutation triangle starting and ending in  $X$  are

$$X \rightarrow E \rightarrow X' \rightarrow \Sigma X \quad \text{and} \quad X' \rightarrow 0 \rightarrow X \rightarrow \Sigma X'.$$

Therefore  $X' = \Sigma^{-1}X = \tau^{-1}X$ . Thus the first triangle is the almost-split triangle starting in  $X$ , since the dimension of  $\mathcal{C}(X', \Sigma X)$  is 1 over  $\mathbb{K}_{X'}$ . Since the pair  $\{x, x'\}$  is not initial,  $\phi(X')$  is not an initial variable; in other words,  $X'$  is not in  $\text{add}(T)$ . Therefore,  $X = \tau X' = \Sigma X'$  is not in  $\text{add} \Sigma T$ , so the mutation is a positive mesh mutation by Lemma 3.15. This gives an injective map from  $\mathcal{M}(\mathbb{B}_\circ)$  to the set of positive mutations.  $\square$

**Corollary 3.27** (Lemma 2.20). *We have that  $|\mathcal{M}(\mathbb{B}_\circ)|$  is the number  $|\mathcal{V}(\mathbb{B}_\circ, \mathbb{P}_\circ)| - n$  of non-initial cluster variables.*

*Proof.* This is a direct consequence of Lemmas 3.25 and 3.26.  $\square$

**Lemma 3.28.** *Let  $\mathcal{A}$  be any cluster algebra admitting a categorification by a Hom-finite, 2-Calabi–Yau, Krull–Schmidt, triangulated category with cluster-tilting objects. Let  $x \in X$  be a cluster variable in a given cluster and let  $x' \in X'$  be obtained by mutating  $X$  at  $x$ . Then precisely one of the two mutations  $\mu_x(X)$  and  $\mu_{x'}(X')$  is a positive mutation.*

*Proof.* In view of Theorem 3.23 (iii), it follows from [Pal08, Lem. 3.3].  $\square$

**Corollary 3.29.** (Proposition 2.22) *For any initial exchange matrix  $\mathbb{B}_\circ$  of mutation type  $A, B, C, D, E, F$  or  $G$ , the linear dependence between the  $\mathfrak{g}$ -vectors of any mutation can be decomposed into positive combinations of linear dependences between  $\mathfrak{g}$ -vectors of non-initial mesh mutations.*

*Proof.* Let  $\mathcal{C}$  be a cluster category of Dynkin type  $A, B, C, D, E, F$  or  $G$ , and let  $T \in \mathcal{C}$  be some basic cluster-tilting object categorifying the given initial exchange matrix  $\mathbb{B}_\circ$ . By Lemma 3.28, we may assume that the mutation under consideration is a positive mutation. In view of Theorem 3.23 (ii) and (iv) it is enough to show that the relation in  $K_0(\mathcal{C}; T)$  given by any triangle  $X \rightarrow E \rightarrow Y \xrightarrow{h} \Sigma X$  with  $h \in (\Sigma T)$  is a positive linear combination of relations coming from Auslander–Reiten triangles with third term not in  $\text{add}(\Sigma T)$ . This categorified statement is precisely Corollary 3.9.  $\square$

It also follows from Theorem 3.23 above that any cluster algebra of finite type has the unique exchange relation property (see Definition 1.8).

**Corollary 3.30.** (Proposition 2.16) *Let  $\mathbb{B}_\circ$  be any finite type exchange matrix, and let  $\mathcal{A}(\mathbb{B}_\circ)$  be the associated cluster algebra without coefficients. Then, for any exchangeable cluster variables  $x$  and  $x'$ , the linear dependence  $\sum_{y \in X \cup X'} \alpha_{X, X'}(\mathfrak{g}_y) \mathfrak{g}_y = 0$  only depends on the pair  $(x, x')$  and not on the specific choice of clusters  $X$  and  $X'$  containing  $x$  and  $x'$  respectively and such that  $X \setminus \{x\} = X' \setminus \{x'\}$ .*

*Proof.* By the results in additive categorification of cluster algebras recalled in Theorem 3.23, the statement follows from Lemma 3.31 below.  $\square$

**Lemma 3.31.** *Let  $\mathcal{C}$  be a cluster category of Dynkin type  $A, B, C, D, E, F$  or  $G$ , and let  $X, Y \in \mathcal{C}$  be such  $\phi(Y)$  is obtained by performing a positive mutation at  $\phi(X)$  in some cluster containing it. Then the linear dependence between the  $\mathfrak{g}$ -vectors given by the positive mutation is*

$$\mathfrak{g}_{\phi(X)} + \mathfrak{g}_{\phi(Y)} = \sum_i \mathfrak{g}_{\phi(E_i)},$$

where  $X \rightarrow \bigoplus_i E_i \rightarrow Y \xrightarrow{h} \Sigma X$  is a non-split triangle and each  $E_i$  is indecomposable.

*Proof.* Let  $T \in \mathcal{C}$  be a basic cluster tilting object such that  $\phi(T)$  is the initial cluster. According to Lemma 3.28, the morphism  $h$  belongs to the ideal  $(\Sigma T)$ . Therefore, the triangle  $X \rightarrow \bigoplus_i E_i \rightarrow Y \xrightarrow{h} \Sigma X$  induces the relation  $[X] + [Y] = \sum_i [E_i]$  in  $K_0(\mathcal{C}; T)$ . Theorem 3.23 (ii) gives the equality  $\mathfrak{g}_{\phi(X)} + \mathfrak{g}_{\phi(Y)} = \sum_i \mathfrak{g}_{\phi(E_i)}$ , where the  $\mathfrak{g}$ -vectors are computed with respect to the initial seed  $\phi(T)$ . By Theorem 3.23 (iii), the middle term of the triangle is uniquely defined, up to isomorphism, by  $X$ , and  $Y$ , and the triangle is therefore an exchange triangle, with respect to any mutation at  $X$ : it does not depend on the choice of a cluster tilting object containing  $X$ . By Theorem 3.23 (iv) this equality is one of the two equalities in Lemma 2.15.  $\square$

#### 4. RELATIONS FOR $\mathbf{g}$ -VECTORS IN BRICK ALGEBRAS VIA EXTRIANGULATED CATEGORIES

The main definitions and first properties on extriangulated categories are recalled after the statements of the main results of this section. See Section 4.4 below. The reader that does not want to dwell into details can safely skip Section 4.4 and focus on any of the first three examples given in Remark 4.1: triangulated categories, exact categories (that are small or have enough projectives or injectives) and extension-closed subcategories of triangulated categories, such as the category  $K^{[-1,0]}(\text{proj } \Lambda)$ , are examples of extriangulated categories.

**4.1. Setting.** We indifferently call *conflations*, written  $X \twoheadrightarrow Y \twoheadrightarrow Z$ , or *extriangles*, written  $X \twoheadrightarrow Y \twoheadrightarrow Z \xrightarrow{\delta}$ , the analogues of short exact sequences or triangles in an extriangulated category.

*Setting for Section 4.2.* In that section, we let  $\mathcal{C}$  be an extriangulated category with a fixed full additive subcategory  $\overline{\mathcal{T}}$ , stable under isomorphisms, under taking direct summands, and satisfying the following three properties:

- (1) Every  $T \in \mathcal{T}$  is projective in  $\mathcal{C}$ ;
- (2) For each  $T \in \mathcal{T}$ , the morphism  $T \rightarrow 0$  is an inflation for the extriangulated structure of  $\mathcal{C}$ ;
- (3) For each  $X \in \mathcal{C}$ , there is an extriangle  $T_1^X \twoheadrightarrow T_0^X \twoheadrightarrow X \xrightarrow{\delta_X}$  in  $\mathcal{C}$  with  $T_0^X, T_1^X$  in  $\mathcal{T}$ .

*Setting for Section 4.3.* In that section, we keep the previous setting, but assume moreover that  $\mathcal{C}$  is Krull–Schmidt,  $\mathbb{K}$ -linear, Ext-finite, and has Auslander–Reiten–Serre duality, and that the subcategory  $\mathcal{T}$  is of the form  $\text{add } T$ , where  $T = T_1 \oplus \cdots \oplus T_n$  is a basic object.

**Remark 4.1.** Examples of categories satisfying the properties above are

- 2-Calabi–Yau triangulated categories admitting a cluster-tilting object (see Section 4.7.1);
- for any Artin algebra  $\Lambda$ , the category  $K^{[-1,0]}(\text{proj } \Lambda)$  of complexes of finitely generated projective  $\Lambda$ -modules concentrated in degrees  $-1$  and  $0$ , with morphisms considered up to homotopy (see Section 4.6);
- more generally, extriangulated categories  $\mathcal{C}$  constructed as follows: if  $\mathcal{T}$  is a rigid subcategory of an extriangulated category  $\mathcal{E}$  (with some assumption ensuring that condition (2) holds) we let  $\mathcal{C}$  be the full subcategory of  $\mathcal{E}$  whose objects satisfy condition (3), equipped with the extriangulated structure obtained from that of  $\mathcal{E}$  by considering those extriangles in  $\mathcal{E}$  all whose terms belong to  $\mathcal{C}$  and whose deflation is  $\mathcal{T}$ -epi (see Section 4.7.2).

**4.2. Statement of preliminary results on extriangulated categories.** So as to be able to state the main theorem of Section 4, we need a few results on extriangulated categories. However, all proofs are postponed to Section 4.5.

We let  $\mathcal{C}$  be as in Section 4.1.

**Notation 4.2.** For any object  $T \in \mathcal{T}$ , we fix an extriangle  $T \twoheadrightarrow 0 \twoheadrightarrow \Sigma T \xrightarrow{\delta}$ .

**Remark 4.3.** As will be proven below (Remark 4.32 and Corollary 4.35), this notation extends to an equivalence of categories from the category  $\mathcal{T}$  of projective objects in  $\mathcal{C}$  to the category  $\Sigma\mathcal{T}$  of injective objects in  $\mathcal{C}$ .

**Notation 4.4.** We let  $\text{Mod } \mathcal{T}$  denote the category of additive functors from  $\mathcal{T}$  to Abelian groups, and  $\text{mod } \mathcal{T}$  its full subcategory of functors that are finitely presented, i.e. cokernels of morphisms between representable functors. We let  $F : \mathcal{C} \rightarrow \text{Mod } \mathcal{T}$  be the functor defined on objects by sending  $X \in \mathcal{C}$  to  $\mathcal{C}(-, X)|_{\mathcal{T}}$ .

**Lemma 4.5.** *For any  $X \in \mathcal{C}$ , the functor  $FX$  is finitely presented. We thus have a functor*

$$F : \mathcal{C} \rightarrow \text{mod } \mathcal{T}.$$

Proposition 4.6 below extends similar results from [BMR07, KR07, KZ08, IY08] (see also Proposition 3.1) to the setting under consideration. We note that the proof requires minor modifications.

**Proposition 4.6.** *The functor  $F$  induces an equivalence of categories*

$$F : \mathcal{C}/(\Sigma\mathcal{T}) \rightarrow \text{mod } \mathcal{T}$$

where  $(\Sigma\mathcal{T})$  is the ideal of morphisms factoring through an object of the form  $\Sigma T$ , for some  $T \in \mathcal{T}$ .

**Remark 4.7.** Because the category  $\mathcal{C}$  does not have weak kernels in general, the category  $\text{mod } \mathcal{T}$  might not be abelian. However, in all our applications, the subcategory  $\mathcal{T}$  is of the form  $\text{add}(T)$  for some object  $T$ . In that case,  $\text{mod } \mathcal{T}$  is equivalent to  $\text{mod } \text{End}_{\mathcal{C}}(T)$  and thus abelian.

**Definition 4.8.** We let  $K_0(\mathcal{C})$  denote the *Grothendieck group* of  $\mathcal{C}$ , that is, the quotient of the free abelian group generated by symbols  $[X]$ , for each  $X \in \mathcal{C}$ , by the relations  $[X] - [Y] + [Z]$ , for each conflation  $X \twoheadrightarrow Y \twoheadrightarrow Z$  in  $\mathcal{C}$ .

**Remark 4.9.** Since  $\mathcal{T}$  is extension-closed in  $\mathcal{C}$ , it inherits an extriangulated structure. Because  $\mathcal{T}$  is made of projective objects in  $\mathcal{C}$ , its extriangulated structure splits and we have  $K_0(\mathcal{T}) \cong K_0^{\text{sp}}(\mathcal{T})$ .

The notion of index from [DK08, Pal08] generalises to our current setting.

**Definition 4.10.** For any object  $X \in \mathcal{C}$ , fix some extriangle

$$T_1^X \twoheadrightarrow T_0^X \twoheadrightarrow X \xrightarrow{\delta_X}$$

and define the *index* of  $X$  by

$$\text{ind}_{\mathcal{T}} X = [T_0^X] - [T_1^X] \in K_0(\mathcal{T}).$$

**Proposition 4.11.** *The assignment  $X \mapsto \text{ind}_{\mathcal{T}} X$  is well-defined and induces an isomorphism*

$$\text{ind}_{\mathcal{T}} : K_0(\mathcal{C}) \xrightarrow{\cong} K_0(\mathcal{T})$$

of abelian groups.

**4.3. Statement of the theorem.** Let  $\mathcal{C}$  be as in Section 4.1.

**Remark 4.12.** Assume moreover that  $\mathcal{C}$  is  $\mathbb{K}$ -linear and Ext-finite. By the preliminary results of Section 4.4, we can apply [INP18, Prop. 4.2] to obtain that  $\text{mod } \mathcal{T}$  is Hom-finite. In particular, if  $\mathcal{T} = \text{add } T$ , then  $\text{End}_{\mathcal{C}}(T)$  is a finite-dimensional  $\mathbb{K}$ -algebra. It thus also follows that Definition 3.6 still makes sense in this more general setup: For any  $X, Y \in \mathcal{C}$ ,

$$\langle X, Y \rangle := \dim_{\mathbb{K}} \text{Hom}_{\mathcal{T}}(FX, FY) = \dim_{\mathbb{K}} \mathcal{C}/(\Sigma\mathcal{T})(X, Y).$$

When this makes sense, we make use of Notation 3.7: if

$$X \twoheadrightarrow E \twoheadrightarrow Y \dashrightarrow$$

is an almost-split sequence (see [INP18] for a definition in this setting), we let

$$\ell_X := [X] + [Y] - [E] \in K_0^{\text{sp}}(\mathcal{C}).$$

**Theorem 4.13.** *Assume that  $\mathcal{C}$  is a  $\mathbb{K}$ -linear, Ext-finite, Krull–Schmidt, extriangulated category with Auslander–Reiten–Serre duality. Assume that  $T$  is a projective object of  $\mathcal{C}$  such that any  $X \in \mathcal{C}$  admits a conflation  $T_1^X \twoheadrightarrow T_0^X \twoheadrightarrow X$  with  $T_0^X, T_1^X \in \text{add}(T)$ , and the morphism  $T \rightarrow 0$  is an inflation. Fix a conflation  $T \rightarrow 0 \rightarrow \Sigma T$ . Then  $\mathcal{C}$  has only finitely many isomorphism classes of indecomposable objects if and only if the set*

$$L := \{\ell_X \mid X \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)\}$$

generates the kernel of the canonical projection  $\mathfrak{g} : K_0^{\text{sp}}(\mathcal{C}) \rightarrow K_0(\mathcal{C})$ . In this case, the set  $L$  is a basis of the kernel of  $\mathfrak{g}$ , and for any  $x \in \ker(\mathfrak{g})$ , we have that

$$x = \sum_{A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)} \frac{\langle x, A \rangle}{\langle \ell_A, A \rangle} \ell_A.$$

**Corollary 4.14.** *Assume that  $\text{ind}(\mathcal{C})$  is finite. Let  $X \twoheadrightarrow E \twoheadrightarrow Y \dashrightarrow$  be any extriangle. Then the element  $x = [X] + [Y] - [E]$  of the kernel of  $\mathfrak{g}$  is a non-negative linear combination of the  $\ell_A$ , with  $A \in \text{ind}(\mathcal{C}) \setminus \text{add}(\Sigma T)$ .*

**4.4. Recollections on extriangulated categories.** Extriangulated categories, recently introduced in [NP19], axiomatize extension-closed subcategories of triangulated categories in a (moderately) similar way that Quillen’s exact categories axiomatize extension-closed subcategories of abelian categories. They appear in representation theory in relation with cotorsion pairs [CZZ18, ZH19, LN19, Liu17], with Auslander–Reiten theory [INP18], with cluster algebras, mutations, or cluster-tilting theory [CZZ18, Pre17, ZZ18, LZ18a, LZ18b, LZ19], with Cohen–Macaulay dg-modules in the remarkable [Jin18]. We also note the generalization, called  $n$ -exangulated categories [HLN17], to a version suited for higher homological algebra.

An extriangulated category is the data of an additive category  $\mathcal{C}$ , of an additive bifunctor  $\mathbb{E} : \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \text{Ab}$  modelling the  $\text{Ext}^1$ -bifunctor, and of an additive realization  $\mathfrak{s}$  sending each element  $\delta \in \mathbb{E}(Z, X)$  to some (equivalence classe of) diagram  $X \rightarrow Y \rightarrow Z$  modelling the short exact sequences or triangles. Some axioms, inspired from the case of extension-closed subcategories of triangulated categories have to be satisfied.

More specifically: fix an additive category  $\mathcal{C}$ , and an additive bifunctor  $\mathbb{E} : \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \text{Ab}$ .

**Definition 4.15.** For any  $X, Z \in \mathcal{C}$ , an element  $\delta \in \mathbb{E}(Z, X)$  is called an  **$\mathbb{E}$ -extension**. A *split*  $\mathbb{E}$ -extension is a zero element  $0 \in \mathbb{E}(Z, X)$ , for some objects  $X, Z \in \mathcal{C}$ . For any two  $\mathbb{E}$ -extensions  $\delta \in \mathbb{E}(Z, X)$ ,  $\delta' \in \mathbb{E}(Z', X')$ , the additivity of  $\mathcal{C}$ ,  $\mathbb{E}$  permits to define the  $\mathbb{E}$ -extension

$$\delta \oplus \delta' \in \mathbb{E}(Z \oplus Z', X \oplus X').$$

**Remark 4.16.** Let  $\delta \in \mathbb{E}(Z, X)$  be an  $\mathbb{E}$ -extension. By functoriality, any morphisms  $f \in \mathcal{C}(X, X')$  and  $h \in \mathcal{C}(Z', Z)$  induce  $\mathbb{E}$ -extensions  $\mathbb{E}(Z, f)(\delta) \in \mathbb{E}(Z, X')$  and  $\mathbb{E}(h, X)(\delta) \in \mathbb{E}(Z', X)$ . For short, we write  $f_*\delta$  and  $h^*\delta$  instead. Using those notations, we have, in  $\mathbb{E}(Z', X')$

$$\mathbb{E}(h, f)(\delta) = h^*f_*\delta = f_*h^*\delta.$$

**Definition 4.17.** A *morphism*  $(f, h) : \delta \rightarrow \delta'$  of  $\mathbb{E}$ -extensions  $\delta \in \mathbb{E}(Z, X)$ ,  $\delta' \in \mathbb{E}(Z', X')$  is a pair of morphisms  $f \in \mathcal{C}(X, X')$  and  $h \in \mathcal{C}(Z, Z')$  in  $\mathcal{C}$ , such that  $f_*\delta = h^*\delta'$ .

**Definition 4.18.** Let  $X, Z \in \mathcal{C}$  be any two objects. Two sequences of morphisms in  $\mathcal{C}$

$$X \xrightarrow{x} Y \xrightarrow{y} Z \quad \text{and} \quad X \xrightarrow{x'} Y' \xrightarrow{y'} Z$$

are said to be *equivalent* if there exists an isomorphism  $g \in \mathcal{C}(Y, Y')$  such that the following diagram commutes.

$$\begin{array}{ccccc} & & Y & & \\ & x \nearrow & \downarrow \cong & \searrow y & \\ X & & & & Z \\ & x' \searrow & \downarrow g & \nearrow y' & \\ & & Y' & & \end{array}$$

The equivalence class of  $X \xrightarrow{x} Y \xrightarrow{y} Z$  is denoted by  $[X \xrightarrow{x} Y \xrightarrow{y} Z]$ .

**Notation 4.19.** For any  $X, Y, Z, A, B, C \in \mathcal{C}$ , and any  $[X \xrightarrow{x} Y \xrightarrow{y} Z]$ ,  $[A \xrightarrow{a} B \xrightarrow{b} C]$ , we let

$$0 = [X \xrightarrow{\begin{bmatrix} 1 \\ 0 \end{bmatrix}} X \oplus Y \xrightarrow{\begin{bmatrix} 0 & 1 \end{bmatrix}} Y]$$

and

$$[X \xrightarrow{x} Y \xrightarrow{y} Z] \oplus [A \xrightarrow{a} B \xrightarrow{b} C] = [X \oplus A \xrightarrow{\begin{bmatrix} x & 0 \\ 0 & a \end{bmatrix}} Y \oplus B \xrightarrow{\begin{bmatrix} y & 0 \\ 0 & b \end{bmatrix}} Z \oplus C].$$

**Definition 4.20.** An *additive realization*  $\mathfrak{s}$  is a correspondence associating, with  $\mathbb{E}$ -extension  $\delta \in \mathbb{E}(Z, X)$ , an equivalence class  $\mathfrak{s}(\delta) = [X \xrightarrow{x} Y \xrightarrow{y} Z]$  and satisfying the following condition:

(\*) Let  $\delta \in \mathbb{E}(Z, X)$  and  $\delta' \in \mathbb{E}(Z', X')$  be any pair of  $\mathbb{E}$ -extensions, with

$$\mathfrak{s}(\delta) = [X \xrightarrow{x} Y \xrightarrow{y} Z] \quad \text{and} \quad \mathfrak{s}(\delta') = [X' \xrightarrow{x'} Y' \xrightarrow{y'} Z'].$$



Then, for any morphism  $(f, h) : \delta \rightarrow \delta'$ , there exists  $g \in \mathcal{C}(Y, Y')$  such that the following diagram commutes:

$$\begin{array}{ccccc} X & \xrightarrow{x} & Y & \xrightarrow{y} & Z \\ f \downarrow & \circlearrowleft & \downarrow g & \circlearrowleft & \downarrow h \\ X' & \xrightarrow{x'} & Y' & \xrightarrow{y'} & Z' \end{array}$$

The sequence  $X \xrightarrow{x} Y \xrightarrow{y} Z$  is said to *realize*  $\delta$  if  $\mathfrak{s}(\delta) = [X \xrightarrow{x} Y \xrightarrow{y} Z]$ , and the triple  $(f, g, h)$  is said to realize  $(f, h)$  if the diagram in (\*) commutes.

**Definition 4.21.** A realization of  $\mathbb{E}$  is called an *additive realization* if the following conditions are satisfied:

- (1) For any  $X, Z \in \mathcal{C}$ , the realization of the split  $\mathbb{E}$ -extension  $0 \in \mathbb{E}(Z, X)$  is given by  $\mathfrak{s}(0) = 0$ .
- (2) For any two  $\mathbb{E}$ -extensions  $\delta \in \mathbb{E}(Z, X)$  and  $\delta' \in \mathbb{E}(Z', X')$ , the realization of  $\delta \oplus \delta'$  is given by  $\mathfrak{s}(\delta \oplus \delta') = \mathfrak{s}(\delta) \oplus \mathfrak{s}(\delta')$ .

**Definition 4.22.** ([NP19, Def. 2.12]) A triple  $(\mathcal{C}, \mathbb{E}, \mathfrak{s})$  is called an *extriangulated category* if the following holds:

- (ET1)  $\mathbb{E} : \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \text{Ab}$  is an additive bifunctor;
- (ET2)  $\mathfrak{s}$  is an additive realization of  $\mathbb{E}$ ;
- (ET3) Let  $\delta \in \mathbb{E}(Z, X)$  and  $\delta' \in \mathbb{E}(Z', X')$  be  $\mathbb{E}$ -extensions, respectively realized by  $X \xrightarrow{x} Y \xrightarrow{y} Z$  and  $X' \xrightarrow{x'} Y' \xrightarrow{y'} Z'$ . Then, for any commutative square

$$\begin{array}{ccccc} X & \xrightarrow{x} & Y & \xrightarrow{y} & Z \\ f \downarrow & \circlearrowleft & \downarrow g & & \\ X' & \xrightarrow{x'} & Y' & \xrightarrow{y'} & Z' \end{array}$$

in  $\mathcal{C}$ , there exists a morphism  $(f, h) : \delta \rightarrow \delta'$  satisfying  $h \circ y = y' \circ g$ .

(ET3)<sup>op</sup> Dual of (ET3).

- (ET4) Let  $\delta \in \mathbb{E}(Z', X)$  and  $\delta' \in \mathbb{E}(X', Y)$  be  $\mathbb{E}$ -extensions realized respectively by

$$X \xrightarrow{f} Y \xrightarrow{f'} Z' \quad \text{and} \quad Y \xrightarrow{g} Z \xrightarrow{g'} X'.$$

Then there exist an object  $Y' \in \mathcal{C}$ , a commutative diagram in  $\mathcal{C}$

$$\begin{array}{ccccccc} X & \xrightarrow{f} & Y & \xrightarrow{f'} & Z' & \xrightarrow{\delta} & \gg \\ \parallel & & \circlearrowleft & \downarrow g & \circlearrowleft & \downarrow d & \\ X & \xrightarrow{h} & Z & \xrightarrow{h'} & Y' & \xrightarrow{\delta''} & \gg \\ & & g' \downarrow & \circlearrowleft & \downarrow e & & \\ & & X' & = & X' & & \\ & & \downarrow \delta' & & \downarrow f'_* \delta' & & \\ & & \downarrow & & \downarrow & & \end{array}$$

and an  $\mathbb{E}$ -extension  $\delta'' \in \mathbb{E}(Y', X)$  realized by  $X \xrightarrow{h} Z \xrightarrow{h'} Y'$ , which satisfy the following compatibilities.

- (i)  $Z' \xrightarrow{d} Y' \xrightarrow{e} X'$  realizes  $f'_* \delta'$ ,
  - (ii)  $d^* \delta'' = \delta$ ,
  - (iii)  $f_* \delta'' = e^* \delta'$ .
- (ET4)<sup>op</sup> Dual of (ET4).

We use the following terminology.

**Notation 4.23.** Let  $(\mathcal{C}, \mathbb{E}, \mathfrak{s})$  be an extriangulated category.

- (1) A sequence  $X \xrightarrow{x} Y \xrightarrow{y} Z$  is called a conflation if it realizes some  $\mathbb{E}$ -extension in  $\mathbb{E}(Z, X)$ . In which case the morphism  $X \xrightarrow{x} Y$  is called an inflation, written  $X \twoheadrightarrow Y$ , and the morphism  $Y \xrightarrow{y} Z$  is called a deflation, written  $Y \twoheadleftarrow Z$ .
- (2) An extriangle is a diagram  $X \xrightarrow{x} Y \xrightarrow{y} Z \dashrightarrow$  where  $X \xrightarrow{x} Y \xrightarrow{y} Z$  is a conflation realizing the  $\mathbb{E}$ -extension  $\delta \in \mathbb{E}(Z, X)$ .
- (3) Similarly, we call morphism of extriangles any diagram

$$\begin{array}{ccccc} X & \xrightarrow{x} & Y & \xrightarrow{y} & Z \dashrightarrow \delta \\ f \downarrow & & \downarrow g & & \downarrow h \\ X' & \xrightarrow{x'} & Y' & \xrightarrow{y'} & Z' \dashrightarrow \delta' \end{array}$$

where  $(f, h) : \delta \rightarrow \delta'$  is a morphism of  $\mathbb{E}$ -extensions realized by  $(f, g, h)$ .

The axioms above ensure that any extriangle induce long-ish exact sequences after application of some covariant or contravariant Hom-functor. In particular in any conflation, the inflation is a weak kernel of the deflation, and the deflation is a weak cokernel of the inflation.

**Proposition 4.24** ([NP19, Props. 3.3 & 3.11]). *Assume that  $(\mathcal{C}, \mathbb{E}, \mathfrak{s})$  is an extriangulated category, and let  $X \xrightarrow{x} Y \xrightarrow{y} Z \dashrightarrow$  be an extriangle. Then the following sequences of natural transformations are exact:*

$$\begin{aligned} \mathcal{C}(Z, -) &\xrightarrow{-\circ y} \mathcal{C}(Y, -) \xrightarrow{-\circ x} \mathcal{C}(X, -) \xrightarrow{\delta^\sharp} \mathbb{E}(Z, -) \xrightarrow{y^*} \mathbb{E}(Y, -) \xrightarrow{x^*} \mathbb{E}(X, -), \\ \mathcal{C}(-, X) &\xrightarrow{x\circ-} \mathcal{C}(-, Y) \xrightarrow{y\circ-} \mathcal{C}(-, Z) \xrightarrow{\delta_\sharp} \mathbb{E}(-, X) \xrightarrow{x_*} \mathbb{E}(-, Y) \xrightarrow{y_*} \mathbb{E}(-, Z), \end{aligned}$$

where  $\delta^\sharp(f) = f_*\delta$  and  $\delta_\sharp(g) = g^*\delta$ .

Any variant of the axiom (ET4) that would hold in an extension-closed subcategory of a triangulated category by applying the octahedron axiom also holds in any extriangulated category. See [NP19, Sect. 3.2] for more details.

**Definition 4.25.** An *almost-split*  $\mathbb{E}$ -extension  $\delta \in \mathbb{E}(Z, X)$  is a non-split  $\mathbb{E}$ -extension such that:

- (AS1)  $f_*\delta = 0$  for any non-section  $f \in \mathcal{C}(X, X')$ .
- (AS2)  $g^*\delta = 0$  for any non-retraction  $g \in \mathcal{C}(Z', Z)$ .

**Definition 4.26.** A non-zero object  $X \in \mathcal{C}$  is said to be *endo-local* if  $\mathcal{C}(X, X)$  is local.

**Proposition 4.27** ([INP18, Prop. 2.5]). *For any non-split  $\mathbb{E}$ -extension  $\delta \in \mathbb{E}(Z, X)$ , the following holds.*

- (1) *If  $\delta$  satisfies (AS1), then  $X$  is endo-local.*
- (2) *If  $\delta$  satisfies (AS2), then  $Z$  is endo-local.*

**Definition 4.28.** An object  $P \in \mathcal{C}$  is called *projective* if, for any  $X \in \mathcal{C}$ , we have  $\mathbb{E}(P, X) = 0$ . Dually, an object  $I \in \mathcal{C}$  is called *injective* if for any  $X \in \mathcal{C}$ , we have  $\mathbb{E}(X, I) = 0$ .

**Proposition 4.29** ([INP18, Prop. 8.1]). *Let  $\Lambda$  be an Artin algebra and let  $K^{[-1,0]}(\text{proj } \Lambda)$  be the full subcategory of the homotopy category  $K^b(\text{proj } \Lambda)$  consisting of complexes concentrated in degrees  $-1$  and  $0$  (using cohomological conventions). Then any endo-local non-projective object  $X \in \mathcal{C}$  permits an almost-split conflation  $\tau X \twoheadrightarrow E \twoheadrightarrow X$  and any endo-local non-injective object  $Y \in \mathcal{C}$  permits an almost-split conflation  $Y \twoheadrightarrow E' \twoheadrightarrow \tau^- Y$ .*

**4.5. Proofs of preliminary results and of Theorem 4.13.** We let  $\mathcal{C}$  and  $\mathcal{T}$  satisfy the assumptions (1), (2) and (3) of Section 4.1. We will make it explicit when more assumptions are needed.

We start by stating some immediate implications of the existence of conflations  $T \twoheadrightarrow 0 \twoheadrightarrow \Sigma T$ , for  $T \in \mathcal{T}$ .

**Lemma 4.30.** *The following holds:*

- (i) *An object belongs to  $\mathcal{T}$  if and only if it is projective in  $\mathcal{C}$ .*
- (ii) *For any  $T, T' \in \mathcal{T}$ , we have  $\mathcal{C}(T, \Sigma T') = 0$ .*
- (iii) *For any  $X \in \mathcal{C}$  and  $T \in \mathcal{T}$ ,  $\mathcal{C}(X, \Sigma T) \cong \mathbb{E}(X, T)$ .*
- (iv) *For any  $X \in \mathcal{C}$  and  $T \in \mathcal{T}$ ,  $\mathcal{C}(T, X) \cong \mathbb{E}(\Sigma T, X)$ .*
- (v) *The full subcategory  $\Sigma\mathcal{T}$  is rigid in  $\mathcal{C}$ .*

*Proof.* (i) If  $X$  is projective in  $\mathcal{C}$ , then the deflation  $T_0^X \rightarrow X$  splits and  $X$  is a summand of  $T_0^X$ .

(ii) This follows from the fact that  $T$  is projective and  $0 \rightarrow \Sigma T'$  is a deflation.

(iii) and (iv) are obtained from the exact sequences of Proposition 4.24 associated with the extriangle  $T \rightarrow 0 \rightarrow \Sigma T \dashrightarrow$ .

(v) For any  $T, T' \in \mathcal{T}$ , we have  $\mathbb{E}(\Sigma T, \Sigma T') \cong \mathcal{C}(T, \Sigma T') = 0$ .  $\square$

**Lemma 4.31.** *Let  $X \in \mathcal{C}$  and let*

$$T_1^X \xrightarrow{f_X} T_0^X \xrightarrow{g_X} X \xrightarrow{\delta_X}, \quad T_0^X \rightarrow 0 \rightarrow \Sigma T_0^X \xrightarrow{\delta_0}, \quad T_1^X \rightarrow 0 \rightarrow \Sigma T_1^X \xrightarrow{\delta_1}$$

*be extriangles with  $T_0^X, T_1^X \in \mathcal{T}$ . Then there are extriangles*

$$T_0^X \xrightarrow{g_X} X \xrightarrow{h_X} \Sigma T_1^X \xrightarrow{(f_X)_* \delta_1}, \quad X \xrightarrow{h_X} \Sigma T_1^X \xrightarrow{\Sigma f_X} \Sigma T_0^X \xrightarrow{(g_X)_* \delta_0}$$

*where  $h_X$  is the unique morphism in  $\mathcal{C}(X, \Sigma T_1^X)$  satisfying  $(h_X)_* \delta_1 = \delta_X$  and  $\Sigma f_X$  is the unique morphism in  $\mathcal{C}(\Sigma T_1^X, \Sigma T_0^X)$  satisfying  $(\Sigma f_X)^* \delta_0 = (f_X)_* \delta_1$ .*

*Proof.* The first extriangle is obtained by applying the dual of [NP19, Prop. 3.15] to  $\delta_X$  and  $\delta_1$ , and the second one is obtained similarly from  $\delta_0$  and  $(f_X)_* \delta_1$ .  $\square$

**Remark 4.32.** For any  $T \in \mathcal{T}$ , fix an extriangle  $T \rightarrow 0 \rightarrow \Sigma T \xrightarrow{\varepsilon_T}$ . As noticed in Lemma 4.31, for any morphism  $T \xrightarrow{f} T'$  in  $\mathcal{T}$ , there is a unique morphism  $\Sigma f \in \mathcal{C}(\Sigma T, \Sigma T')$  such that  $f_* \varepsilon_T = (\Sigma f)^* \varepsilon_{T'}$  (i.e. such that  $(f, \Sigma f)$  is a morphism from  $\varepsilon_T$  to  $\varepsilon_{T'}$ ), as illustrated below:

$$\begin{array}{ccccc} T & \longrightarrow & 0 & \longrightarrow & \Sigma T \xrightarrow{\varepsilon_T} \gg \\ f \downarrow & & \downarrow & & \downarrow \Sigma f \\ T' & \longrightarrow & 0 & \longrightarrow & \Sigma T' \xrightarrow{\varepsilon_{T'}} \gg \end{array}$$

This gives an equivalence of additive categories

$$\Sigma : \mathcal{T} \rightarrow \Sigma\mathcal{T}$$

where  $\Sigma\mathcal{T}$  is the full subcategory of  $\mathcal{C}$  whose objects are isomorphic to objects of the form  $\Sigma T$ , for some  $T \in \mathcal{T}$ .

**Lemma 4.33.** *Every morphism with domain in  $\mathcal{T}$  is an inflation.*

*Proof.* Let  $T \xrightarrow{t} X$  be a morphism with  $T \in \mathcal{T}$ . Using the notation of Remark 4.32, there is an extriangle  $T \rightarrow 0 \rightarrow \Sigma T \xrightarrow{\varepsilon_T}$ . Consider the extriangle  $X \xrightarrow{g} Y \xrightarrow{h} \Sigma T \xrightarrow{t_* \varepsilon_T}$ . By [NP19, Prop. 3.17], there is a commutative diagram of extriangles

$$\begin{array}{ccccccc} T & \longrightarrow & 0 & \longrightarrow & \Sigma T & \xrightarrow{\varepsilon_T} & \gg \\ \downarrow t' & & \downarrow & & \downarrow & & \\ X & \xrightarrow{g} & Y & \xrightarrow{h} & \Sigma T & \xrightarrow{t_* \varepsilon_T} & \gg \\ \downarrow g & & \downarrow 1 & & \downarrow & & \\ Y & \xrightarrow{=} & Y & & & & \\ \downarrow h^* \varepsilon_T & & \downarrow & & & & \\ \mathbb{Y} & & \mathbb{Y} & & & & \end{array}$$

satisfying  $(t')_* \varepsilon_T = t_* \varepsilon_T$ . We thus have  $t' = t$ .  $\square$

**Remark 4.34.** It follows from the proof of Lemma 4.33 that conditions (1), (2), (3) in Section 4.1 are equivalent to conditions (1), (2), (3'), where

$$(3') \quad \mathcal{C} = \mathcal{T} * \Sigma\mathcal{T}.$$

*Proof of Lemma 4.5.* Applying the functor  $F$  to the extriangle  $T_1^X \twoheadrightarrow T_0^X \twoheadrightarrow X \xrightarrow{\delta_X}$  induces an exact sequence  $FT_1^X \rightarrow FT_0^X \rightarrow FX \rightarrow \mathbb{E}(T, T_1^X) = 0$ , showing that  $FX$  is finitely presented.  $\square$

*Proof of Proposition 4.6.* Recall that  $F : \mathcal{C} \rightarrow \text{mod } \mathcal{T}$  denotes the functor sending an object  $X$  to the module  $\mathcal{C}(-, X)|_{\mathcal{T}}$ . By Lemma 4.30(v), the ideal  $(\Sigma\mathcal{T})$  of morphisms factoring through an object in  $\Sigma\mathcal{T}$  is included in the kernel of  $F$ . Conversely, let  $X \xrightarrow{f} Y$  be such that  $Ff = 0$ . By Lemma 4.31, there is a conflation  $T_0 \xrightarrow{g} X \xrightarrow{h} \Sigma T_1$  with  $T_0, T_1 \in \mathcal{T}$ . By assumption, the composition  $f \circ g$  vanishes, which implies that  $f$  factors through  $\Sigma T_1$ . The functor  $F$  thus induces a faithful functor, still denoted  $F$ , from  $\mathcal{C}/(\Sigma\mathcal{T})$  to  $\text{mod } \mathcal{T}$ . It is well-known (see for instance [ASS06, Lem. 3.1]) that  $F$  restricts to an equivalence of categories  $\mathcal{T} \rightarrow \text{proj } \mathcal{T}$ . Because  $\mathcal{T}$  consists of projective objects in  $\mathcal{C}$ , the image under  $F$  of every conflation is a right exact sequence. The fact that  $F$  is full and dense can thus be proven as in the case of triangulated categories, by using Lemma 4.33.  $\square$

**Corollary 4.35.** *The objects in  $\Sigma\mathcal{T}$  are precisely the injective objects in  $\mathcal{C}$ .*

*Proof.* First note that any injective object belongs to  $\Sigma\mathcal{T}$ , by Lemma 4.31. Let us prove that the converse holds. Let  $\Sigma T \twoheadrightarrow X \xrightarrow{f} Y \xrightarrow{\delta} \Sigma T$  be an extriangle with  $T \in \mathcal{T}$ . Since  $\mathcal{C}(-, \Sigma T)|_{\mathcal{T}} = 0$  and  $f$  is  $\mathcal{T}$ -epic, the morphism  $\mathcal{C}(-, f)|_{\mathcal{T}}$  is an isomorphism in  $\text{mod } \mathcal{T}$ . By Proposition 4.6, there are morphisms  $Y \xrightarrow{s} X$ ,  $Y \xrightarrow{h} \Sigma T'$ ,  $\Sigma T' \xrightarrow{t} Y$ , for some  $T' \in \mathcal{T}$  satisfying

$$fs = id_Y + th.$$

By Lemma 4.30(v),  $\Sigma\mathcal{T}$  is a rigid subcategory, so that  $t^*\delta = 0$ . Equivalently, there is a morphism  $\Sigma T' \xrightarrow{k} X$  such that  $t = fk$ . We thus have  $f(s - kh) = id_Y$ , showing that the extriangle splits.  $\square$

**Lemma 4.36.** *The index is well-defined. More precisely, for any object  $X \in \mathcal{C}$  and any two conflations  $T_1 \xrightarrow{f} T_0 \xrightarrow{g} X$ ,  $T'_1 \xrightarrow{f'} T'_0 \xrightarrow{g'} X$  with  $T_0, T_1, T'_0, T'_1 \in \mathcal{T}$ , we have  $[T_0] - [T_1] = [T'_0] - [T'_1]$  in  $K_0(\mathcal{T})$ .*

*Proof.* Applying [NP19, Prop. 3.15] gives a commutative diagram made of conflations

$$\begin{array}{ccccc} & & T_1 & \xlongequal{\quad} & T_1 \\ & & \downarrow & \circlearrowleft & \downarrow \\ T'_1 & \longrightarrow & Y & \longrightarrow & T_0 \\ \parallel & \circlearrowleft & \downarrow & \circlearrowleft & \downarrow \\ T'_1 & \longrightarrow & T'_0 & \longrightarrow & X \end{array}$$

Since the objects in  $\mathcal{T}$  are projective, the two conflations with middle term  $Y$  split and there are isomorphisms  $T'_1 \oplus T_0 \cong Y \cong T_1 \oplus T'_0$ . The equality  $[T'_1] + [T_0] = [T_1] + [T'_0]$  thus holds in  $K_0(\mathcal{T})$ .  $\square$

**Remark 4.37.** We note that Lemma 4.36 only requires the subcategory  $\mathcal{T}$  to be rigid, and not made of projective objects. However, this stronger assumption is used in the proof of Lemma 4.38 below.

**Lemma 4.38.** *The index descends to  $K_0(\mathcal{C})$ : For any conflation  $X \twoheadrightarrow Y \twoheadrightarrow Z$  in  $\mathcal{C}$ , we have  $\text{ind}_{\mathcal{T}} Y = \text{ind}_{\mathcal{T}} X + \text{ind}_{\mathcal{T}} Z$  in  $K_0(\mathcal{T})$ .*

*Proof.* Let  $X \twoheadrightarrow Y \twoheadrightarrow Z$  be a conflation in  $\mathcal{C}$ . Fix conflations  $T_1^X \twoheadrightarrow T_0^X \twoheadrightarrow X$ ,  $T_1^Z \twoheadrightarrow T_0^Z \twoheadrightarrow Z$  with  $T_0^X, T_1^X, T_0^Z, T_1^Z \in \mathcal{T}$ . By [NP19, Prop. 3.15] and axiom (ET4)<sup>op</sup>, there are commutative diagrams of conflations

$$\begin{array}{ccc}
& T_1^Z \xlongequal{\quad} T_1^Z & \\
& \downarrow \quad \circ \quad \downarrow & \\
X \longrightarrow X \oplus T_0^Z \longrightarrow T_0^Z & & \\
\parallel \quad \circ \quad \downarrow \quad \circ \quad \downarrow & & \\
X \longrightarrow Y \longrightarrow Z & & \\
\end{array}
\qquad
\begin{array}{ccccc}
T_1^X & \longrightarrow & B & \longrightarrow & T_1^Z \\
\parallel & \circ & \downarrow & \circ & \downarrow \\
T_1^X & \longrightarrow & T_0^X \oplus T_0^Z & \longrightarrow & X \oplus T_0^Z \\
& & \downarrow & \circ & \downarrow \\
& & Y & \xlongequal{\quad} & Y
\end{array}$$

where we have used the fact that  $T_0^Z$  is projective in  $\mathcal{C}$ . Moreover, the conflation with middle term  $B$  splits, which implies that  $B$  is isomorphic to  $T_1^X \oplus T_1^Z$ .  $\square$

*Proof of Proposition 4.11.* By Lemma 4.36 and Lemma 4.38, the index induces an well-defined morphism of abelian groups  $\text{ind}_{\mathcal{T}} : K_0(\mathcal{C}) \rightarrow K_0(\mathcal{T})$ . It remains to prove that it is an isomorphism. Let  $\pi : K_0(\mathcal{T}) \rightarrow K_0(\mathcal{C})$  send a class  $[T] \in K_0(\mathcal{T})$  to the class  $[T] \in K_0(\mathcal{C})$ . The existence, for any  $T \in \mathcal{T}$ , of a conflation  $0 \twoheadrightarrow T \twoheadrightarrow T$  shows that  $\pi$  is right inverse to  $\text{ind}_{\mathcal{T}}$ . To see that it is also a left inverse, note that if  $T_1 \twoheadrightarrow T_0 \twoheadrightarrow X$  is a conflation in  $\mathcal{C}$ , then the equality  $[X] = [T_0] - [T_1]$  holds in  $K_0(\mathcal{C})$ .  $\square$

*Proof of Theorem 4.13.* The proof is now similar to the proof of Theorem 3.8, by using Proposition 4.6 instead of Proposition 3.1, Proposition 4.11 instead of Corollary 3.13, and the fact that  $\mathcal{T}$  is made of projective objects instead of Lemma 3.15.  $\square$

*Proof of Corollary 4.14.* The proof is similar to that of Corollary 3.9.  $\square$

**4.6. Application to 2-term complexes of projectives and to gentle algebras.** Let  $\Lambda$  be an Artin algebra. Then the homotopy category  $K^b(\text{proj } \Lambda)$  is a triangulated category, and we consider its full subcategory  $K^{[-1,0]}(\text{proj } \Lambda)$  of complexes concentrated in degrees  $-1$  and  $0$  (with cohomological conventions).

**Proposition 4.39.** *Let  $\Lambda$  be any Artin algebra. Then the category  $K^{[-1,0]}(\text{proj } \Lambda)$  is an extriangulated category satisfying the assumptions (1) to (3) of Section 4.1, with  $\mathcal{T} = \text{add}(\Lambda)$ . If, moreover,  $\Lambda$  is finite-dimensional over a field  $\mathbb{K}$ , then  $K^{[-1,0]}(\text{proj } \Lambda)$  satisfies all assumptions of Section 4.1.*

*Proof.* The category  $K^{[-1,0]}(\text{proj } \Lambda)$  is closed under extensions in  $K^b(\text{proj } \Lambda)$ , so it is an extriangulated category whose conflations are induced by triangles in  $K^b(\text{proj } \Lambda)$  by [NP19, Rem. 2.18]. Now, the object  $\Lambda$  is projective in  $K^{[-1,0]}(\text{proj } \Lambda)$ , since if  $X \twoheadrightarrow Y \twoheadrightarrow Z$  is a conflation, then we get a long exact sequence

$$\text{Hom}_{K^b}(\Lambda, Y) \rightarrow \text{Hom}_{K^b}(\Lambda, Z) \rightarrow \text{Hom}_{K^b}(\Lambda, \Sigma X),$$

and the last term vanishes, since  $\Sigma X$  is a complex concentrated in degrees  $-2$  and  $-1$ , while  $\Lambda$  is in degree  $0$ . This proves that  $\Lambda$  is projective.

The morphism  $\Lambda \rightarrow 0$  is an inflation, since  $\Lambda \twoheadrightarrow 0 \twoheadrightarrow \Sigma \Lambda$  is a conflation. Moreover, if  $X = P_1 \xrightarrow{f} P_0$  is an object of  $K^{[-1,0]}(\text{proj } \Lambda)$ , then it lies in a conflation  $P_1 \xrightarrow{f} P_0 \twoheadrightarrow X$  by definition. We have proved that properties (1) to (3) of Section 4.1 are satisfied.

Finally, assume that  $\Lambda$  is finite-dimensional over a field  $\mathbb{K}$ . Then  $K^{[-1,0]}(\text{proj } \Lambda)$  is Krull-Schmidt,  $\mathbb{K}$ -linear and Ext-finite, since this is true for  $K^b(\text{proj } \Lambda)$  for any finite-dimensional algebra  $\Lambda$ . Moreover, it has Auslander–Reiten–Serre duality by [INP18, Prop. 6.1].  $\square$

The extriangulated category  $K^{[-1,0]}(\text{proj } \Lambda)$  is the setting in which we can finally prove point (ii) of Proposition 2.34, using results of [DIJ19] on  $\mathfrak{g}$ -vectors. Before doing so, we introduce the notion of mutation conflation for two-term silting objects.

**Definition 4.40.** Recall that a two-term silting object is a complex  $T$  in  $K^{[-1,0]}(\text{proj } \Lambda)$  such that  $\text{Hom}_{K^b}(T, \Sigma T) = 0$  and the number of isomorphism classes of indecomposable summands of  $T$  is the same as that of  $\Lambda$ .

**Remark 4.41.** The definition given above is only equivalent to the usual definition of a silting object for two-term complexes of projectives.

**Definition 4.42.** A conflation  $X \twoheadrightarrow E \twoheadrightarrow Y$  of  $K^{[-1,0]}(\text{proj } \Lambda)$  is called a *mutation conflation* if there are basic, two-term, silting objects  $X \oplus R, Y \oplus R$ , with  $X$  and  $Y$  indecomposable, such that the inflation  $X \twoheadrightarrow E$  is a left (add  $R$ )-approximation (i.e. any morphism from  $X$  to an object in add  $R$  factors through  $X \twoheadrightarrow E$ ).

**Remark 4.43.** In Definition 4.42, the requirement that  $X$  and  $Y$  are indecomposable implies the map  $E \twoheadrightarrow Y$  is a right (add  $R$ )-approximation, and that both approximations are minimal.

**Proposition 4.44.** *Let  $\Lambda$  be a finite-dimensional  $\mathbb{K}$ -algebra, where  $\mathbb{K}$  is a field. Let  $X$  and  $Y$  be objects of  $K^{[-1,0]}(\text{proj } \Lambda)$ .*

- (1) *If there is a mutation conflation (see Definition 4.42) of the form  $X \twoheadrightarrow E \twoheadrightarrow Y$ , then there can be no mutation conflation of the form  $Y \twoheadrightarrow E' \twoheadrightarrow X$ .*
- (2) *Assume that  $X \twoheadrightarrow E \twoheadrightarrow Y$  and  $X \twoheadrightarrow E' \twoheadrightarrow Y$  are two mutation conflations. Then  $E$  and  $E'$  are isomorphic.*

*Proof.* We first prove (1). Assume that  $X \twoheadrightarrow E \twoheadrightarrow Y$  and  $Y \twoheadrightarrow E' \twoheadrightarrow X$  are two mutation conflations. Applying the functor  $\text{Hom}_{K^b}(\Sigma^{-1}Y, -)$  to the second sequence, we get an exact sequence of abelian groups

$$\text{Hom}_{K^b}(\Sigma^{-1}Y, E') \rightarrow \text{Hom}_{K^b}(\Sigma^{-1}Y, X) \rightarrow \text{Hom}_{K^b}(\Sigma^{-1}Y, \Sigma Y).$$

By definition of a mutation conflation, we have that  $\text{Hom}_{K^b}(\Sigma^{-1}Y, E') = 0$ . Moreover, since  $Y$  is concentrated in homological degrees  $-1$  and  $0$ , we get that  $\text{Hom}_{K^b}(\Sigma^{-1}Y, \Sigma Y) = 0$ . Therefore,  $\text{Hom}_{K^b}(\Sigma^{-1}Y, X) = 0$ . However, since the conflation  $X \twoheadrightarrow E \twoheadrightarrow Y$  is not split, we have that  $\text{Hom}_{K^b}(\Sigma^{-1}Y, X) \neq 0$ , a contradiction. This proves (1).

We now prove (2). Let  $X \twoheadrightarrow E \twoheadrightarrow Y$  and  $X \twoheadrightarrow E' \twoheadrightarrow Y$  be two mutation conflations. By [DIJ19, Thm. 6.5] (based on [DK08, Thm 2.3]), rigid objects in  $K^{[-1,0]}(\text{proj } \Lambda)$  are determined by their  $\mathbf{g}$ -vector. The datum of the  $\mathbf{g}$ -vector of an object of  $K^{[-1,0]}(\text{proj } \Lambda)$  is equivalent to that of its class in the Grothendieck group  $K_0(K^{[-1,0]}(\text{proj } \Lambda))$ , where  $K^{[-1,0]}(\text{proj } \Lambda)$  is viewed as an extriangulated category (see Proposition 4.39). In this Grothendieck group, we have that  $[E] = [E'] = [X] + [Y]$ . Thus  $E$  and  $E'$  are isomorphic.  $\square$

**Corollary 4.45.** *Point (ii) of Proposition 2.34 holds.*

*Proof.* Let  $\omega$  and  $\omega'$  be in facets  $F$  and  $F'$  as in the statement of Proposition 2.34. For every walk  $\omega''$ , let  $P(\omega'')$  be the object of  $K^{[-1,0]}(\text{proj } \Lambda)$  corresponding to  $\omega''$ . Then the walks  $\mu$  and  $\nu$  defined in the same statement yield a mutation conflation

$$P(\omega) \twoheadrightarrow P(\mu) \oplus P(\nu) \twoheadrightarrow P(\omega') \quad \text{or} \quad P(\omega') \twoheadrightarrow P(\mu) \oplus P(\nu) \twoheadrightarrow P(\omega).$$

Assume that there are other facets  $F_0$  and  $F'_0$  also satisfying the hypotheses of Proposition 2.34. Then they give rise to walks  $\mu'$  and  $\nu'$  and an exchange conflation

$$P(\omega) \twoheadrightarrow P(\mu') \oplus P(\nu') \twoheadrightarrow P(\omega') \quad \text{or} \quad P(\omega') \twoheadrightarrow P(\mu') \oplus P(\nu') \twoheadrightarrow P(\omega).$$

By Proposition 4.44, we get that  $P(\mu) \oplus P(\nu)$  and  $P(\mu') \oplus P(\nu')$  are isomorphic, and that the mutation conflations either both have the form  $P(\omega) \twoheadrightarrow P(\mu) \oplus P(\nu) \twoheadrightarrow P(\omega')$  or both have the form  $P(\omega') \twoheadrightarrow P(\mu) \oplus P(\nu) \twoheadrightarrow P(\omega)$ . Without loss of generality, assume that they have the first form.

In particular, the leftmost morphisms of both mutation conflations are minimal add  $(P(\mu) \oplus P(\nu))$ -approximations of  $P(\omega)$ . As such, they are isomorphic as morphisms. They determine common substrings of  $\omega$  and  $\mu$  and of  $\omega$  and  $\nu$ , which in turn determine  $\sigma$ . Point (ii) of Proposition 2.34 is proved.  $\square$

We now come to the main result of this section.

**Theorem 4.46.** *Let  $\Lambda$  be an Artin algebra all of whose indecomposable objects are  $\tau$ -rigid bricks. Then the almost-split conflations of  $K^{[-1,0]}(\text{proj } \Lambda)$  are mutation conflations if and only if for any non-projective indecomposable  $\Lambda$ -module  $M$ , the space  $\text{Hom}_\Lambda(M, \tau^2 M)$  vanishes.*

**Remark 4.47.** Assume that  $\Lambda$  is a finite-dimensional brick algebra which is representation-finite. Then [DIJ19, Thm. 6.2] implies that the assumptions of Theorem 4.46 are satisfied.

**Corollary 4.48.** *Let  $\Lambda$  be a finite dimensional brick algebra of finite representation type. Assume moreover that, for any indecomposable  $\Lambda$ -module  $M$ , the space  $\text{Hom}_\Lambda(M, \tau^2 M)$  vanishes. Then the support  $\tau$ -tilting fan of  $\Lambda$  has the unique exchange property and its type cone is simplicial.*

As a consequence of Corollary 4.48, the method of Part I apply and give an explicit description of all realizations of the support  $\tau$ -tilting fan of  $\Lambda$ . Another consequence is an algebraic proof of Corollary 2.43, that we restate below.

**Corollary 4.49** (Corollary 2.43). *For any brick and 2-acyclic gentle algebra, the type cone of its support  $\tau$ -tilting fan is simplicial.*

The remaining part of this section is devoted to proving Theorem 4.46 and Corollary 4.49.

**Lemma 4.50.** *Let  $\Lambda$  be any Artin algebra. Let  $X \xrightarrow{a} Y \xrightarrow{b} Z$  be an almost-split conflation in  $K^{[-1,0]}(\text{proj } \Lambda)$  such that  $Z$  is not in  $\text{add}(\Sigma\Lambda)$ . Denote by  $F$  the functor  $\text{Hom}_{K^b}(\Lambda, -) : K^{[-1,0]}(\text{proj } \Lambda) \rightarrow \text{mod } \Lambda$ . Then there is an almost-split sequence in  $\text{mod } \Lambda$ :*

$$0 \rightarrow FX \rightarrow FY \rightarrow FZ \rightarrow 0$$

*Proof.* The almost-split conflation induces an exact sequence

$$F\Sigma^{-1}Y \rightarrow F\Sigma^{-1}Z \rightarrow FX \rightarrow FY \rightarrow FZ \rightarrow F\Sigma X.$$

Because  $X$  is concentrated in non-positive degrees,  $F\Sigma X = 0$ . Let us verify that the map  $F\Sigma^{-1}Y \rightarrow F\Sigma^{-1}Z$  is surjective. Let  $\Lambda \xrightarrow{f} \Sigma^{-1}Z$  be a morphism in  $K^b(\text{proj } \Lambda)$ . Since  $Y \xrightarrow{b} Z$  is right almost-split, and  $Z$  is indecomposable not in  $\text{add}(\Sigma\Lambda)$ , the morphism  $\Sigma f$  factors through  $b$ . This implies the required surjectivity, and we have a short exact sequence

$$0 \rightarrow FX \xrightarrow{Fa} FY \xrightarrow{Fb} FZ \rightarrow 0.$$

Because  $\text{mod } \Lambda$  and  $K^b(\text{proj } \Lambda)$  are Krull–Schmidt, it is immediate to check that  $Fb$  (resp.  $Fa$ ) inherits from  $b$  (resp.  $a$ ) the property of being right (resp. left) almost-split.  $\square$

**Lemma 4.51.** *Let  $\Lambda$  be an Artin algebra, let  $\tau X \rightarrow E \rightarrow X$  be an Auslander–Reiten conflation in  $K^{[-1,0]}(\text{proj } \Lambda)$  and denote  $FX = M$ .*

- (1)  $X \notin \text{add}(\Sigma\Lambda)$ ;
- (2)  $M$  and  $\tau M$  are  $\tau$ -rigid;
- (3)  $\text{Hom}_\Lambda(M, \tau^2 M) = 0$ ;
- (4)  $\tau M$  is a brick.

*Then  $\tau X \rightarrow E \rightarrow X$  is a mutation conflation.*

*Proof.* First note that the results [AIR14, Lems. 3.4 & 3.5], even though stated for finite dimensional algebras, hold with the same proofs for any Artin algebra. For convenience of the reader, we recall those two results: Let  $Y, Z \in K^{[-1,0]}(\text{proj } \Lambda)$  be indecomposable and not in  $\text{add}(\Sigma\Lambda)$ , and let  $P \in \text{proj } \Lambda$ . Then  $\text{Hom}_{K^b}(Y, \Sigma Z) = 0$  if and only if  $\text{Hom}_\Lambda(FZ, \tau FY) = 0$  and  $\text{Hom}_{K^b}(P, Y) = 0$  if and only if  $\text{Hom}_\Lambda(P, FY) = 0$ .

Note also that Lemma 4.50 implies that  $F\tau X$  is isomorphic to  $\tau M$ .

By assumption,  $X$  is not in  $\text{add}(\Sigma\Lambda)$ . The same is true of  $\tau X$  since objects in  $\text{add}(\Sigma\Lambda)$  are injective in  $K^{[-1,0]}(\text{proj } \Lambda)$  and an Auslander–Reiten conflation does not split. It thus follows from [AIR14, Lem. 3.4] that  $X$  and  $\tau X$  are rigid in  $K^{[-1,0]}(\text{proj } \Lambda)$ . We have to prove that both  $E \oplus X$  and  $E \oplus \tau X$  are rigid.

$$(1) \operatorname{Hom}_{K^b}(E, \Sigma X) = 0.$$

The Auslander–Reiten conflation induces an exact sequence

$$\operatorname{Hom}_{K^b}(X, \Sigma X) \rightarrow \operatorname{Hom}_{K^b}(E, \Sigma X) \rightarrow \operatorname{Hom}_{K^b}(\tau X, \Sigma X).$$

As already remarked,  $X$  is rigid so that the left-most term vanishes. By assumption

$$\operatorname{Hom}_{\Lambda}(FX, \tau F\tau X) = \operatorname{Hom}_{\Lambda}(M, \tau^2 M) = 0,$$

so that the right-most term also vanishes by [AIR14, Lem. 3.4].

$$(2) \operatorname{Hom}_{K^b}(\tau X, \Sigma E) = 0.$$

Since  $\Lambda$  is projective in  $K^{[-1,0]}(\operatorname{proj} \Lambda)$ , the sequence  $\tau M \rightarrow FE \rightarrow M$  is short exact. It induces a sequence

$$\operatorname{Hom}_{\Lambda}(M, \tau^2 M) \rightarrow \operatorname{Hom}_{\Lambda}(FE, \tau^2 M) \rightarrow \operatorname{Hom}_{\Lambda}(\tau M, \tau^2 M)$$

from which we deduce that  $\operatorname{Hom}_{\Lambda}(FE, \tau^2 M) = 0$ . This implies  $\operatorname{Hom}_{K^b}(\tau X, \Sigma E) = 0$  by [AIR14, Lem. 3.4].

$$(3) \operatorname{Hom}_{K^b}(X, \Sigma E) = 0.$$

Let us show that  $\operatorname{Hom}_{\Lambda}(FE, \tau M) = 0$ . Let  $FE \xrightarrow{f} \tau M$  be any morphism, and consider the short exact sequence  $0 \rightarrow \tau M \xrightarrow{a} FE \xrightarrow{b} M \rightarrow 0$  induced by the Auslander–Reiten conflation. Since  $\tau M$  is a brick, the composition  $fa$  is zero. The morphism  $f$  then factors through the cokernel  $b$ , which implies  $f = 0$  since  $M$  is  $\tau$ -rigid.

$$(4) \operatorname{Hom}_{K^b}(E, \Sigma E) = 0.$$

The Auslander–Reiten conflation induces an exact sequence

$$\operatorname{Hom}_{K^b}(X, \Sigma E) \rightarrow \operatorname{Hom}_{K^b}(E, \Sigma E) \rightarrow \operatorname{Hom}_{K^b}(\tau X, \Sigma E).$$

We can conclude by (2) and (3).

$$(5) \operatorname{Hom}_{K^b}(E, \Sigma \tau X) = 0.$$

We have an exact sequence

$$\operatorname{Hom}_{K^b}(E, E) \rightarrow \operatorname{Hom}_{K^b}(E, X) \rightarrow \operatorname{Hom}_{K^b}(E, \Sigma \tau X) \rightarrow \operatorname{Hom}_{K^b}(E, \Sigma E).$$

The first map is surjective since  $E \rightarrow X$  is right almost-split (note that  $E$  cannot contain any summand isomorphic to  $X$ ). We can conclude by (4).  $\square$

**Lemma 4.52.** *Let  $\Lambda$  be an Artin algebra, and let  $Y \rightarrow E \rightarrow X$  be a conflation in  $K^{[-1,0]}(\operatorname{proj} \Lambda)$ . Then:*

- (1) *If  $\operatorname{Hom}_{K^b}(Y, \Sigma E) = 0$ , we have  $\operatorname{Hom}_{\Lambda}(FX, \tau FY) = 0$ .*
- (2) *If moreover  $X \notin \operatorname{add}(\Sigma \Lambda)$  and the conflation is almost-split, then  $\operatorname{Hom}_{\Lambda}(FX, \tau^2 FX) = 0$ .*

*Proof.* By Lemma 4.50, (2) follows from (1). Let us prove (1). The conflation induces an exact sequence  $\operatorname{Hom}_{K^b}(Y, \Sigma E) \rightarrow \operatorname{Hom}_{K^b}(Y, \Sigma X) \rightarrow \operatorname{Hom}_{K^b}(Y, \Sigma^2 Y)$ . The complex  $Y$  being two-term, we have  $\operatorname{Hom}_{K^b}(Y, \Sigma^2 Y) = 0$ . Assuming that  $\operatorname{Hom}_{K^b}(Y, \Sigma E) = 0$ , we deduce that  $\operatorname{Hom}_{K^b}(Y, \Sigma X) = 0$ , and hence that  $\operatorname{Hom}_{\Lambda}(FX, \tau FY) = 0$  by [AIR14, Lem. 3.4].  $\square$

**Lemma 4.53.** *Let  $\Lambda$  be an Artin algebra whose indecomposable injective modules are  $\tau$ -rigid, and let  $P$  be an indecomposable projective  $\Lambda$ -module. Then the Auslander–Reiten conflation  $Y \rightarrow E \rightarrow \Sigma P$  in  $K^{[-1,0]}(\operatorname{proj} \Lambda)$  is a mutation conflation if  $FY$  is a brick.*

*Proof.* In this proof, we implicitly identify the projective indecomposable  $\Lambda$ -module  $P$  with the complex  $P$  concentrated in degree 0.

We check that the conflation  $Y \rightarrow E \rightarrow \Sigma P$  is a mutation conflation.

(0) Since  $P$  is concentrated in only one degree, it is rigid in  $K^{[-1,0]}(\operatorname{proj} \Lambda)$  and so is  $\Sigma P$ . Moreover,  $FY$  is indecomposable and injective. By assumption, it is  $\tau$ -rigid, hence  $Y$  is rigid in  $K^{[-1,0]}(\operatorname{proj} \Lambda)$  by [AIR14, Lem. 3.4].

(1) We have  $\operatorname{Hom}_{K^b}(E, \Sigma^2 P) = 0$  since  $E$  is concentrated in degrees  $-1$  and  $0$ .



(2)  $\mathrm{Hom}_{K^b}(Y, \Sigma E) = 0$ : There is an exact sequence

$$\mathrm{Hom}_{K^b}(Y, \Sigma Y) \rightarrow \mathrm{Hom}_{K^b}(Y, \Sigma E) \rightarrow \mathrm{Hom}_{K^b}(Y, \Sigma^2 P),$$

where the first term vanishes by (0) and the last term vanishes since  $Y$  is in degrees  $-1, 0$  while  $\Sigma^2 P$  is concentrated in degree  $-2$ .

(3)  $\mathrm{Hom}_{K^b}(E, \Sigma Y) = 0$ : Consider the exact sequence

$$\mathrm{Hom}_{K^b}(\Sigma Y, \Sigma Y) \rightarrow \mathrm{Hom}_{K^b}(\Sigma P, \Sigma Y) \rightarrow \mathrm{Hom}_{K^b}(E, \Sigma Y) \rightarrow \mathrm{Hom}_{K^b}(Y, \Sigma Y).$$

Its last term vanishes by (0). Let us prove that its first morphism is surjective. Composition with  $\alpha$  and  $F\alpha$  yields a commutative square

$$\begin{array}{ccc} \mathrm{Hom}_{K^b}(Y, Y) & \xrightarrow{\alpha^*} & \mathrm{Hom}_{K^b}(P, Y) \\ \downarrow & \circlearrowleft & \downarrow \\ \mathrm{Hom}_{\Lambda}(FY, FY) & \xrightarrow{(F\alpha)^*} & \mathrm{Hom}_{\Lambda}(FP, FY) \end{array}$$

where the vertical maps are surjective. Since  $\Lambda$  is rigid and  $Y$  is two-term, we can apply [IY08, Prop. 6.2] to the triangulated category  $K^b(\mathrm{proj} \Lambda)$  (or Proposition 4.6 to the extriangulated  $K^{[-1,0]}(\mathrm{proj} \Lambda)$ ). As a consequence, the right-most vertical map is bijective. Because  $FY$  is a brick,  $\mathrm{End}_{\Lambda}(FY)$  is a division ring. Moreover,  $FY$  is the indecomposable injective with simple socle the simple top of  $P$ , so that the  $\mathrm{End}_{\Lambda}(FY)$ -module  $\mathrm{Hom}_{\Lambda}(FP, FY)$  is one-dimensional over  $\mathrm{End}_{\Lambda}(FY)$ . It follows that the vertical map  $(F\alpha)^*$  is either zero or bijective. But  $\alpha$  is non-zero with domain in  $\mathrm{add} \Lambda$  so that  $F\alpha$  is non-zero; and  $(F\alpha)^*(1_{FY}) = F\alpha$  so that  $(F\alpha)^*$  is non-zero. By commutativity, this implies the surjectivity of the top vertical morphism  $\alpha^*$ . Since the shift functor is an automorphism, the morphism  $\mathrm{Hom}_{K^b}(\Sigma Y, \Sigma Y) \rightarrow \mathrm{Hom}_{K^b}(\Sigma P, \Sigma Y)$  is also surjective, and  $\mathrm{Hom}_{K^b}(E, \Sigma Y) = 0$ .

(4)  $\mathrm{Hom}_{K^b}(E, \Sigma E) = 0$ : In the exact sequence

$$\mathrm{Hom}_{K^b}(E, \Sigma Y) \rightarrow \mathrm{Hom}_{K^b}(E, \Sigma E) \rightarrow \mathrm{Hom}_{K^b}(E, \Sigma^2 P),$$

the first term is zero by (3) and the last term vanishes since  $P$  is concentrated in degree zero.

(5)  $\mathrm{Hom}_{K^b}(\Sigma P, \Sigma E) = 0$ : Let  $P \xrightarrow{f} E$  be any morphism.

$$\begin{array}{ccccc} & & P & & \\ & & \swarrow g & \searrow f & \searrow 0 \\ & & P & \xrightarrow{\alpha} & Y & \xrightarrow{\beta} & E & \longrightarrow & \Sigma P \\ & \swarrow g & \swarrow h & \swarrow \beta h & \downarrow & \swarrow h' & & & \\ & Y & \xrightarrow{\beta} & E & & & & & \end{array}$$

Since  $P$  is rigid,  $f$  factors through the inflation  $\beta$  in the conflation  $Y \rightarrow E \rightarrow \Sigma P$ , and there is some morphism  $g$  such that  $f = \beta g$ . By (3), the morphism  $g$  factors through  $P \xrightarrow{\alpha} Y$ : there is some  $h : Y \rightarrow Y$  such that  $g = h\alpha$ . We then have  $f = \beta g = \beta(h\alpha) = \beta(h-1)\alpha$ . Since  $Y$  is endo-local, the morphism  $h$  or  $h-1$  is an automorphism, and we may assume that  $h$  is an automorphism. The morphism  $\beta h$  is not a section (otherwise  $\beta$  would be a section) and  $\beta$  is left-almost split: there is an endomorphism  $h'$  of  $E$  such that  $\beta h = h'\beta$ . Therefore, we have  $f = \beta h\alpha = h'\beta\alpha = 0$ .  $\square$

*Proof of Theorem 4.46.* The theorem follows from the slightly more general statements of Lemmas 4.51 to 4.53.  $\square$

**Lemma 4.54.** *Let  $\Lambda$  be a brick and 2-acyclic gentle algebra. Then, for any indecomposable  $\Lambda$ -module  $M$  we have  $\mathrm{Hom}_{\Lambda}(M, \tau^2 M) = 0$ .*

*Proof.* Let  $\Lambda = \mathbb{K}Q/I$  be any gentle algebra of finite representation type, and let  $M$  be an indecomposable  $\Lambda$ -module. Write  $\sigma$  for the string corresponding to  $\tau M$ . Then the walks (i.e. the

maximal strings in the blossoming bound quiver of  $(Q, I)$  associated with  $M$  and  $\tau M$  are respectively  $\omega_M = \wedge\sigma\wedge = p^{-1}\alpha\sigma\beta^{-1}q$  and  $\omega_{\tau M} = \vee\sigma\vee = p'\alpha'^{-1}\sigma\beta'q'^{-1}$ , where  $p, p', q, q'$  are paths and  $\alpha, \alpha', \beta, \beta'$  are arrows in the blossoming quiver.

Assume that  $\text{Hom}_\Lambda(M, \tau^2 M) \neq 0$ . By [PPP17, Theorem 2.46] or [BDM<sup>+</sup>17, Theorem 5.1], the walk  $\omega_M$  kisses the walk  $\omega_{\tau M}$ : there is a substring  $\rho$  of  $\omega_M$  and  $\omega_{\tau M}$  that is strictly on top of  $\omega_M$  and strictly at the bottom of  $\omega_{\tau M}$ . Remark that  $\rho$  cannot start nor end at some endpoint of  $\sigma$  (because  $\rho$  is a top substring of  $\omega_M$ ).

If the substring  $\rho$  of  $\omega_M$  is contained in  $\sigma$ , by the previous remark it is strictly below  $\sigma$ . This implies that  $\omega_M$  kisses itself, hence that  $M$  is not  $\tau$ -rigid. Similarly, if  $\rho$  is contained in  $\sigma$  as a substring of  $\omega_{\tau M}$ , then  $\tau M$  is not  $\tau$ -rigid. In both cases, the brick- $\tau$ -rigid correspondence of [DIJ19] implies that  $\Lambda$  is not a brick algebra.

Note that  $\rho$  cannot contain  $\sigma$ , because  $\sigma$  is the only common substring of  $\omega_M$  and  $\omega_{\tau M}$  that contains  $\sigma$ . Assume now that  $\rho$ , viewed either as a substring of  $\omega_M$  or of  $\omega_{\tau M}$  is not contained in  $\sigma$ . Since  $\rho$  is strictly on top of  $\omega_M$ , it contains the source of  $\alpha$  or the source of  $\beta$ . Similarly,  $\rho$  contains the target of  $\alpha'$  or the target of  $\beta'$ . Because the target of  $\alpha$  is the source of  $\alpha'$  (and the target of  $\beta$  is the source of  $\beta'$ ), this implies that  $Q$  contains either a non-oriented cycle with at most one relation, in which case  $\Lambda$  is not a brick algebra, or a 2-cycle, in which case  $\Lambda$  is not 2-acyclic.  $\square$

*Proof of Corollary 4.49.* The unique exchange property follows from Proposition 4.44 (2). By Lemma 4.54, the assumptions of Theorem 4.46 are satisfied. We can thus apply Theorem 4.13 and its corollary, which shows that there is the same number of extremal exchange pairs of the support  $\tau$ -tilting fan (i.e. the non-kissing fan) as there are meshes in the Auslander–Reiten quiver of  $\Lambda$ . Hence the type cone of the support  $\tau$ -tilting fan is simplicial.  $\square$

**4.7. Application to other examples of categories.** In this section, we give two more examples of families of categories to which Theorem 4.13 and Corollary 4.14 apply.

**4.7.1. 2-Calabi–Yau triangulated categories.** Let  $\mathcal{C}$  be a triangulated category with shift functor  $\Sigma$ . We assume moreover that  $\mathcal{C}$  is  $\mathbb{K}$ -linear, Krull–Schmidt, Hom-finite, 2-Calabi–Yau, with a cluster-tilting object  $T$ . Then  $\mathcal{C}$  satisfies all the assumptions of Section 4.1 for Section 4.3 but, possibly, assumption (1).

We fix this issue by considering a relative extriangulated structure. Let  $\mathbb{E}_T$  be the additive sub-bifunctor of  $\mathcal{C}(-, \Sigma-)$  formed by those morphisms that factor through  $\text{add } \Sigma T$ . Then  $(\mathcal{C}, \mathbb{E}_T)$  becomes extriangulated by [HLN17, Prop. 3.14] (this can also be checked directly). The extriangles of  $\mathcal{C}$  are precisely the triangles  $X \xrightarrow{f} Y \xrightarrow{g} Z \xrightarrow{h} \rightarrow$ , for which the morphism  $h$  factors through  $\text{add } \Sigma T$ . By construction, Condition (1) is now satisfied. Moreover, the triangles appearing in Conditions (2) and (3) are extriangles for this relative structure, which shows that those two conditions are still satisfied for the extriangulated structure  $(\mathcal{C}, \mathbb{E}_T)$ .

**Remark 4.55.** The index of an object  $X$  in the triangulated category  $\mathcal{C}$ , coincide with its class in the Grothendieck group of  $\mathcal{C}$  for the relative extriangulated structure given by  $\mathbb{E}_T$ .

**Remark 4.56.** The main results of Section 3.2 can thus be viewed as specific cases of the results of Section 4: Theorem 3.8 and Corollary 3.9 are consequences of Theorem 4.13 and Corollary 4.14.

**4.7.2. Objects presented by a subcategory.** We now describe a setup satisfying the assumptions of Section 4.1 that, at the same time, subsumes all examples given so far, while being easily checked in practice.

Let  $(\mathcal{E}, \mathbb{E}, \mathfrak{s})$  be an extriangulated category (for example, a small exact category or a triangulated category), and let  $\mathcal{T}$  be an essentially small subcategory of  $\mathcal{E}$ .

For any  $X, Y \in \mathcal{E}$ , let  $\mathbb{E}_{\mathcal{T}}(X, Y)$  be the subset of  $\mathbb{E}(X, Y)$  consisting of those  $\delta$  that satisfy  $f^*\delta = 0$ , for any  $T \in \mathcal{T}$  and any  $T \xrightarrow{f} X$ . It is easily seen that  $\mathbb{E}_{\mathcal{T}}$  is an additive subfunctor of  $\mathbb{E}$ . Consider  $(\mathcal{E}, \mathbb{E}_{\mathcal{T}}, \mathfrak{s}_{\mathcal{T}})$  endowed with the restriction of the additive realization  $\mathfrak{s}$ . Since the deflations in  $(\mathcal{E}, \mathbb{E}_{\mathcal{T}}, \mathfrak{s}_{\mathcal{T}})$  are precisely the deflations in  $(\mathcal{E}, \mathbb{E}, \mathfrak{s})$  that are  $\mathcal{T}$ -epic, they are closed

under composition. We can thus apply [HLN17, Prop. 3.14] to obtain that  $(\mathcal{E}, \mathbb{E}_{\mathcal{T}}, \mathfrak{s}_{\mathcal{T}})$  is an extriangulated category. With that relative structure, the objects in  $\mathcal{T}$  become projective. Define  $\mathcal{C}$  to be the full subcategory of  $\mathcal{E}$  whose objects  $X$  admit an  $\mathfrak{s}_{\mathcal{T}}$ -conflation  $T_1 \twoheadrightarrow T_0 \twoheadrightarrow X$ .

**Lemma 4.57.** *The full subcategory  $\mathcal{C}$  is extension-closed in  $(\mathcal{E}, \mathbb{E}_{\mathcal{T}}, \mathfrak{s}_{\mathcal{T}})$ , and thus inherits an extriangulated structure.*

*Proof.* This follows from the proof of Lemma 4.38. □

**Notation 4.58.** Write  $\mathcal{T}^\perp$  for the full subcategory of  $\mathcal{E}$  whose objects are those objects  $X \in \mathcal{E}$  that satisfy  $\mathcal{E}(T, X) = 0$ , for any  $T \in \mathcal{T}$ .

**Proposition 4.59.** *Assume that, for any  $T \in \mathcal{T}$ , there is an  $\mathfrak{s}$ -conflation  $T \twoheadrightarrow 0 \twoheadrightarrow X_T$  in  $\mathcal{E}$  with  $X_T \in \mathcal{T}^\perp$ . Then the extriangulated category  $\mathcal{C}$  satisfies the assumptions (1) to (3) of Section 4.1.*

*Proof.* For any  $T \in \mathcal{T}$  the existence of an extriangle  $0 \twoheadrightarrow T \twoheadrightarrow T \xrightarrow{0}$  shows that  $\mathcal{T}$  is a full subcategory of  $\mathcal{C}$ . By Lemma 4.57, the category  $\mathcal{C}$  is extriangulated and, by definition of this extriangulated structure, the objects in  $\mathcal{T}$  are projective in  $\mathcal{C}$ . Assumption (3) is satisfied by the definition of  $\mathcal{C}$ , and assumption (2) is equivalent to that of the proposition. □

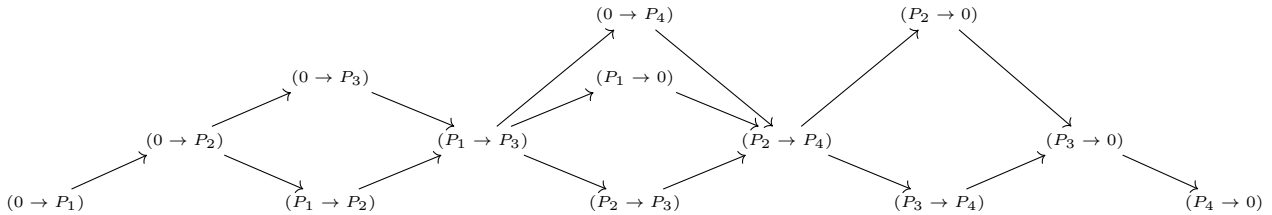
**Remark 4.60.** The categories considered in Sections 4.6 and 4.7.1 all fall into the setting of Proposition 4.59.

**4.8. Examples.** We conclude with a couple of examples for two associative algebras.

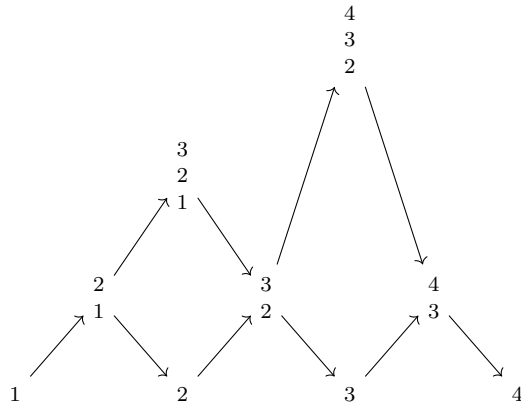
**Example 4.61** (A gentle algebra). Consider the algebra  $\Lambda$  given the the path algebra of the quiver

$$1 \xrightarrow{\alpha} 2 \xrightarrow{\beta} 3 \xrightarrow{\gamma} 4$$

modulo the relation  $\gamma\beta\alpha = 0$ . The Auslander–Reiten quiver of the extriangulated category  $K^{[-1,0]}(\text{proj } \Lambda)$  is depicted below.



The Auslander–Reiten quiver of the module category is obtained by taking the quotient by the ideal generated by the shifted projective modules.



The conditions of Theorem 4.46 are satisfied.



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(Arnaud Padrol) INSTITUT DE MATHÉMATIQUES DE JUSSIEU - PARIS RIVE GAUCHE, SORBONNE UNIVERSITÉ, PARIS

*E-mail address:* `arnau.padrol@imj-prg.fr`.

*URL:* <https://webusers.imj-prg.fr/~arnau.padrol/>

(Yann Palu) LAMFA, UNIVERSITÉ PICARDIE JULES VERNE, AMIENS

*E-mail address:* `yann.palu@u-picardie.fr`

*URL:* <http://www.lamfa.u-picardie.fr/palu/>

(Vincent Pilaud) CNRS & LIX, ÉCOLE POLYTECHNIQUE, PALAISEAU

*E-mail address:* `vincent.pilaud@lix.polytechnique.fr`

*URL:* <http://www.lix.polytechnique.fr/~pilaud/>

(Pierre-Guy Plamondon) LABORATOIRE DE MATHÉMATIQUES D'ORSAY, UNIVERSITÉ PARIS-SUD, CNRS, UNIVERSITÉ PARIS-SACLAY

*E-mail address:* `pierre-guy.plamondon@math.u-psud.fr`

*URL:* <https://www.math.u-psud.fr/~plamondon/>