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# OPETOPIC ALGEBRAS I: ALGEBRAIC STRUCTURES ON OPETOPIC SETS

CÉDRIC HO THANH AND CHAITANYA LEENA SUBRAMANIAM

ABSTRACT. We define a family of structures called “opetopic algebras”, which are algebraic structures with an underlying opetopic set. Examples of such are categories, planar operads, and Loday’s combinads over planar trees. Opetopic algebras can be defined in two ways, either as the algebras of a “free pasting diagram” parametric right adjoint monad, or as models of a small projective sketch over the category of opetopes. We define an opetopic nerve functor that fully embeds each category of opetopic algebras into the category of opetopic sets. In particular, we obtain fully faithful opetopic nerve functors for categories and for planar coloured Set-operads.

This paper is the first in a series aimed at using opetopic spaces as models for higher algebraic structures.

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## 1. INTRODUCTION

This paper deals with algebraic structures whose operations have *higher dimensional “tree-like” arities*. As an example in lieu of a definition, a category  $\mathcal{C}$  is an algebraic structure whose operation of *composition* has as its inputs, or “arities”, sequences of composable morphisms of the category. These sequences can be seen as *filiform* or *linear* trees. Moreover, each morphism of  $\mathcal{C}$  can itself be seen as an operation whose arity is a single point (i.e. an object of  $\mathcal{C}$ ). A second example, one dimension above, is that of a planar coloured Set-operad  $\mathcal{P}$  (a.k.a. a nonsymmetric multicategory), whose operation of composition has planar trees of operations (a.k.a. multimorphisms) of  $\mathcal{P}$  as arities. Moreover, the arity of an operation of  $\mathcal{P}$  is an ordered list (a filiform tree) of colours (a.k.a. objects) of  $\mathcal{P}$ . Heuristically extending this pattern leads one to presume that such an algebraic structure one dimension above planar operads should have an operation of composition whose arities are trees of things that can themselves be seen as operations whose arities are planar trees. Indeed, such algebraic structures are precisely the *PT-combinads in Set* (combinads over the combinatorial pattern of planar trees) of Loday [Lod12].

Structure	Sets =0-algebras	Categories =1-algebras	Operads =2-algebras	PT-combinads =3-algebras	...
Arity	{*} =1-opetopes	Lists =2-opetopes	Trees =3-opetopes	4-opetopes	...

The goal of this article is to give a precise definition of the previous sequence of algebraic structures.

**1.1. Context.** It is well-known that higher dimensional tree-like arities are encoded by the opetopes (*operation polytopes*) of Baez and Dolan [BD98], which were originally introduced in order to give a definition of weak  $n$ -categories and a precise formulation of the “microcosm” principle.

The fundamental definitions of [BD98] are those of  $\mathcal{P}$ -opetopic sets and  $n$ -coherent  $\mathcal{P}$ -algebras (for a coloured symmetric Set-operad  $\mathcal{P}$ ), the latter being  $\mathcal{P}$ -opetopic sets along with certain “horn-filling” operations that are “universal” in a suitable sense. When  $\mathcal{P}$  is the identity monad on Set (i.e. the unicolour symmetric Set-operad with a single unary operation),  $\mathcal{P}$ -opetopic sets are simply called *opetopic sets*, and  $n$ -coherent  $\mathcal{P}$ -algebras are the authors’ proposed definition of *weak  $n$ -categories*.

While the coinductive definitions in [BD98] of  $\mathcal{P}$ -opetopic sets and  $n$ -coherent  $\mathcal{P}$ -algebras are straightforward and general, they have the disadvantage of not defining a *category* of  $\mathcal{P}$ -opetopes such that presheaves over it are precisely  $\mathcal{P}$ -opetopic sets, even though this is ostensibly the case. Directly defining the category of  $\mathcal{P}$ -opetopes turns out to be a tedious and non-trivial task, and was worked out explicitly by Cheng in [Che03, Che04a] for the particular case of the identity monad on Set, giving the category  $\mathbb{O}$  of opetopes.

The complexity in the definition of a category  $\mathbb{O}_{\mathcal{P}}$  of  $\mathcal{P}$ -opetopes has its origin in the difficulty of working with a suitable notion of *symmetric tree*. Indeed, the objects of  $\mathbb{O}_{\mathcal{P}}$  are trees of trees of ... of trees of operations of the symmetric operad  $\mathcal{P}$ , and their automorphism groups are determined by the action of the (“coloured”) symmetric groups on the sets of operations of  $\mathcal{P}$ .

However, when the action of the symmetric groups on the sets of operations of  $\mathcal{P}$  is free, it turns out that the objects of the category  $\mathbb{O}_{\mathcal{P}}$  are rigid, i.e. have no non-trivial automorphisms (this follows from [Che04a, proposition 3.2]). The identity monad on Set is of course such an operad, and this vastly simplifies the definition of  $\mathbb{O}$ . Indeed, such operads are precisely the (finitary) *polynomial monads* in Set, and the machinery of polynomial endofunctors and polynomial monads developed in [Koc11, KJBM10, GK13] gives a very satisfactory definition of  $\mathbb{O}$  [HT18, CHTM19] which we review in sections 2 and 3.

**1.2. Contributions.** The main contribution of the present article is to show how the polynomial definition of  $\mathbb{O}$  allows, for all  $k, n \in \mathbb{N}$  with  $k \leq n$ , a definition of  $(k, n)$ -opetopic algebras, which constitute a full subcategory of the category  $\mathcal{Psh}(\mathbb{O})$  of opetopic sets. More precisely, we show that the polynomial monad whose set of operations is the set  $\mathbb{O}_{n+1}$  of  $(n+1)$ -dimensional opetopes can be extended to a parametric right adjoint monad whose algebras are the  $(k, n)$ -opetopic algebras. Important particular cases are the categories of  $(1, 1)$ - and  $(1, 2)$ -opetopic algebras, which are the categories  $\mathcal{Cat}$  and  $\mathcal{Op}_{\text{col}}$  of small categories and coloured planar Set-operads respectively. Loday’s combinads over the combinatorial pattern of planar trees [Lod12] are also recovered as  $(1, 3)$ -opetopic algebras.

We further show that each category of  $(k, n)$ -opetopic algebras admits a fully faithful *opetopic nerve functor* to  $\mathcal{Psh}(\mathbb{O})$ . As a direct consequence of this framework, we obtain commutative triangles of adjunctions

$$\begin{array}{ccc}
 & \mathcal{Cat} & \\
 h \swarrow & & \nwarrow u \\
 \mathcal{Psh}(\mathbb{O}) & \xrightarrow{N} & \mathcal{Psh}(\Delta) \\
 \xleftarrow{h^*} & \xrightarrow{h_!} & \xleftarrow{N_u} \\
 & \perp & \\
 & \mathcal{Psh}(\Delta) & 
 \end{array}
 \qquad
 \begin{array}{ccc}
 & \mathcal{Op}_{\text{col}} & \\
 h \swarrow & & \nwarrow u \\
 \mathcal{Psh}(\mathbb{O}_{\geq 1}) & \xrightarrow{N} & \mathcal{Psh}(\Omega) \\
 \xleftarrow{h^*} & \xrightarrow{h_!} & \xleftarrow{N_u} \\
 & \perp & \\
 & \mathcal{Psh}(\Omega) & 
 \end{array}
 \tag{1.2.1}$$

where  $\Delta$  is the category of simplices,  $\Omega$  is the planar version of Moerdijk and Weiss’s category of *dendrices* and  $\mathbb{O}_{\geq 1}$  is the full subcategory of  $\mathbb{O}$  on opetopes of dimension  $> 0$ . This gives a direct comparison between the opetopic nerve of a category (resp. a planar operad) and its corresponding well-known simplicial (resp. dendroidal) nerve.

This formalism seems to provide infinitely many types of  $(k, n)$ -opetopic algebras. However this is not really the case, as the notion stabilises at the level of combinads. Specifically, we show a phenomenon we call *algebraic trompe-l’œil*, where an  $(k, n)$ -opetopic algebra is entirely specified by its underlying opetopic set and by a  $(1, 3)$ -opetopic algebra. In other words, its algebraic data can be “compressed” into a  $(1, 3)$ -algebra (a combinad). The intuition behind this is that fundamentally, opetopes are just trees whose nodes are themselves trees, and that once this is obtained at the level of combinads, opetopic algebras can encode no further useful information.

**1.3. Outline.** We begin by recalling elements of the theory of polynomial functors and polynomial monads in section 2. This formalism is the basis for the modern definition of opetopes and of the category of opetopes [KJBM10, CHTM19] that we survey in section 3. Section 4 contains the central constructions of this article, namely those of opetopic algebras and coloured opetopic algebras, as well as the definition of the opetopic nerve functor, which is a full embedding of (coloured) opetopic algebras into opetopic sets. Section 5 is devoted to showing how the algebraic information carried by opetopes turns out to be limited.

**1.4. Related work.** The  $(k, n)$ -opetopic algebras that we obtain are related to the  $n$ -coherent  $\mathcal{P}$ -algebras of [BD98] as follows: for  $n \geq 1$ ,  $(1, n)$ -opetopic algebras are precisely 1-coherent  $\mathcal{P}$ -algebras for  $\mathcal{P}$  the polynomial monad  $\mathbb{O}_{n-1} \leftarrow E_n \rightarrow \mathbb{O}_n \rightarrow \mathbb{O}_{n-1}$ . We therefore do not obtain all  $n$ -coherent  $\mathcal{P}$ -algebras with our framework, and this means in particular that we cannot capture all the weak  $n$ -categories of [BD98] (except for  $n = 1$ , which are just usual 1-categories). This is not unexpected, as weak  $n$ -categories are not defined just by *equations* on the opetopes of an opetopic set, but by its more subtle *universal* opetopes.

However, we are able to promote the triangles of (1.2.1) to Quillen equivalences of simplicial model categories. This, along with a proof that opetopic spaces (i.e. simplicial presheaves on  $\mathbb{O}$ ) model  $(\infty, 1)$ -categories and planar  $\infty$ -operads, will be the subject of the second paper of this series.

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**1.6. Preliminary category theory.** We review relevant notions and basic results from the theory of locally presentable categories. Original references are [GU71, SGA72], and most of this material can be found in [AR94].

**1.6.1. Presheaves and nerve functors.** For  $\mathcal{C} \in \text{Cat}$ , we write  $\mathcal{Psh}(\mathcal{C})$  for the category of Set-valued presheaves over  $\mathcal{C}$ , i.e. the category of functors  $\mathcal{C}^{\text{op}} \rightarrow \text{Set}$  and natural transformations between them. If  $X \in \mathcal{Psh}(\mathcal{C})$  is a presheaf, then its *category of elements*  $\mathcal{C}/X$  is the comma category  $\mathbf{y} \downarrow X$ , where  $\mathbf{y} : \mathcal{C} \rightarrow \mathcal{Psh}(\mathcal{C})$  is the Yoneda embedding.

Let  $\mathcal{C} \in \text{Cat}$  and  $F : \mathcal{C} \rightarrow \mathcal{D}$  be a functor to a (not necessarily small) category  $\mathcal{D}$ . Then the *nerve functor associated to  $F$*  (also called the *nerve of  $F$* ) is the functor  $N_F : \mathcal{D} \rightarrow \mathcal{Psh}(\mathcal{C})$  mapping  $d \in \mathcal{D}$  to  $\mathcal{D}(F-, d)$ . The functor  $F$  is said to be *dense* if for all  $d \in \mathcal{D}$ , the colimit of  $F \downarrow d \rightarrow \mathcal{C} \xrightarrow{F} \mathcal{D}$  exists in  $\mathcal{D}$ , and is canonically isomorphic to  $d$ .  $F$  is dense if and only if  $N_F$  is fully faithful.

Let  $i : \mathcal{C} \rightarrow \mathcal{D}$  be a functor between small categories. Then the precomposition functor  $i^* : \mathcal{Psh}(\mathcal{D}) \rightarrow \mathcal{Psh}(\mathcal{C})$  has a left adjoint  $i_!$  and a right adjoint  $i_*$ , given by left and right Kan extension along  $i^{\text{op}}$  respectively. If  $i$  has a right adjoint  $j$ , then  $i^* \dashv j^*$ , or equivalently,  $i^* \cong j_!$ . Note that the nerve of  $i$  is the functor  $N_i = i^* \mathbf{y}_{\mathcal{D}}$ , where  $\mathbf{y}_{\mathcal{D}} : \mathcal{D} \rightarrow \mathcal{Psh}(\mathcal{D})$  is the Yoneda embedding. Recall that  $i^*$  is the nerve of the functor  $\mathbf{y}_{\mathcal{D}} i$  and that  $i_*$  is the nerve of the functor  $N_i = i^* \mathbf{y}_{\mathcal{D}}$ , i.e. it is the nerve of the nerve of  $i$ .

**1.6.2. Orthogonality.** Let  $\mathcal{C}$  be a category, and  $l, r \in \mathcal{C}^{\rightarrow}$ . We say that  $l$  is *left orthogonal to  $r$*  (equivalently,  $r$  is *right orthogonal to  $l$* ), written  $l \perp r$ , if for any solid commutative square as follows, there exists a *unique* dashed arrow making the two triangles commute (the relation  $\perp$  is also known as the *unique lifting property*):

$$\begin{array}{ccc} \cdot & \xrightarrow{\quad} & \cdot \\ \downarrow l & \dashrightarrow & \downarrow r \\ \cdot & \xrightarrow{\quad} & \cdot \end{array}$$

If  $\mathcal{C}$  has a terminal object  $1$ , then for all  $X \in \mathcal{C}$ , we write  $l \perp X$  if  $l$  is left orthogonal to the unique map  $X \rightarrow 1$ . Let  $\mathbf{L}$  and  $\mathbf{R}$  be two classes of morphisms of  $\mathcal{C}$ . We write  $\mathbf{L} \perp \mathbf{R}$  if for all  $l \in \mathbf{L}$  and  $r \in \mathbf{R}$  we have  $l \perp r$ . The class of all morphisms  $f$  such that  $\mathbf{L} \perp f$  (resp.  $f \perp \mathbf{R}$ ) is denoted  $\mathbf{L}^{\perp}$  (resp.  ${}^{\perp}\mathbf{R}$ ).

**1.6.3. Localisations.** Let  $\mathbf{J}$  be a class of morphisms of a category  $\mathcal{C}$ . Recall that the *localisation of  $\mathcal{C}$  at  $\mathbf{J}$*  is a functor  $\gamma_{\mathbf{J}} : \mathcal{C} \rightarrow \mathbf{J}^{-1}\mathcal{C}$  such that  $\gamma_{\mathbf{J}} f$  is an isomorphism for every  $f \in \mathbf{J}$ , and such that  $\gamma_{\mathbf{J}}$  is universal for this property. We say that  $\mathbf{J}$  has the *2-out-of-3* (or *3-for-2*) property when for every composable pair  $\cdot \xrightarrow{f} \cdot \xrightarrow{g} \cdot$  of morphisms in  $\mathcal{C}$ , if any two of  $f$ ,  $g$  and  $gf$  are in  $\mathbf{J}$ , then so is the third.

Assume now that  $\mathcal{C}$  is a small category, and that  $\mathbf{J}$  is a *set* (rather than a proper class) of morphisms of  $\mathcal{C}$ , and consider the full subcategory  $\mathcal{C}_{\mathbf{J}} \hookrightarrow \mathcal{Psh}(\mathcal{C})$  of all those  $X \in \mathcal{Psh}(\mathcal{C})$  such that  $\mathbf{J} \perp X$ . A category is *locally presentable* if and only if it is equivalent to one of the form  $\mathcal{C}_{\mathbf{J}}$ . The pair  $({}^{\perp}(\mathbf{J}^{\perp}), \mathbf{J}^{\perp})$  forms an *orthogonal factorisation system*, meaning that any morphism  $f$  in  $\mathcal{C}$  can be factored as  $f = pi$ , where  $p \in \mathbf{J}^{\perp}$  and  $i \in {}^{\perp}(\mathbf{J}^{\perp})$ . Applied to the unique arrow  $X \rightarrow 1$ , this factorisation provides a left adjoint (i.e. a reflection)  $a_{\mathbf{J}} : \mathcal{Psh}(\mathcal{C}) \rightarrow \mathcal{C}_{\mathbf{J}}$  to the inclusion  $\mathcal{C}_{\mathbf{J}} \hookrightarrow \mathcal{Psh}(\mathcal{C})$ . Furthermore,  $a_{\mathbf{J}}$  is the localisation of  $\mathcal{Psh}(\mathcal{C})$  at  $\mathbf{J}$ .<sup>(1)</sup>

<sup>(1)</sup>The results of this paragraph still hold when  $\mathcal{Psh}(\mathcal{C})$  is replaced by a locally  $\kappa$ -presentable category, i.e. one of the form  $\mathcal{C}_{\mathbf{J}}$  with  $\kappa$  a regular cardinal and  $\mathbf{J}$  a set of  $\kappa$ -small morphisms. We call a localisation of the form  $a_{\kappa} : \mathcal{C}_{\mathbf{J}} \rightarrow (\mathcal{C}_{\mathbf{J}})_{\kappa}$  the *Gabriel–Ulmer localisation* of  $\mathcal{C}_{\mathbf{J}}$  at  $\mathbf{K}$ .

With  $\mathcal{C}$  and  $\mathbf{J}$  as in the previous paragraph, the class of  $\mathbf{J}$ -local isomorphisms  $\mathbf{W}_{\mathbf{J}}$  is the class of all morphisms  $f \in \mathcal{Psh}(\mathcal{C})^{\rightarrow}$  such that for all  $X \in \mathcal{C}_{\mathbf{J}}$ ,  $f \perp X$  (that is,  $\mathbf{W}_{\mathbf{J}} = {}^{\perp}\mathcal{C}_{\mathbf{J}}$ ). It is the smallest class of morphisms that contains  $\mathbf{J}$ , that satisfies the 3-for-2 property, and that is closed under colimits in  $\mathcal{Psh}(\mathcal{C})^{\rightarrow}$  [GU71, theorem 8.5]. Thus the localisation  $a_{\mathbf{J}}$  is also the localisation of  $\mathcal{Psh}(\mathcal{C})$  at  $\mathbf{W}_{\mathbf{J}}$ . Furthermore,  $\mathbf{W}_{\mathbf{J}}$  is closed under pushouts.

1.6.4. *Projective sketches.* A *projective sketch* is the data of a  $\mathcal{C} \in \mathbf{Cat}$  and a set  $K$  of cones in  $\mathcal{C}$ . For  $\mathcal{B}$  a category with all limits, the category of *models in  $\mathcal{B}$  of  $(\mathcal{C}, K)$*  is the category of functors  $\mathcal{C} \rightarrow \mathcal{B}$  that take each cone in  $K$  to a limit cone, and natural transformations between them. If  $(\mathcal{C}, K)$  is a projective sketch, then equivalently,  $K$  can be seen as a set of cocones in  $\mathcal{C}^{\text{op}}$ , or as a set of subrepresentables (subobjects of representables) in  $\mathcal{Psh}(\mathcal{C}^{\text{op}})$ . Let  $\mathcal{C}_K^{\text{op}} \hookrightarrow \mathcal{Psh}(\mathcal{C}^{\text{op}})$  be the full subcategory of all  $X \in \mathcal{Psh}(\mathcal{C}^{\text{op}})$  such that  $K \perp X$ . Then  $\mathcal{C}_K^{\text{op}}$  is precisely the category of models in  $\mathbf{Set}$  of the projective sketch  $(\mathcal{C}, K)$ . Let  $\kappa$  be a regular cardinal, and let  $(\mathcal{C}, K)$  be a projective sketch in which each cone in  $K$  is to a  $\kappa$ -small diagram. Then  $\mathcal{C}_K^{\text{op}}$  is a locally  $\kappa$ -presentable category, and the inclusion  $\mathcal{C}_K^{\text{op}} \hookrightarrow \mathcal{Psh}(\mathcal{C}^{\text{op}})$  preserves  $\kappa$ -filtered colimits.

## 2. POLYNOMIAL FUNCTORS AND POLYNOMIAL MONADS

We survey elements of the theory of polynomial functors, trees, and monads. For more comprehensive references, see [Koc11, GK13].

2.1. **Polynomial functors.** A *polynomial (endo)functor  $P$  over  $I$*  is a diagram in  $\mathbf{Set}$  of the form

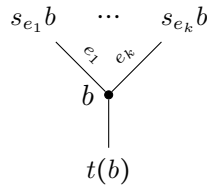
$$I \xleftarrow{s} E \xrightarrow{p} B \xrightarrow{t} I. \quad (2.1.1)$$

$P$  is said to be *finitary* if the fibres of  $p : E \rightarrow B$  are finite sets. We will always assume polynomial functors to be finitary. A morphism from a polynomial functor  $P$  over  $I$  to a polynomial functor  $P'$  over  $I'$  (on the second row) is a commutative diagram of the form

$$\begin{array}{ccccccc} I & \xleftarrow{s} & E & \xrightarrow{p} & B & \xrightarrow{t} & I \\ f_0 \downarrow & & f_2 \downarrow & \lrcorner & f_1 \downarrow & & f_0 \downarrow \\ I' & \xleftarrow{s'} & E' & \xrightarrow{p'} & B' & \xrightarrow{t} & I' \end{array}$$

where the middle square is cartesian (i.e. is a pullback square). If  $P$  and  $P'$  are both polynomial functors over  $I$ , then a morphism from  $P$  to  $P'$  over  $I$  is a commutative diagram as above, but where  $f_0$  is required to be the identity. Let  $\mathbf{PolyEnd}$  denote the category of polynomial functors and morphisms of polynomial functors, and  $\mathbf{PolyEnd}(I)$  the category of polynomial functors over  $I$  and morphisms of polynomial functors over  $I$ .

We use the following terminology for a polynomial functor  $P$  as in equation (2.1.1), which is motivated by the intuition that a polynomial functor encodes a multi-sorted signature of function symbols. The elements of  $B$  are called the *nodes* or *operations* of  $P$ , and for every node  $b$ , the elements of the fibre  $E(b) := p^{-1}(b)$  are called the *inputs* or *arities* of  $b$ . The elements of  $I$  are called the *colours* or *sorts* of  $P$ . For every input  $e$  of a node  $b$ , we denote its colour by  $s_e(b) := s(e)$ .



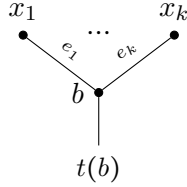
The term “polynomial (endo)functor” is due to the association of  $P$  to the composite endofunctor

$$P : \text{Set}/I \xrightarrow{s^*} \text{Set}/E \xrightarrow{p_*} \text{Set}/B \xrightarrow{t_!} \text{Set}/I$$

where we have denoted  $a_!$  and  $a_*$  the left and right adjoints to the pullback functor  $a^*$  along a map of sets  $a$ . Explicitly, for  $(X_i \mid i \in I) \in \text{Set}/I$ ,  $P(X)$  is given by the “polynomial”

$$P(X) = \left( \sum_{b \in B(j)} \prod_{e \in E(b)} X_{s(e)} \mid j \in I \right), \quad (2.1.2)$$

where  $B(i) := t^{-1}(i)$  and  $E(b) = p^{-1}(b)$ . Visually, elements of  $P(X)_j$  are nodes  $b \in B$  such that  $tb = j$ , and whose inputs are decorated by elements of  $(X_i \mid i \in I)$  in a manner compatible with their colours. Graphically, an element of  $PX_i$  can be represented as



with  $b \in B$  such that  $t(b) = i$ , and  $x_j \in X_{s_{e_j}b}$  for  $1 \leq j \leq k$ . Moreover, the endofunctor  $P : \text{Set}/I \rightarrow \text{Set}/I$  preserves connected limits:  $s^*$  and  $p_*$  preserve all limits (as right adjoints), and  $t_!$  preserves and reflects connected limits.

This construction extends to a fully faithful functor  $\text{PolyEnd}(I) \rightarrow \text{Cart}(\text{Set}/I)$ , the latter being the category of endofunctors of  $\text{Set}/I$  and cartesian natural transformations<sup>(2)</sup>. In fact, the image of this full embedding consists precisely of those endofunctors that preserve connected limits [GK13, section 1.18]. The composition of endofunctors gives  $\text{Cart}(\text{Set}/I)$  the structure of a monoidal category, and  $\text{PolyEnd}(I)$  is stable under this monoidal product [GK13, proposition 1.12]. The identity polynomial functor  $I \leftarrow I \rightarrow I \rightarrow I$  is associated to the identity endofunctor; thus  $\text{PolyEnd}(I)$  is a monoidal subcategory of  $\text{Cart}(\text{Set}/I)$ .

A *polynomial monad over  $I$*  is a monoid in  $\text{PolyEnd}(I)$ . Note that a polynomial monad over  $I$  is thus necessarily a cartesian monad on  $\text{Set}/I$ .<sup>(3)</sup>

**2.2. Trees.** A polynomial functor  $T = \left( T_0 \xleftarrow{s} T_2 \xrightarrow{p} T_1 \xrightarrow{t} T_0 \right)$  is a (*polynomial*) *tree* [Koc11, section 1.0.3] if

- (1) the sets  $T_0$ ,  $T_1$  and  $T_2$  are finite (in particular, each node has finitely many inputs);
- (2) the map  $t$  is injective;
- (3) the map  $s$  is injective, and the complement of its image  $T_0 - \text{im } s$  has a single element, called the *root*;
- (4) let  $T_0 = T_2 + \{r\}$ , with  $r$  the root, and define the *walk-to-root* function  $\sigma$  by  $\sigma(r) = r$ , and otherwise  $\sigma(e) = tp(e)$ ; then we ask that for all  $x \in T_0$ , there exists  $k \in \mathbb{N}$  such that  $\sigma^k(x) = r$ .

We call the colours of a tree its *edges* and the inputs of a node the *input edges* of that node.

Let  $\text{Tree}$  be the full subcategory of  $\text{PolyEnd}$  whose objects are trees. Note that it is the category of *symmetric* or *non-planar* trees (the automorphism group of a tree is in general non-trivial) and that its morphisms correspond to inclusions of non-planar subtrees. An *elementary tree* is a tree with at most one node. Let  $el\text{Tree}$  be the full subcategory of  $\text{Tree}$  spanned by elementary trees.

<sup>(2)</sup>We recall that a natural transformation is *cartesian* if all its naturality squares are cartesian.

<sup>(3)</sup>We recall that a monad is *cartesian* if its endofunctor preserves pullbacks and its unit and multiplication are cartesian natural transformations.

For  $P \in \text{PolyEnd}$ , the category  $\text{tr } P$  of  $P$ -trees is the comma category  $\mathcal{T}\text{ree} \downarrow P$ . The fundamental difference between  $\mathcal{T}\text{ree}$  and  $\text{tr } P$  is that the latter is always rigid i.e. it has no non-trivial automorphisms [Koc11, proposition 1.2.3]. In particular, this implies that  $\text{PolyEnd}$  does not have a terminal object.

Let us introduce some notation. Every  $P$ -tree  $T \in \text{tr } P$  corresponds to a morphism from a tree (which we shall denote by  $\langle T \rangle$ ) to  $P$ , so that  $T : \langle T \rangle \rightarrow P$ . We point out that  $\langle T \rangle_1$  is the set of nodes of  $\langle T \rangle$ , while  $T_1 : \langle T \rangle_1 \rightarrow P_1$  is a decoration of the nodes of  $\langle T \rangle$  by nodes of  $P$ , and likewise for edges.

For  $P \in \text{PolyEnd}$ , its *category of elements*<sup>(4)</sup>  $\text{elt } P$  is the comma category  $\text{el}\mathcal{T}\text{ree} \downarrow P$ . Explicitly, for  $P$  as in equation (2.1.1), the set of objects of  $\text{elt } P$  is  $I + B$ , and for each  $b \in B$ , there is a morphism  $t : t(b) \rightarrow b$ , and a morphism  $s_e : s_e(b) \rightarrow b$  for each  $e \in E(b)$ . Remark that there is no non-trivial composition of arrows in  $\text{elt } P$ .

**Proposition 2.2.1** ([Koc11, proposition 2.1.3]). *There is an equivalence of categories  $\mathcal{P}\text{sh}(\text{elt } P) \simeq \text{PolyEnd}/P$ .*

*Proof.* For  $X \in \mathcal{P}\text{sh}(\text{elt } P)$ , construct the following polynomial functor over  $P$ :

$$\begin{array}{ccccccc} \sum_{i \in I} X_i & \longleftarrow & E_X & \longrightarrow & \sum_{b \in B} X_b & \longrightarrow & \sum_{i \in I} X_i \\ \downarrow & & \downarrow & \lrcorner & \downarrow & & \downarrow \\ I & \longleftarrow & E & \longrightarrow & B & \longrightarrow & I, \end{array}$$

where  $E_X \rightarrow \sum_{i \in I} X_i$  is given by the maps  $X_{s_e} : X_b \rightarrow X_{s_e b}$ , for  $b \in B$  and  $e \in E(b)$ . In the other direction, note that the full inclusion  $\text{el}\mathcal{T}\text{ree} \hookrightarrow \text{PolyEnd}$  induces a full inclusion  $\iota : \text{elt } P \hookrightarrow \text{PolyEnd}/P$  whose nerve functor  $\text{PolyEnd}/P \rightarrow \mathcal{P}\text{sh}(\text{elt } P)$  maps  $Q \in \text{PolyEnd}/P$  to  $\text{PolyEnd}/P(\iota-, Q)$ . The two constructions are easily seen to define the required equivalence of categories.  $\square$

**2.3. Addresses.** Let  $T \in \mathcal{T}\text{ree}$  be a polynomial tree and  $\sigma$  be its walk-to-root function. We define the *address* function  $\&$  inductively on edges as follows:

- (1) if  $r$  is the root edge, let  $\&r := []$ ,
- (2) if  $e \in T_0 - \{r\}$  and if  $\&\sigma(e) = [x]$ , define  $\&e := [xe]$ .

The address of a node  $b \in T_1$  is defined as  $\&b := \&tb$ . Note that this function is injective since  $t$  is. Let  $T^\bullet$  denote its image, the set of *node addresses* of  $T$ , and let  $T^\dagger$  be the set of addresses of leaf edges, i.e. those not in the image of  $t$ .

Assume now that  $T : \langle T \rangle \rightarrow P$  is a  $P$ -tree. If  $b \in \langle T \rangle_1$  has address  $\&b = [p]$ , write  $s_{[p]} T := T_1(b)$ . For convenience, we let  $T^\bullet := \langle T \rangle^\bullet$ , and  $T^\dagger := \langle T \rangle^\dagger$ .

*Remark 2.3.1.* The formalism of addresses is a useful bookkeeping syntax for the operations of grafting and substitution on trees. The syntax of addresses will extend to the category of opetopes and will allow us to give a precise description of the composition of morphisms in the category of opetopes (see definition 3.3.2) as well as certain constructions on opetopic sets.

**2.4. Grafting.** Let  $P$  be a polynomial endofunctor as in equation (2.1.1). For  $i \in I$ , define  $\mathfrak{l}_i \in \text{tr } P$  as having underlying tree

$$\{i\} \longleftarrow \emptyset \longrightarrow \emptyset \longrightarrow \{i\}, \quad (2.4.1)$$

along with the obvious morphism to  $P$ . This corresponds to a tree with no nodes and a unique edge decorated by  $i$ . Define  $Y_b \in \text{tr } P$ , the *corolla* at  $b$ , as having underlying tree

$$s(E(b)) + \{*\} \longleftarrow E(b) \longrightarrow \{b\} \longrightarrow s(E(b)) + \{*\}, \quad (2.4.2)$$

<sup>(4)</sup>Not to be confused with the category of elements of a presheaf over some category.



where the right map sends  $b$  to  $*$ . This corresponds to a  $P$ -tree with a unique node, decorated by  $b$ . Observe that for  $T \in \text{tr } P$ , giving a morphism  $l_i \rightarrow T$  is equivalent to specifying the address  $[p]$  of an edge address of  $T$  decorated by  $i$ . Likewise, morphisms of the form  $Y_b \rightarrow T$  are in bijection with addresses of nodes of  $T$  decorated by  $b$ .

For  $S, T \in \text{tr } P$ ,  $[l] \in S^{\downarrow}$  such that the leaf of  $S$  at  $[l]$  and the root edge of  $T$  are decorated by the same  $i \in I$ , define the *grafting*  $S \circ_{[l]} T$  of  $S$  and  $T$  on  $[l]$  by the following pushout (in  $\text{tr } P$ ):

$$\begin{array}{ccc} l_i & \xrightarrow{[]}& T \\ [l] \downarrow & \lrcorner & \downarrow \\ S & \longrightarrow & S \circ_{[l]} T. \end{array} \quad (2.4.3)$$

Note that if  $S$  (resp.  $T$ ) is a trivial tree, then  $S \circ_{[l]} T = T$  (resp.  $= S$ ). We assume, by convention, that the grafting operator  $\circ$  associates to the right.

**Proposition 2.4.4** ([Koc11, proposition 1.1.21]). *Every  $P$ -tree is either of the form  $l_i$ , for some  $i \in I$ , or obtained by iterated graftings of corollas.*

Take  $T, U_1, \dots, U_k \in \text{tr } P$ , where  $T^{\downarrow} = \{[l_1], \dots, [l_k]\}$ , and assume the grafting  $T \circ_{[l_i]} U_i$  is defined for all  $i$ . Then the *total grafting* will be denoted concisely by

$$T \bigcirc_{[l_i]} U_i = (\dots (T \circ_{[l_1]} U_1) \circ_{[l_2]} U_2 \dots) \circ_{[l_k]} U_k. \quad (2.4.5)$$

It is easy to see that the result does not depend on the order in which the graftings are performed.

Let  $[p] \in T^{\bullet}$  and  $b = s_{[p]} T$ . Then  $T$  can be decomposed as

$$T = A \circ_{[p]} Y_b \bigcirc_{[e_i]} B_i, \quad (2.4.6)$$

where  $E(b) = \{e_1, \dots, e_k\}$ , and  $A, B_1, \dots, B_k \in \text{tr } P$ . For  $U$  a  $P$ -tree with a bijection  $\wp : U^{\downarrow} \rightarrow E(b)$  over  $I$ , we define the *substitution*  $T \sqsupset_{[p]} U$  as

$$T \sqsupset_{[p]} U := A \circ_{[p]} U \bigcirc_{\wp^{-1}e_i} B_i. \quad (2.4.7)$$

In other words, the node at address  $[p]$  in  $T$  has been replaced by  $U$ , and the map  $\wp$  provided “rewiring instructions” to connect the leaves of  $U$  to the rest of  $T$ .

We denote by  $\text{tr}^{\downarrow} P$  the set of  $P$ -trees with a marked leaf, i.e. endowed with the address of one of its leaves. Similarly, we denote by  $\text{tr}^{\bullet} P$  the set of  $P$ -trees with a marked node.

**2.5. Polynomial monads.** Recall that a polynomial monad over  $I \in \text{Set}$  is a monoid in the monoidal category  $\text{PolyEnd}(I)$ . Let  $\text{PolyMnd}(I)$  be the category of monoids in  $\text{PolyEnd}(I)$ . That is,  $\text{PolyMnd}(I)$  is the category of polynomial monads over  $I$  and morphisms of polynomial functors over  $I$  that are also monad morphisms.

Given a polynomial endofunctor  $P$  as in equation (2.1.1), we can define a new polynomial functor  $P^*$  as

$$I \xleftarrow{s} \text{tr}^{\downarrow} P \xrightarrow{p} \text{tr } P \xrightarrow{t} I \quad (2.5.1)$$

where  $s$  maps a  $P$ -tree with a marked leaf to the decoration of that leaf,  $p$  forgets the marking, and  $t$  maps a tree to the decoration of its root. Remark that for  $T \in \text{tr } P$  we have  $p^{-1}T = T^{\downarrow}$ .

**Theorem 2.5.2** ([Koc11, section 1.2.7], [KJBM10, sections 2.7 – 2.9]). *The polynomial functor  $P^*$  has a canonical structure of a polynomial monad. Furthermore, the functor  $(-)^*$  is left adjoint to the forgetful functor  $\text{PolyMnd}(I) \rightarrow \text{PolyEnd}(I)$ , and the adjunction is monadic.*

We abuse notation slightly by letting  $(-)^*$  denote the associated monad on  $\text{PolyEnd}(I)$ . Let  $M$  be a polynomial monad as in equation (2.1.1):

$$I \xleftarrow{s} E \xrightarrow{p} B \xrightarrow{t} I,$$

As a polynomial monad,  $M$  is a  $(-)^*$ -algebra, and we will write its structure map  $M^* \rightarrow M$  as

$$\begin{array}{ccccc} I & \longleftarrow & \text{tr}^\perp M & \longrightarrow & \text{tr} M & \longrightarrow & I \\ \parallel & & \wp \downarrow & \lrcorner & \downarrow \mathfrak{t} & & \parallel \\ I & \longleftarrow & E & \longrightarrow & B & \longrightarrow & I. \end{array} \quad (2.5.3)$$

For  $T \in \text{tr} M$ , we call  $\wp_T : T^\perp \xrightarrow{\cong} E(\mathfrak{t}T)$  the *readdressing* function of  $T$ , and  $\mathfrak{t}T \in B$  is called the *target* of  $T$ . If we think of an element  $b \in B$  as the corolla  $\mathcal{Y}_b$ , then the target map  $\mathfrak{t}$  “contracts” a tree to a corolla, and since the middle square is a pullback, the number of leaves is preserved. The map  $\wp_T$  establishes a coherent correspondence between the set  $T^\perp$  of leaf addresses of a tree  $T$  and the elements of  $E(T)$ .

**2.6. The polynomial Baez–Dolan  $(-)^+$  construction.** Let  $M$  be a polynomial monad as in equation (2.1.1), and define  $M^+$  to be

$$B \xleftarrow{s} \text{tr}^\bullet M \xrightarrow{p} \text{tr} M \xrightarrow{t} B \quad (2.6.1)$$

where  $s$  maps an  $M$ -tree with a marked node to the label of that node,  $p$  forgets the marking, and  $\mathfrak{t}$  is the target map. If  $T \in \text{tr} M$ , remark that  $p^{-1}T = T^\bullet$  is the set of node addresses of  $T$ . If  $[p] \in T^\bullet$ , then  $s[p] := s_{[p]} T$ .

**Theorem 2.6.2** ([KJBM10, section 3.2]). *The polynomial functor  $M^+$  has a canonical structure of a polynomial monad.*

The  $(-)^+$  construction is an endofunctor on  $\text{PolyMnd}$  whose definition is motivated as follows. If we begin with a polynomial monad  $M$ , then the colours of  $M^+$  are the operations of  $M$ . The operations of  $M^+$ , along with their output colour, are given by the monad multiplication of  $M$ : they are the *relations* of  $M$ , i.e. the reductions of trees of  $M$  to operations of  $M$ . The monad multiplication on  $M^+$  is given as follows: the reduction of a tree of  $M^+$  to an operation of  $M^+$  (which is a tree of  $M$ ) is obtained by *substituting* trees of  $M$  into nodes of trees of  $M$ .

Let  $M$  be a finitary (i.e. the fibers of  $p$  below are finite, or equivalently,  $p_*$ , and therefore  $M = t \circ p_* \circ s^*$ , preserves filtered colimits) polynomial monad whose underlying polynomial functor is

$$I \xleftarrow{s} E \xrightarrow{p} B \xrightarrow{t} I.$$

The Baez–Dolan construction gives the polynomial monad  $M^+$  whose underlying polynomial functor is

$$B \xleftarrow{s} \text{tr}^\bullet M \xrightarrow{p} \text{tr} M \xrightarrow{t} B.$$

Recall also from theorem 2.5.2 that the category  $\text{PolyMnd}(I)$  is the category of  $(-)^*$ -algebras. The following fact is analogous to proposition 2.2.1 and is at the heart of the Baez–Dolan construction (indeed, it is even the original *definition* of the construction, see [BD98, definition 15]).

**Proposition 2.6.3.** *For  $M$  a polynomial monad, there is an equivalence of categories  $\text{Alg}(M^+) \simeq \text{PolyMnd}(I)/M$ .*

*Proof.* Given a  $M^+$ -algebra  $M^+X \xrightarrow{x} X$  in  $\text{Set}/B$ , define  $\Phi X \in \text{PolyEnd}(I)/M$  as

$$\begin{array}{ccccccc} I & \longleftarrow & E_X & \longrightarrow & X & \longrightarrow & I \\ \parallel & & \downarrow & \lrcorner & \downarrow & & \parallel \\ I & \longleftarrow & E & \longrightarrow & B & \longrightarrow & I. \end{array}$$

There is an evident bijection  $\text{tr } \Phi X \cong M^+X$  in  $\text{Set}/I$ , and the structure map  $x$  extends by pullback along  $E_X \rightarrow X$  to a map  $(\Phi X)^* \rightarrow \Phi X$  in  $\text{PolyEnd}(I)$ . It is easy to verify that this determines a  $(-)^*$ -algebra structure on  $\Phi X$ , and that the map  $\Phi X \rightarrow M$  in  $\text{PolyEnd}(I)$  is a morphism of  $(-)^*$ -algebras. Conversely, given an  $N \in \text{PolyMnd}(I)/M$  whose underlying polynomial functor is

$$I \longleftarrow E' \longrightarrow B' \longrightarrow I,$$

then the bijection  $\text{tr } N \cong M^+B'$  in  $\text{Set}/I$  and the  $(-)^*$ -algebra map  $N^* \rightarrow N$  provide a map  $M^+B' \xrightarrow{\Psi N} B'$  in  $\text{Set}/I$ . It is easy to verify that  $\Psi N$  is the structure map of a  $M^+$ -algebra and that the constructions  $\Phi$  and  $\Psi$  are functorial and mutually inverse.  $\square$

*Remark 2.6.4.* The previous result provides an equivalence between  $\text{PolyMnd}(I)/M$  and the category of  $M^+$ -algebras. A ‘‘coloured’’ version of this result can be (informally) stated as follows: for  $\text{Alg}^{\text{col}}(M^+)$  a suitable category of coloured  $M^+$ -algebras, there is an equivalence  $\text{Alg}^{\text{col}}(M^+) \simeq \text{PolyMnd}/M$ , where  $\text{PolyMnd}$  is the category of all polynomial monads (for all  $I$  in  $\text{Set}$ ).

### 3. OPETOPES

In this section, we use the formalism of polynomial functors and polynomial monads of section 2 to define opetopes and morphisms between them. This gives us a category  $\mathbb{O}$  of opetopes and a category  $\text{Psh}(\mathbb{O})$  of opetopic sets. Our construction of opetopes is precisely that of [KJBM10], and by [KJBM10, theorem 3.16], also that of [Lei04, Lei98], and by [Che04b, corollary 2.6], also that of [Che03]. As we will see, the category  $\mathbb{O}$  is rigid, i.e. it has no non-trivial automorphisms (it is in fact a *direct* category).

**3.1. Polynomial definition of opetopes.** Let  $\mathfrak{Z}^0$  be the identity polynomial monad on  $\text{Set}$ :

$$\{*\} \longleftarrow \{*\} \longrightarrow \{*\} \longrightarrow \{*\},$$

and let  $\mathfrak{Z}^n := (\mathfrak{Z}^{n-1})^+$ . Write  $\mathfrak{Z}^n$  as

$$\mathbb{O}_n \xleftarrow{\mathfrak{s}} E_{n+1} \xrightarrow{\mathfrak{p}} \mathbb{O}_{n+1} \xrightarrow{\mathfrak{t}} \mathbb{O}_n. \quad (3.1.1)$$

An  $n$ -dimensional opetope (or simply  $n$ -opetope)  $\omega$  is by definition an element of  $\mathbb{O}_n$ , and we write  $\dim \omega = n$ . The unique 0-opetope is denoted  $\blacklozenge$  and called the *point*, and the unique 1-opetope is denoted  $\blacksquare$  and called the *arrow*.

If  $n \geq 2$ , then  $\omega \in \mathbb{O}_n$  is a  $\mathfrak{Z}^{n-2}$ -tree, i.e. a tree whose nodes are labeled in  $(n-1)$ -opetopes, and edges are labeled in  $(n-2)$ -opetopes. In particular, 2-opetopes are  $\mathfrak{Z}^0$ -trees, i.e. linear trees, and thus in bijection with  $\mathbb{N}$ . We will refer to them as *opetopic integers*, and write  $\mathbf{n}$  for the 2-opetope having exactly  $n$  nodes. An opetope  $\omega \in \mathbb{O}_n$  with  $n \geq 2$  is called *degenerate* if its underlying tree has no nodes (thus consists of a unique edge); it is *non degenerate* otherwise.

Following (2.5.3), for  $\omega \in \mathbb{O}_{n+2}$ , the structure of polynomial monad  $(\mathfrak{Z}^n)^* \rightarrow \mathfrak{Z}^n$  gives a bijection  $\wp_\omega : \omega^\downarrow \rightarrow (\mathfrak{t}\omega)^\bullet$  between the leaves of  $\omega$  and the nodes of  $\mathfrak{t}\omega$ , preserving the decoration by  $n$ -opetopes.

**3.2. Higher addresses.** By definition, an opetope  $\omega$  of dimension  $n \geq 2$  is a  $\mathfrak{Z}^{n-2}$ -tree, and thus the formalism of tree addresses presented in section 2.3 can be applied to designate nodes of  $\omega$ , also called its *source faces* or simply *sources*. In this section, we refine this formalism into the concept of *higher dimensional address*, which turns out to be more convenient. This material is largely taken from [CHTM19, section 2.2.3].

Start by defining the set  $\mathbb{A}_n$  of *n-addresses* as follows:

$$\mathbb{A}_0 = \{*\}, \quad \mathbb{A}_{n+1} = \text{lists } \mathbb{A}_n,$$

where lists  $X$  is the set of finite lists (or words) on the alphabet  $X$ . Explicitly, the unique 0-address is  $*$  (also written  $[]$  by convention), while an  $(n+1)$ -address is a sequence of  $n$ -addresses. Such sequences are enclosed by brackets. Note that the address  $[]$ , associated to the empty word, is in  $\mathbb{A}_n$  for all  $n \geq 0$ . However, the surrounding context will almost always make the notation unambiguous. Here are examples of higher addresses:

$$[] \in \mathbb{A}_1, \quad [***] \in \mathbb{A}_1, \quad [[][*]()] \in \mathbb{A}_2, \quad [[[[*]]]] \in \mathbb{A}_4.$$

For  $\omega \in \mathbb{O}$  an opetope, nodes of  $\omega$  can be specified uniquely using higher addresses, as we now show. Recall that  $E_{n-1}$  is the set of arities of  $\mathfrak{Z}^{n-2}$ , see (3.1.1). In  $\mathfrak{Z}^0$ , set  $E_1(\blacksquare) = \{*\}$ , so that the unique node address of  $\blacksquare$  is  $*$  in  $\mathbb{A}_0$ . For  $n \geq 2$ , recall that an opetope  $\omega \in \mathbb{O}_n$  is a  $\mathfrak{Z}^{n-2}$ -tree  $\omega : \langle \omega \rangle \rightarrow \mathfrak{Z}^{n-2}$ , and write  $\langle \omega \rangle$  as

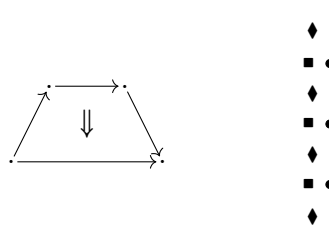
$$I_\omega \longleftarrow E_\omega \longrightarrow B_\omega \longrightarrow I_\omega.$$

A node  $b \in B_\omega$  has an address  $\&b \in \text{lists } E_\omega$ , which by  $\omega_2 : E_\omega \rightarrow E_{n-1}$  is mapped to an element of lists  $E_{n-1}$ . By induction, elements of  $E_{n-1}$  are  $(n-2)$ -addresses, whence  $\omega_2(\&b) \in \text{list } \mathbb{A}_{n-2} = \mathbb{A}_{n-1}$ . For the induction step, elements of  $E_n(\omega)$  are nodes of  $\langle \omega \rangle$ , which we identify by their aforementioned  $(n-1)$ -addresses. Consequently, for all  $n \geq 1$  and  $\omega \in \mathbb{O}_n$ , elements of  $E_n(\omega) = \omega^\bullet$  can be seen as the set of  $(n-1)$ -addresses of the nodes of  $\omega$ , and similarly,  $\omega^\downarrow$  can be seen as the set of  $(n-1)$ -addresses of edges of  $\omega$ .

We now identify the nodes of  $\omega \in \mathbb{O}_{n+2}$  with their addresses. In particular, for  $[p] \in \omega^\bullet$  a node address of  $\omega$ , we make use of the notation  $\mathfrak{s}_{[p]}\omega$  of section 2.2 to refer to the decoration of the node at address  $[p]$ , which is an  $(n+1)$ -opetope. Let  $[l] = [p[q]] \in \mathbb{A}_{n-1}$  be an address such that  $[p] \in \omega^\bullet$  and  $[q] \in (\mathfrak{s}_{[p]}\omega)^\bullet$ . Then as a shorthand, we write

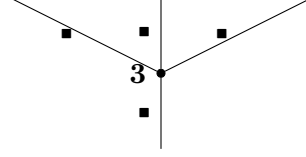
$$\mathfrak{e}_{[l]}\omega := \mathfrak{s}_{[q]}\mathfrak{s}_{[p]}\omega. \quad (3.2.1)$$

**Example 3.2.2.** Consider the 2-opetope on the left, called **3**:



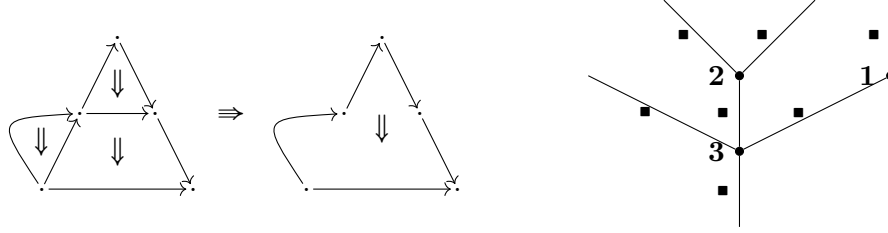
Its underlying pasting diagram consists of 3 arrows  $\blacksquare$  grafted linearly. Since the only node address of  $\blacksquare$  is  $*$  in  $\mathbb{A}_0$ , the underlying tree of **3** can be depicted as on the right. On the left are the decorations: nodes are decorated with  $\blacksquare \in \mathbb{O}_1$ , while the edges are decorated with  $\blacklozenge \in \mathbb{O}_0$ . For each node in the tree, the set of input edges of that node is in bijective correspondence with the node addresses of the decorating opetope, and that address is written on the right of each edges. In this low dimensional example, those addresses can only be  $*$ . Finally, on the right of each node is its 1-address, which is just a sequence of 0-addresses giving “walking instructions” to get from the root to that node.

The 2-opetope **3** can then be seen as a corolla in some 3-opetope as follows:



As previously mentioned, the set of input edges is in bijective correspondence with the set of node addresses of **3**.

Here is now an example of a 3-opetope, with its annotated underlying tree on the right (the 2-opetopes **1** and **2** are analogous to **3**):



**Lemma 3.2.3.** *Let  $n \geq 2$ ,  $\nu, \nu' \in \mathbb{O}_n$ , and  $[l] \in \nu^\bullet$  be such that  $e_{[l]} \nu = e_{[]} \nu'$ . In particular, the grafting  $\nu \circ_{[l]} \nu'$  is well-defined, and by **(Glob1)** and **(Glob2)**,  $s_{\wp_\nu[l]} t\nu = e_{[l]} \nu = e_{[]} \nu' = tt\nu'$ . We have*

$$t(\nu \circ_{[l]} \nu') = (t\nu) \square_{\wp_\nu[l]} (t\nu').$$

*Proof.* This is a direct consequence of the fact that  $\mathfrak{Z}^{n-2}$  is a polynomial monad, i.e. a  $(-)^*$ -algebra.  $\square$

**3.3. The category of opetopes.** In this subsection, we define the category  $\mathbb{O}$  of opetopes, originally introduced in [HT18].

**Proposition 3.3.1** (Opetopic identities, [HT18, theorem 4.1]). *Let  $\omega \in \mathbb{O}_n$  with  $n \geq 2$ .*

- (1) (Inner edge) For  $[p[q]] \in \omega^\bullet$  (forcing  $\omega$  to be non degenerate), we have  $ts_{[p[q]]}\omega = s_{[q]}s_{[p]}\omega$ .
- (2) (Globularity 1) If  $\omega$  is non degenerate, we have  $ts_{[]} \omega = tt\omega$ .
- (3) (Globularity 2) If  $\omega$  is non degenerate, and  $[p[q]] \in \omega^!$ , we have  $s_{[q]}s_{[p]}\omega = s_{\wp_\omega[p[q]]}t\omega$ .
- (4) (Degeneracy) If  $\omega$  is degenerate, we have  $s_{[]}t\omega = tt\omega$ .

**Definition 3.3.2** ([HT18, section 4.2]). With these identities in mind, we define the category  $\mathbb{O}$  of opetopes by generators and relations as follows.

- (1) (Objects) We set  $\text{ob } \mathbb{O} = \sum_{n \in \mathbb{N}} \mathbb{O}_n$ .
- (2) (Generating morphisms) Let  $\omega \in \mathbb{O}_n$  with  $n \geq 1$ . We introduce a generator  $t\omega \xrightarrow{t} \omega$ , called the *target embedding*. If  $[p] \in \omega^\bullet$ , then we introduce a generator  $s_{[p]}\omega \xrightarrow{s_{[p]}} \omega$ , called a *source embedding*. A *face embedding* is either a source or the target embedding.
- (3) (Relations) We impose 4 relations described by the following commutative squares, that are well defined thanks to proposition 3.3.1. Let  $\omega \in \mathbb{O}_n$  with  $n \geq 2$ 
  - (a) (**Inner**) for  $[p[q]] \in \omega^\bullet$  (forcing  $\omega$  to be non degenerate), the following square must commute:

$$\begin{array}{ccc} s_{[q]}s_{[p]}\omega & \xrightarrow{s_{[q]}} & s_{[p]}\omega \\ t \downarrow & & \downarrow s_{[p]} \\ s_{[p[q]]}\omega & \xrightarrow{s_{[p[q]]}} & \omega \end{array}$$

(b) **(Glob1)** if  $\omega$  is non degenerate, the following square must commute:

$$\begin{array}{ccc} \mathbf{t} \mathbf{t} \omega & \xrightarrow{\mathbf{t}} & \mathbf{t} \omega \\ \mathbf{t} \downarrow & & \downarrow \mathbf{t} \\ \mathbf{s}[\ ] \omega & \xrightarrow{\mathbf{s}[\ ]} & \omega. \end{array}$$

(c) **(Glob2)** if  $\omega$  is non degenerate, and for  $[p[q]] \in \omega^\perp$ , the following square must commute:

$$\begin{array}{ccc} \mathbf{s}_{\wp\omega[p[q]]} \mathbf{t} \omega & \xrightarrow{\mathbf{s}_{\wp\omega[p[q]]}} & \mathbf{t} \omega \\ \mathbf{s}_{[q]} \downarrow & & \downarrow \mathbf{t} \\ \mathbf{s}_{[p]} \omega & \xrightarrow{\mathbf{s}_{[p]}} & \omega. \end{array}$$

(d) **(Degen)** if  $\omega$  is degenerate, the following square must commute:

$$\begin{array}{ccc} \mathbf{t} \mathbf{t} \omega & \xrightarrow{\mathbf{t}} & \mathbf{t} \omega \\ \mathbf{s}[\ ] \downarrow & & \downarrow \mathbf{t} \\ \mathbf{t} \omega & \xrightarrow{\mathbf{t}} & \omega. \end{array}$$

See [HT18] for a graphical explanation of a geometrical interpretation of those relations.

For  $n \in \mathbb{N}$ , we let  $\mathbb{O}_{\leq n}$  be the full subcategory of  $\mathbb{O}$  spanned by opetopes of dimension at most  $n$ . The subcategories  $\mathbb{O}_{< n}$ ,  $\mathbb{O}_{\geq n}$ ,  $\mathbb{O}_{> n}$ , and  $\mathbb{O}_{=n}$  are defined similarly. Note that the latter is simply the set  $\mathbb{O}_n$ .

**3.4. Opetopic sets.** Write  $\mathcal{Psh}(\mathbb{O})$  for the category of opetopic sets, i.e. Set-valued presheaves over  $\mathbb{O}$ . For  $X \in \mathcal{Psh}(\mathbb{O})$  and  $\omega \in \mathbb{O}$ , we will refer to the elements of the set  $X_\omega$  as the *cells* of  $X$  of form  $\omega$ . The representable presheaf at  $\omega \in \mathbb{O}_n$  is denoted  $O[\omega]$ . Its cells are morphisms of  $\mathbb{O}$  of the form  $\mathbf{f} : \psi \longrightarrow \omega$ , for  $\mathbf{f}$  a sequence of face embeddings, which we write  $\mathbf{f}\omega \in O[\omega]_\psi$  for short. For instance, the cell of maximal dimension is simply  $\omega$  (as the corresponding sequence of face embeddings is empty), its  $(n-1)$ -cells are  $\{\mathbf{s}_{[p]} \omega \mid [p] \in \omega^\bullet\} \cup \{\mathbf{t}\omega\}$ , and there is no cell of dimension  $> n$ . The *boundary*  $\partial O[\omega]$  of  $\omega$  is the maximal subpresheaf of  $O[\omega]$  not containing the cell  $\omega$ . We write  $\mathbf{b}_\omega : \partial O[\omega] \hookrightarrow O[\omega]$  for the *boundary inclusion*. The *target horn*  $\Lambda^\mathbf{t}[\omega]$  is the maximal subpresheaf of  $\partial O[\omega]$  not containing the cell  $\mathbf{t}\omega$ , and we write  $\mathbf{h}_\omega : \Lambda^\mathbf{t}[\omega] \hookrightarrow O[\omega]$  for the *target horn inclusion*.

**Lemma 3.4.1.** *For  $\omega \in \mathbb{O}$ , with  $\dim \omega \geq 1$  the following square is a pushout and a pullback<sup>(5)</sup>, where all arrows are canonical inclusions:*

$$\begin{array}{ccc} \partial O[\mathbf{t}\omega] & \longrightarrow & \Lambda^\mathbf{t}[\omega] \\ \downarrow & & \downarrow \\ O[\mathbf{t}\omega] & \longrightarrow & \partial O[\omega]. \end{array}$$

<sup>(5)</sup>Recall that in a topos, the pushout of a monomorphism along any arrow is a monomorphism, and the pushout square is a pullback square – this property is sometimes called “adhesivity”, and is a consequence of van Kampen-ness, or descent, for pushouts of monomorphisms.

**Lemma 3.4.2.** *Let  $n \geq 1$ ,  $\nu \in \mathbb{O}_n$ ,  $[l] \in \nu^\downarrow$ , and  $\psi \in \mathbb{O}_{n-1}$  be such that  $\mathbf{e}_{[l]} \nu = \mathbf{t} \psi$ , so that the grafting  $\nu \circ_{[l]} \mathbf{Y}_\psi$  is well-defined. Then the following square is a pushout:*

$$\begin{array}{ccc} O[\mathbf{e}_{[l]} \nu] & \xrightarrow{\mathbf{t}} & O[\psi] \\ \mathbf{e}_{[l]} \downarrow & & \downarrow \mathbf{s}_{[l]} \\ \Lambda^{\mathbf{t}}[\nu] & \longrightarrow & \Lambda^{\mathbf{t}}[\nu \circ_{[l]} \mathbf{Y}_\psi]. \end{array}$$

We now introduce notations for important sets of morphisms:

$$\mathbf{B} := \{ \mathbf{b}_\omega : \partial O[\omega] \hookrightarrow O[\omega] \mid \omega \in \mathbb{O} \}, \quad (3.4.3)$$

$$\mathbf{H} := \{ \mathbf{h}_\omega : \Lambda^{\mathbf{t}}[\omega] \hookrightarrow O[\omega] \mid \omega \in \mathbb{O} \}, \quad (3.4.4)$$

$$\mathbf{O} := \{ \mathbf{o}_\omega : \emptyset \hookrightarrow O[\omega] \mid \omega \in \mathbb{O} \}. \quad (3.4.5)$$

For  $F : \mathbb{O} \rightarrow \text{hom } \mathcal{C}$  a function that maps opetopes to morphisms in some category  $\mathcal{C}$ , and  $\mathbf{M}$  the set of maps defined by  $\mathbf{M} := \{ F(\omega) \mid \omega \in \mathbb{O} \}$ . Then for  $n \in \mathbb{N}$ , we define  $\mathbf{M}_{\geq n} := \{ F(\omega) \mid \omega \in \mathbb{O}_{\geq n} \}$ , and similarly for  $\mathbf{M}_{>n}$ ,  $\mathbf{M}_{\leq n}$ ,  $\mathbf{M}_{<n}$ , and  $\mathbf{M}_{=n}$ . For convenience, the latter is abbreviated  $\mathbf{M}_n$ . If  $m \leq n$ , we also let  $\mathbf{M}_{m,n} = \mathbf{M}_{\geq m} \cap \mathbf{M}_{\leq n}$ . By convention,  $\mathbf{M}_{\leq n} = \emptyset$  if  $n < 0$ . For example,  $\mathbf{H}_{\geq 2} = \{ \mathbf{h}_\omega \mid \omega \in \mathbb{O}_{\geq 2} \}$ , and  $\mathbf{H}_{n,n+1} = \mathbf{H}_n \cup \mathbf{H}_{n+1}$ . With those notations in mind, let

$$\mathbf{A}_{k,n} := \mathbf{O}_{<n-k} \cup \mathbf{H}_{\geq n+1}. \quad (3.4.6)$$

**Lemma 3.4.7.** (1) *Let  $X \in \mathcal{P}\text{sh}(\mathbb{O})$  such that  $\mathbf{H}_{n,n+1} \perp X$ . Then  $\mathbf{B}_{n+1} \perp X$ . In general, every morphism in  $\mathbf{B}_{\geq n+1}$  is an  $\mathbf{H}_{\geq n}$ -local isomorphism.*

(2) *Let  $X \in \mathcal{P}\text{sh}(\mathbb{O})$  such that  $(\mathbf{H}_{n,n+1} \cup \mathbf{B}_{n+2}) \perp X$ . Then  $\mathbf{H}_{n+2} \perp X$ . In particular, if  $(\mathbf{H}_{n,n+1} \cup \mathbf{B}_{\geq n+2}) \perp X$ , then  $\mathbf{H}_{\geq n} \perp X$ .*

*Proof.* (1) Let  $\omega \in \mathbb{O}_{n+1}$ . By 2-for-3, since the composite  $\mathbf{h}_\omega : \Lambda^{\mathbf{t}}[\omega] \hookrightarrow \partial O[\omega] \hookrightarrow O[\omega]$  is in  $\mathbf{H}_{n,n+1}$ , it suffices to show that  $(\Lambda^{\mathbf{t}}[\omega] \hookrightarrow \partial O[\omega]) \perp X$ . Let  $f : \Lambda^{\mathbf{t}}[\omega] \rightarrow X$  be a morphism. The existence of a lift  $\partial O[\omega] \rightarrow X$  follows from the existence of a lift  $O[\omega] \rightarrow X$ . Next, given two lifts  $g, h : \partial O[\omega] \rightarrow X$  of  $f$ , by lemma 3.4.1, it suffices to show that they coincide on  $O[\mathbf{t}\omega]$  to show that they are equal. But since they coincide on  $\Lambda^{\mathbf{t}}[\omega]$ , they coincide on  $\Lambda^{\mathbf{t}}[\mathbf{t}\omega]$ , and hence on  $O[\mathbf{t}\omega]$  since  $\mathbf{h}_{\mathbf{t}\omega} \perp X$ .

(2) Let  $\omega \in \mathbb{O}_{n+2}$  and  $f : \Lambda^{\mathbf{t}}[\omega] \rightarrow X$ . Then the restriction  $f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}$  of  $f$  to  $\Lambda^{\mathbf{t}}[\mathbf{t}\omega]$  extends to a unique  $f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}^{O[\mathbf{t}\omega]}$ . We now show that the following square commutes:

$$\begin{array}{ccc} \partial O[\mathbf{t}\omega] & \longrightarrow & \Lambda^{\mathbf{t}}[\omega] \\ \downarrow & \searrow f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}^{O[\mathbf{t}\omega]} & \downarrow f \\ O[\mathbf{t}\omega] & \longrightarrow & X. \end{array} \quad (3.4.8)$$

Tautologically, we have  $f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]} = f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}^{O[\mathbf{t}\omega]}|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}$ , and in particular,  $f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\mathbf{t}\omega]} = f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}^{O[\mathbf{t}\omega]}|_{\Lambda^{\mathbf{t}}[\mathbf{t}\mathbf{t}\omega]}$ . Since  $\mathbf{H}_{n-2} \perp X$ , we have  $f|_{O[\mathbf{t}\mathbf{t}\omega]} = f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}^{O[\mathbf{t}\omega]}|_{O[\mathbf{t}\mathbf{t}\omega]}$ . Therefore, square (3.4.8) commutes, and by lemma 3.4.1,  $f$  extends to a unique  $f|_{\partial O[\omega]}^{\partial O[\omega]} : \partial O[\omega] \rightarrow O[\omega]$  such that  $f|_{\partial O[\omega]}^{\partial O[\omega]}|_{O[\mathbf{t}\omega]} = f|_{\Lambda^{\mathbf{t}}[\mathbf{t}\omega]}^{O[\mathbf{t}\omega]}$ . Since  $\mathbf{B}_n \perp X$ ,  $f|_{\partial O[\omega]}^{\partial O[\omega]}$  extends to a unique morphism  $O[\omega] \rightarrow X$ .  $\square$

**Lemma 3.4.9.** *Let  $n \in \mathbb{N}$ , and  $\omega \in \mathbb{O}_{n+2}$ . Then the inclusion  $\Lambda^{\mathbf{t}}[\mathbf{t}\omega] \hookrightarrow \Lambda^{\mathbf{t}}[\omega]$  is a relative  $\mathbf{H}_{n+1}$ -cell complex.*

*Proof.* We show that the morphism  $\Lambda^{\mathbf{t}}[\mathbf{t}\omega] \hookrightarrow \Lambda^{\mathbf{t}}[\omega]$  is a (finite) composite of pushouts of elements of  $\mathbf{H}_{n+1}$ . Let  $X_0 = \Lambda^{\mathbf{t}}[\mathbf{t}\omega]$ . At stage  $k \geq 0$ , let  $J$  be the (necessarily finite) set of inclusions  $j = (j_1, j_2)$  in  $\mathcal{Psh}(\mathbb{O})^{\rightarrow}$  as on the left

$$\begin{array}{ccc} \Lambda^{\mathbf{t}}[\psi_j] & \xrightarrow{j_1} & X_k \\ \mathbf{h}_{\psi_j} \downarrow & & \downarrow \\ O[\psi_j] & \xrightarrow{j_2} & \Lambda^{\mathbf{t}}[\omega], \end{array} \quad \begin{array}{ccc} \coprod_{j \in J} \Lambda^{\mathbf{t}}[\psi_j] & \xrightarrow{j_1} & X_k \\ \mathbf{h}_{\psi_j} \downarrow & & \downarrow \\ \coprod_{j \in J} O[\psi_j] & \xrightarrow{j_2} & X_{k+1}. \end{array}$$

where  $\psi_j \in \mathbb{O}_{n+1}$ , such that  $j_1$  that do not factor through  $X_l$  for any  $l < k$ . Define  $X_{k+1}$  with the pushout on the right. There is a  $k$ , bounded by the height of the tree  $\omega \in \text{tr } \mathfrak{Z}^n$ , at which the sequence converges to  $\Lambda^{\mathbf{t}}[\mathbf{t}\omega] = X_0 \hookrightarrow X_1 \hookrightarrow \dots \hookrightarrow X_k = \Lambda^{\mathbf{t}}[\omega]$ .  $\square$

**Corollary 3.4.10.** (1) Let  $n \in \mathbb{N}$ , and  $\omega \in \mathbb{O}_{n+2}$ . Then the target embedding  $\mathbf{t}\omega \rightarrow \omega$  of  $\omega$  is an  $\mathbf{H}_{n+1, n+2}$ -local isomorphism.

(2) Let  $k, n \in \mathbb{N}$ , and  $\omega \in \mathbb{O}_{\geq n+2}$ . Then the target embedding  $\mathbf{t}\omega \rightarrow \omega$  is an  $\mathbf{A}_{k, n}$ -local isomorphism.

*Proof.* (1) In the square below

$$\begin{array}{ccc} \Lambda^{\mathbf{t}}[\mathbf{t}\omega] & \xrightarrow{\mathbf{h}_{\mathbf{t}\omega}} & O[\mathbf{t}\omega] \\ r \downarrow & & \downarrow \mathbf{t} \\ \Lambda^{\mathbf{t}}[\omega] & \xrightarrow{\mathbf{h}_{\omega}} & O[\omega] \end{array}$$

the map  $r$  is an  $\mathbf{H}_{n+1}$ -local isomorphism by lemma 3.4.9, and the horizontal maps are in  $\mathbf{H}_{n+1, n+2}$ . The result follows by 2-for-3.

(2) Let  $\omega \in \mathbb{O}_m$ . Since  $\mathbf{H}_{m-1, m+1} \subset \mathbf{A}_{k, n}$  by definition, this follows from the previous point.  $\square$

**Corollary 3.4.11.** Let  $\psi \in \mathbb{O}_n$ .

(1)  $\mathbf{t}\mathbf{t} = \mathbf{s}_{\square} \mathbf{t} : \psi \rightarrow \mathbf{l}_{\psi}$  is in  $\mathbf{H}_{n+2}$ .

(2) The morphisms  $\mathbf{s}_{\square} : \psi \rightarrow \mathbf{Y}_{\psi}$  are  $\mathbf{H}_{n+1, n+2}$ -local isomorphisms.

*Proof.* (1) The embedding  $\mathbf{t}\mathbf{t} = \mathbf{s}_{\square} \mathbf{t} : \psi \rightarrow \mathbf{l}_{\psi}$  is precisely the horn inclusion  $\mathbf{h}_{\mathbf{l}_{\psi}}$  of the degenerate  $(n+2)$ -opetope  $\mathbf{l}_{\psi}$ .

(2) The source embedding  $\mathbf{s}_{\square} : \psi \rightarrow \mathbf{Y}_{\psi}$  is precisely the horn inclusion  $\mathbf{h}_{\mathbf{Y}_{\psi}}$  of the  $(n+1)$ -opetope  $\mathbf{Y}_{\psi}$ . The target embedding  $\mathbf{t} : \psi \rightarrow \mathbf{Y}_{\psi}$  is the morphism  $\mathbf{t} : \mathbf{t}\mathbf{t}\mathbf{l}_{\psi} \rightarrow \mathbf{t}\mathbf{l}_{\psi}$  and is the vertical arrow in the diagram below.

$$\begin{array}{ccc} \psi = \Lambda^{\mathbf{t}}[\mathbf{l}_{\psi}] & & \\ \mathbf{t} \downarrow & \searrow \mathbf{h}_{\mathbf{l}_{\psi}} & \\ \mathbf{Y}_{\psi} = \mathbf{t}\mathbf{l}_{\psi} & \xrightarrow{\mathbf{t}} & \mathbf{l}_{\psi}. \end{array}$$

The horizontal arrow is an  $\mathbf{H}_{n+1, n+2}$ -local isomorphism by corollary 3.4.10 and the diagonal arrow is in  $\mathbf{H}_{n+2}$  by point (1). The result follows by 2-for-3.  $\square$

**3.5. Extensions.** Recall that a functor between small categories  $u : \mathcal{A} \rightarrow \mathcal{B}$  induces a restriction  $u^* : \mathcal{Psh}(\mathcal{B}) \rightarrow \mathcal{Psh}(\mathcal{A})$  that admits both adjoints  $u_! \dashv u^* \dashv u_*$ , given by pointwise left and right Kan extensions.

Let  $m \in \mathbb{N}$  and  $n \in \mathbb{N} \cup \{\infty\}$  be such that  $m \leq n$ , and let  $\mathbb{O}_{m, n}$  be the full subcategory of  $\mathbb{O}$  spanned by opetopes  $\omega$  such that  $m \leq \dim \omega \leq n$ . For instance,  $\mathbb{O}_{m, \infty} = \mathbb{O}_{\geq m}$ .

The inclusion  $\iota^{\geq m} : \mathbb{O}_{m, n} \rightarrow \mathbb{O}_{\geq m}$  induces a restriction functor  $(-)_m : \mathcal{Psh}(\mathbb{O}_{\geq m}) \rightarrow \mathcal{Psh}(\mathbb{O}_{m, n})$ , called *truncation*, that have both a left adjoint  $\iota_!^{\geq m}$  and a right adjoint  $\iota_*^{\geq m}$ . Explicitly, for  $X \in \mathcal{Psh}(\mathbb{O}_{m, n})$ ,



the presheaf  $\iota_1^{\geq m} X$  is the “extension by 0”, i.e.  $(\iota_1^{\geq m} X)_{m,n} = X$ , and  $(\iota_1^{\geq m} X)_\psi = \emptyset$  for all  $\psi \in \mathbb{O}_{>n}$ . On the other hand,  $\iota_*^{\geq m} X$  is the “canonical extension” of  $X$  into a presheaf over  $\mathbb{O}_{\geq m}$ : we have  $(\iota_*^{\geq m} X)_{m,n} = X$ , and  $\mathbf{B}_{>n} \perp \iota_*^{\geq m} X$ , which uniquely determines  $\iota_*^{\geq m} X$ .

Likewise, the inclusion  $\iota_*^{\leq n} : \mathbb{O}_{m,n} \longrightarrow \mathbb{O}_{\leq n}$  induces a restriction functor  $\mathcal{Psh}(\mathbb{O}_{\leq n}) \longrightarrow \mathcal{Psh}(\mathbb{O}_{m,n})$ , also denoted by  $(-)_m$  and again called *truncation*, that have both a left adjoint  $\iota_1^{\leq n}$  and a right adjoint  $\iota_*^{\leq n}$ . Explicitly, for  $X \in \mathcal{Psh}(\mathbb{O}_{m,n})$ , the presheaf  $\iota_1^{\leq n} X$  is the “canonical extension” of  $X$  into a presheaf over  $\mathbb{O}_{\leq n}$ :

$$\iota_1^{\leq n} X = \operatorname{colim}_{O[\psi]_{m,n} \rightarrow X} O[\psi].$$

On the other hand,  $\iota_*^{\leq n} X$  is the “terminal extension” of  $X$  in that  $(\iota_*^{\leq n} X)_{m,n} = X$ , and  $(\iota_*^{\leq n} X)_\psi$  is a singleton, for all  $\psi \in \mathbb{O}_{<n}$ . Note that  $\mathbf{O}_{<m} \perp \iota_*^{\leq n} X$ , and that it is uniquely determined by this property.

For  $n < \infty$ , we write  $(-)_{\leq n}$  for  $(-)_{0,n} : \mathcal{Psh}(\mathbb{O}_{\geq 0}) = \mathcal{Psh}(\mathbb{O}) \longrightarrow \mathcal{Psh}(\mathbb{O}_{0,n}) = \mathcal{Psh}(\mathbb{O}_{\leq n})$ , and let  $(-)_{<n} = (-)_{\leq n-1}$  if  $n \geq 0$ . Similarly, we note  $(-)_{m,n} : \mathcal{Psh}(\mathbb{O}_{\leq \infty}) = \mathcal{Psh}(\mathbb{O}) \longrightarrow \mathcal{Psh}(\mathbb{O}_{m,\infty}) = \mathcal{Psh}(\mathbb{O}_{\geq m})$  by  $(-)_{\geq m}$ , and let  $(-)_{>m} = (-)_{\geq m+1}$ .

- Proposition 3.5.1.** (1) *The functors  $\iota_1^{\geq m}$ ,  $\iota_*^{\geq m}$ ,  $\iota_1^{\leq n}$ , and  $\iota_*^{\leq n}$  are fully faithful.*  
(2) *A presheaf  $X \in \mathcal{Psh}(\mathbb{O}_{\geq m})$  is in the essential image of  $\iota_1^{\geq m}$  if and only if  $X_{>n} = \emptyset$ .*  
(3) *A presheaf  $X \in \mathcal{Psh}(\mathbb{O}_{\geq m})$  is in the essential image of  $\iota_*^{\geq m}$  if and only if for all  $\omega \in \mathbb{O}_{>n}$  we have  $(\mathbf{b}_\omega)_{\geq m} \perp X$ .*  
(4) *A presheaf  $X \in \mathcal{Psh}(\mathbb{O}_{\leq n})$  is in the essential image of  $\iota_*^{\leq n}$  if and only if for all  $\omega \in \mathbb{O}_{<m}$  we have  $(\mathbf{o}_\omega)_{\leq n} \perp X$ , i.e.  $X_\omega$  is a singleton.*

*Proof.* The first point follows from the fact that  $\iota^{\geq m}$  and  $\iota^{\leq n}$  are fully faithful, and [SGA72, exposé I, proposition 5.6]. The rest is straightforward verifications.  $\square$

To ease notations, we sometimes leave truncations implicit, e.g. point (3) of last proposition can be reworded as: a presheaf  $X \in \mathcal{Psh}(\mathbb{O}_{\geq m})$  is in the essential image of  $\iota_*^{\geq m}$  if and only if  $\mathbf{B}_{>n} \perp X$ .

#### 4. THE OPETOPIC NERVE OF OPETOPIC ALGEBRAS

**4.1. Opetopic algebras.** Let  $k \leq n \in \mathbb{N}$ . Recall that  $\mathbb{O}_{n-k,n} \hookrightarrow \mathbb{O}$  is the full subcategory of opetopes of dimension at least  $n-k$  and at most  $n$ . A *k-coloured, n-dimensional opetopic algebra*, or  $(k, n)$ -opetopic algebra, will be an algebraic structure on a presheaf over  $\mathbb{O}_{n-k,n}$ . Specifically, we describe a monad on the category  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$ , whose algebras are the  $(k, n)$ -opetopic algebras. Such an algebra  $X$  has “operations” (its cells of dimension  $n$ ) that can be “composed” in ways encoded by  $(n+1)$ -opetopes<sup>(6)</sup>. The operations of  $X$  will be “coloured” by its cells dimension  $< n$ , which determines which operations can be composed together.

As we will see, the fact that the operations and relations of an  $(k, n)$ -opetopic algebra are encoded by opetopes of dimension  $> n$  results in the category  $\mathcal{Alg}^k(\mathfrak{Z}^n)$  of  $(k, n)$ -opetopic algebras always having a canonical full and faithful *nerve functor* to the category  $\mathcal{Psh}(\mathbb{O})$  of opetopic sets (theorem 4.5.10).

We now claim some examples. A classification of  $(k, n)$ -opetopic algebras is given by proposition 4.3.5.

**Example 4.1.1** (Monoids and categories). Let  $k = 0$  and  $n = 1$ . Then  $\mathbb{O}_{n-k,n} = \mathbb{O}_1 = \{\ast\}$ , and  $\mathcal{Psh}(\mathbb{O}_{n-k,n}) = \mathbf{Set}$ . The category of  $(0, 1)$ -opetopic algebras is precisely the category of associative monoids. If  $k = 1$  instead, then  $\mathbb{O}_{n-k,n} = \mathbb{O}_{0,1}$ , and  $\mathcal{Psh}(\mathbb{O}_{n-k,n}) = \mathbf{Graph}$ , the category of directed graphs. The category of  $(1, 1)$ -opetopic algebras is precisely the category of small categories.

**Example 4.1.2** (Coloured and uncoloured planar operads). Let  $k = 0$  and  $n = 2$ . Then  $\mathbb{O}_{n-k,n} = \mathbb{O}_2 \cong \mathbb{N}$ , and  $\mathcal{Psh}(\mathbb{O}_2) \simeq \mathbf{Set}/\mathbb{N}$ . The category of  $(0, 2)$ -opetopic algebras is precisely the category of planar, uncoloured  $\mathbf{Set}$ -operads. If  $k = 1$  instead, then  $\mathcal{Psh}(\mathbb{O}_{1,2})$  is the category of planar, coloured collections. The category of  $(1, 2)$ -opetopic algebras is precisely the category of planar, coloured  $\mathbf{Set}$ -operads.

<sup>(6)</sup>Recall that an  $(n+1)$ -opetope is precisely a pasting scheme of  $n$ -opetopes.

**Example 4.1.3** (Combinads). Let  $k = 0$  and  $n = 3$ . Then  $\mathbb{O}_{n-k,n} = \mathbb{O}_3$  is the set of planar finite trees, and  $(0, 3)$ -opetopic algebras are exactly the *combinads* over the combinatorial pattern of non-symmetric trees, presented in [Lod12].

**4.2. Parametric right adjoint monads.** In preparation to the main results of this section, we survey elements of the theory of parametric right adjoint (p.r.a.) monads, which will be essential to the definition and description of  $(k, n)$ -opetopic algebras. A comprehensive treatment of this theory can be found in [Web07].

Let  $T : \mathcal{C} \rightarrow \mathcal{D}$  be a functor, and let  $\mathcal{C}$  have a terminal object  $1$ . Then  $T$  factors as

$$\mathcal{C} = \mathcal{C}/1 \xrightarrow{T_1} \mathcal{D}/T1 \rightarrow \mathcal{D}.$$

We say that  $T$  is a *parametric right adjoint* (abbreviated p.r.a.) if  $T_1$  has a left adjoint  $E$ .

We immediately restrict ourselves to the case  $\mathcal{C} = \mathcal{D} = \mathcal{Psh}(\mathcal{A})$  for a small category  $\mathcal{A}$ . Then  $T_1$  is the nerve of the restriction  $E : \mathcal{A}/T1 \rightarrow \mathcal{Psh}(\mathcal{A})$ , and the usual formula for nerve functors gives

$$TX_a = \sum_{x \in T1_a} \mathcal{Psh}(\mathcal{A})(Ex, X) \quad (4.2.1)$$

for  $X \in \mathcal{Psh}(\mathcal{A})$  and  $a \in \mathcal{A}$ . In fact, it is clear that the data of the object  $T1 \in \mathcal{Psh}(\mathcal{A})$  and of the functor  $E$  completely describe (via equation (4.2.1)) the functor  $T$  up to unique isomorphism.

A *p.r.a. monad* is a monad whose endofunctor is a p.r.a. and whose unit and multiplication are cartesian natural transformations<sup>(7)</sup>. Assume now that  $T : \mathcal{Psh}(\mathcal{A}) \rightarrow \mathcal{Psh}(\mathcal{A})$  is a p.r.a. monad. Define  $\Theta_0$  to be the full subcategory of  $\mathcal{Psh}(\mathcal{A})$  spanned by the image of  $E : \mathcal{A}/T1 \rightarrow \mathcal{Psh}(\mathcal{A})$ . Objects of  $\Theta_0$  are called *T-cardinals*. By [Web07, proposition 4.20], the Yoneda embedding  $\mathcal{A} \hookrightarrow \mathcal{Psh}(\mathcal{A})$  factors as

$$\mathcal{A} \xhookrightarrow{i} \Theta_0 \xhookrightarrow{i_0} \mathcal{Psh}(\mathcal{A}),$$

or in other words, representable presheaves are *T-cardinals*.

Every p.r.a. monad on a presheaf category is an example of a *monad with arities* [BMW12]. The theory of monads with arities provides a remarkable amount of information about the free-forgetful adjunction  $\mathcal{Psh}(\mathcal{A}) \rightleftarrows \mathcal{Alg}(T)$  and about the category of algebras  $\mathcal{Alg}(T)$ . We summarise those results that we will use below.

**Proposition 4.2.2.** *The fully faithful functor  $i_0 : \Theta_0 \hookrightarrow \mathcal{Psh}(\mathcal{A})$  is dense, or equivalently, its associated nerve functor  $N_0 : \mathcal{Psh}(\mathcal{A}) \hookrightarrow \mathcal{Psh}(\Theta_0)$  is fully faithful.*

*Proof.* We denote the inclusion  $\mathcal{A} \hookrightarrow \Theta_0$  by  $i$ , and note that  $N_0$  is isomorphic to  $i_* : \mathcal{Psh}(\mathcal{A}) \rightarrow \mathcal{Psh}(\Theta_0)$ . Now,  $i$  is fully faithful, and by [SGA72, exposé I, proposition 5.6], this is equivalent to  $i_*$  being fully faithful.  $\square$

**Corollary 4.2.3.** *Let  $J_{\mathcal{A}} := \{\varepsilon_{\theta} : i_! i^* \theta \rightarrow \theta \mid \theta \in \Theta_0 - \text{im } i\}$ , where  $\varepsilon_{\theta}$  is the counit at  $\theta$ . Then a presheaf  $X \in \mathcal{Psh}(\Theta_0)$  is in the essential image of  $N_0$  if and only if  $J_{\mathcal{A}} \perp X$ .*

*Proof.* By the formula  $i_* Y = \mathcal{Psh}(\mathcal{A})(\Theta_0(i-, -), Y)$  we have the sequence of isomorphisms

$$\begin{aligned} (i_* Y)_{\theta} &= \mathcal{Psh}(\mathcal{A})(\Theta_0(i-, \theta), Y) \\ &\cong \mathcal{Psh}(\mathcal{A})(i^* \theta, i^* i_* Y) && \text{since } i_* \text{ is fully faithful} \\ &\cong \mathcal{Psh}(\Theta_0)(i_! i^* \theta, i_* Y) && \text{since } i_! \dashv i^*. \end{aligned}$$

<sup>(7)</sup>P.r.a. monads on presheaf categories are a strict generalisation of polynomial monads, since an endofunctor  $\text{Set}/I \rightarrow \text{Set}/I$  is a polynomial functor iff it is a p.r.a., see [Web07, example 2.4].

It is easy to check that one direction of the previous isomorphism is pre-composition by  $\varepsilon_\theta$ . Conversely, take  $X \in \mathcal{Psh}(\Theta_0)$  such that  $\varepsilon_\theta \perp X$  for all  $\theta \in \Theta_0$ . Then

$$\begin{aligned} i^* i_* X_\theta &\cong \mathcal{Psh}(\Theta_0)(\theta, i^* i_* X) \\ &\cong \mathcal{Psh}(\Theta_0)(i_! i^* \theta, X) \\ &\cong \mathcal{Psh}(\Theta_0)(\theta, X) && \text{since } \varepsilon_\theta \perp X \\ &\cong X_\theta, \end{aligned}$$

and thus  $X \in \text{im } i^*$ . Thus a presheaf  $X$  is isomorphic to one of the form  $i_* Y$  if and only if we have  $\varepsilon_\theta \perp X$  for all  $\theta \in \Theta_0$ . But if  $\theta \in \text{im } i$ , then the associated counit map is already an isomorphism, hence we can restrict to  $J_{\mathcal{A}}$ .  $\square$

Let the (identity-on-objects, fully faithful) factorisation of the composite functor  $F_T i_0 : \Theta_0 \hookrightarrow \mathcal{Psh}(\mathcal{A}) \rightarrow \text{Alg}(T)$  be denoted

$$\Theta_0 \xrightarrow{t} \Theta_T \xleftarrow{i_T} \text{Alg}(T). \quad (4.2.4)$$

**Theorem 4.2.5.** (1) *The fully faithful functor  $i_T : \Theta_T \hookrightarrow \text{Alg}(T)$  is dense, or equivalently, its associated nerve functor  $N_T : \text{Alg}(T) \hookrightarrow \mathcal{Psh}(\Theta_T)$  is fully faithful.*

(2) *The following diagram is an exact adjoint square<sup>(8)</sup>.*

$$\begin{array}{ccc} \mathcal{Psh}(\mathcal{A}) & \begin{array}{c} \xrightarrow{F_T} \\ \perp \\ \xleftarrow{U_T} \end{array} & \text{Alg}(T) \\ N_0 \downarrow & & \downarrow N_T \\ \mathcal{Psh}(\Theta_0) & \begin{array}{c} \xrightarrow{t_!} \\ \perp \\ \xleftarrow{t^*} \end{array} & \mathcal{Psh}(\Theta_T) \end{array}$$

*In particular, both squares commute up to natural isomorphism.*

(3) *(Nerve theorem) Any  $X \in \mathcal{Psh}(\Theta_T)$  is in the essential image of  $N_T$  if and only if  $t^* X$  is in the essential image of  $N_0$ .*

*Proof.* See [Web07, theorem 4.10], and [BMW12, proposition 1.9].  $\square$

**Corollary 4.2.6.** *Let  $J_T := t_! J_{\mathcal{A}} = \{t_! \varepsilon_\theta : t_! i_! i^* \theta \rightarrow t_! \theta \mid \theta \in \Theta_0 - \text{im } i\}$ , where  $\varepsilon_\theta : i_! i^* \theta \rightarrow \theta$  is the counit at  $\theta$ . Then  $X \in \mathcal{Psh}(\Theta_T)$  is in the essential image of  $N_T$  if and only if  $J_T \perp X$ .*

*Proof.* This follows from theorem 4.2.5 point (3), and from corollary 4.2.3.  $\square$

**4.3. Coloured  $\mathfrak{Z}^n$ -algebras.** In this section, we extend the polynomial monad  $\mathfrak{Z}^n$  over  $\text{Set}/\mathbb{O}_n = \mathcal{Psh}(\mathbb{O}_n)$  to a p.r.a. monad  $\mathfrak{Z}^n$  over  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$ , for  $k \leq n \in \mathbb{N}$ .

This new setup will encompass more known examples (see proposition 4.3.5). For instance, recall that the polynomial monad  $\mathfrak{Z}^2$  on  $\text{Set}/\mathbb{O}_2 \cong \text{Set}/\mathbb{N}$  is exactly the monad of planar operads. The extension of  $\mathfrak{Z}^2$  will retrieve *coloured* planar operads as algebras. Similarly, the polynomial monad  $\mathfrak{Z}^1$  on  $\text{Set}$  is the free-monoid monad, which we would like to vary to obtain “coloured monoids”, i.e. small categories.

**4.3.1. The p.r.a. endofunctor  $\mathfrak{Z}^n$ .** Let  $k \leq n \in \mathbb{N}$ . Let us define a p.r.a. endofunctor  $\mathfrak{Z}^n$  (that ) on the category  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$ , that will restrict to the polynomial monad  $\mathfrak{Z}^n : \mathcal{Psh}(\mathbb{O}_n) \rightarrow \mathcal{Psh}(\mathbb{O}_n)$  in the case  $k = 0$ . Following section 4.2, to define the p.r.a. endofunctor  $\mathfrak{Z}^n$  as the composite

$$\mathcal{Psh}(\mathbb{O}_{n-k,n}) \xrightarrow{\mathfrak{Z}_!^n} \mathcal{Psh}(\mathbb{O}_{n-k,n})/\mathfrak{Z}^n 1 \simeq \mathcal{Psh}(\mathbb{O}_{n-k,n}/\mathfrak{Z}^n 1) \rightarrow \mathcal{Psh}(\mathbb{O}_{n-k,n}),$$

<sup>(8)</sup>There exists a natural isomorphism  $N_0 U_T \cong t^* N_T$  whose mate  $t_! N_0 \rightarrow N_T F_T$  is invertible (satisfies the Beck-Chevalley condition).

up to unique isomorphism, it suffices to define its value  $\mathfrak{Z}^n 1$  on the terminal presheaf, and to define a functor  $E : \mathbb{O}_{n-k,n}/\mathfrak{Z}^n 1 \rightarrow \mathcal{Psh}(\mathbb{O}_{n-k,n})$ . Define  $\mathfrak{Z}^n 1$  as:

$$(\mathfrak{Z}^n 1)_\psi := \{*\}, \quad (\mathfrak{Z}^n 1)_\omega := \{\nu \in \mathbb{O}_{n+1} \mid \mathfrak{t}\nu = \omega\}.$$

where  $\psi \in \mathbb{O}_{n-k,n-1}$  and  $\omega \in \mathbb{O}_n$ . We define the functor  $E : \mathbb{O}_{n-k,n}/\mathfrak{Z}^n 1 \rightarrow \mathcal{Psh}(\mathbb{O}_{n-k,n})$  as follows. On objects, for  $\psi$  and  $\nu$  as above,

$$E\psi := \mathbb{O}_{n-k,n}[\psi], \quad E\nu := \Lambda^{\mathfrak{t}}[\nu],$$

and on morphisms as the canonical inclusions. The functor  $\mathfrak{Z}_1^n : \mathcal{Psh}(\mathbb{O}_{n-k,n}) \rightarrow \mathcal{Psh}(\mathbb{O}_{n-k,n}/\mathfrak{Z}^n 1)$  is defined as the right adjoint to the left Kan extension of  $E$  along the Yoneda embedding. We now recover the endofunctor  $\mathfrak{Z}^n$  explicitly using equation (4.2.1): for  $\psi \in \mathbb{O}_{n-k,n-1}$  we have  $(\mathfrak{Z}^n X)_\psi \cong X_\psi$ , and for  $\omega \in \mathbb{O}_n$  we have

$$(\mathfrak{Z}^n X)_\omega \cong \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \omega}} \mathcal{Psh}(\mathbb{O}_{n-k,n})(\Lambda^{\mathfrak{t}}[\nu], X).$$

Note that  $(\mathfrak{Z}^n X)_\omega$  matches with the ‘‘uncolored’’ version of  $\mathfrak{Z}_n$  of equation (3.1.1).

**4.3.2. The p.r.a. monad structure on  $\mathfrak{Z}^n$ .** Recall from section 4.2 that a p.r.a. monad is a monad  $M$  whose unit  $\text{id} \rightarrow M$  and multiplication  $MM \rightarrow M$  are cartesian, and such that  $M$  is a p.r.a. endofunctor. We now endow the p.r.a. endofunctor  $\mathfrak{Z}^n$  with the structure of a p.r.a. monad over  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$ . We first specify the unit and multiplication  $\eta_1 : 1 \rightarrow \mathfrak{Z}^n 1$  and  $\mu_1 : \mathfrak{Z}^n \mathfrak{Z}^n 1 \rightarrow \mathfrak{Z}^n 1$  on the terminal object 1, and extend them to cartesian natural transformations (lemma 4.3.2). Next, we check that the required monad identities hold for 1 (lemma 4.3.3), which automatically gives us the desired monad structure on  $\mathfrak{Z}^n$ .

**Lemma 4.3.1.** *The polynomial functor  $\mathfrak{Z}^n \mathfrak{Z}^n : \text{Set}/\mathbb{O}_n \rightarrow \text{Set}/\mathbb{O}_n$  is given by*

$$\mathbb{O}_n \xleftarrow{\mathfrak{e}} E \longrightarrow \mathbb{O}_{n+2}^{(2)} \xrightarrow{\mathfrak{t}\mathfrak{t}} \mathbb{O}_n,$$

where

(1)  $\mathbb{O}_{n+2}^{(2)}$  is the set of  $(n+2)$  opetopes of height 2, i.e. of the form

$$Y_\nu \bigcirc_{[[p_i]]} Y_{\nu_i},$$

with  $\nu, \nu_i \in \mathbb{O}_{n+1}$  and  $[p_i]$  ranging over a (possibly empty) subset of  $\nu^\bullet$ ,

(2) for  $\xi \in \mathbb{O}_{n+2}^{(2)}$ ,  $E(\xi) = \xi^\dagger$ ,

(3) for  $\xi \in \mathbb{O}_{n+2}^{(2)}$  and  $[l] \in E(\xi) = \xi^\dagger$ ,  $\mathfrak{e}[l] = \mathfrak{e}_{[l]}\mathfrak{t}$ .

We now define  $\eta_1$  and  $\mu_1$ .

- (1) The presheaf  $\mathfrak{Z}^n 1 \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$  is pointed in the following way: the morphism  $\eta_1 : 1 \rightarrow \mathfrak{Z}^n 1$  is the identity in dimension  $< n$ , and given by  $\omega \mapsto Y_\omega$  for  $\omega \in \mathbb{O}_n$ .
- (2) First, note that for every non-degenerate  $\nu \in \mathbb{O}_{n+1}$ , a morphism  $x : \Lambda^{\mathfrak{t}}[\nu] \rightarrow \mathfrak{Z}^n 1$  in  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$  and an element of  $\mathfrak{Z}^n \mathfrak{Z}^n 1$ , this corresponds to an opetope  $\bar{\nu} \in \mathbb{O}_{n+2}$  height 2 (see lemma 4.3.1) such that  $\mathfrak{s}_{\square} \bar{\nu} = \nu$ .

Next, the map of presheaves  $\mu_1 : \mathfrak{Z}^n \mathfrak{Z}^n 1 \rightarrow \mathfrak{Z}^n 1$  is defined as the identity function on opetopes of dimension  $n-k \leq d < n$ , and as the function

$$\begin{aligned} \mu_{1,\omega} : \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \omega}} \mathcal{Psh}(\mathbb{O}_{n-k,n})(\Lambda^{\mathfrak{t}}[\nu], \mathfrak{Z}^n 1) &\longrightarrow \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \omega}} \mathcal{Psh}(\mathbb{O}_{n-k,n})(\Lambda^{\mathfrak{t}}[\nu], 1) \\ (\nu, x) &\longmapsto (\mathfrak{t}\bar{\nu}, *) && \text{if } \nu \text{ non-degen.} \\ (\nu, *) &\longmapsto (\nu, *) && \text{if } \nu \text{ degen.} \end{aligned}$$

on opetopes  $\omega \in \mathbb{O}_n$ . This is well-defined thanks to **(Glob1)**.

**Lemma 4.3.2.** *For  $X \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$ , the unique morphism  $! : X \rightarrow 1$  induces pullback squares*

$$\begin{array}{ccc} X & \xrightarrow{\eta_X} & \mathfrak{Z}^n X \\ \downarrow ! & \lrcorner & \downarrow \mathfrak{Z}^{n!} \\ 1 & \xrightarrow{\eta_1} & \mathfrak{Z}^n 1, \end{array} \quad \begin{array}{ccc} \mathfrak{Z}^n \mathfrak{Z}^n X & \xrightarrow{\mu_X} & \mathfrak{Z}^n X \\ \mathfrak{Z}^n \mathfrak{Z}^{n!} \downarrow & \lrcorner & \downarrow \mathfrak{Z}^{n!} \\ \mathfrak{Z}^n \mathfrak{Z}^n 1 & \xrightarrow{\mu_1} & \mathfrak{Z}^n 1 \end{array}$$

*Proof.* Straightforward verifications, see appendix A for details.  $\square$

We have suggestively named the topmost arrows  $\eta_X$  and  $\mu_X$ , since this choice of pullback square for each  $X$  gives cartesian natural transformations  $\eta : \text{id} \rightarrow \mathfrak{Z}^n$  and  $\mu : \mathfrak{Z}^n \mathfrak{Z}^n \rightarrow \mathfrak{Z}^n$ .

**Lemma 4.3.3.** *The following diagrams commute:*

$$\begin{array}{ccc} \mathfrak{Z}^n 1 & \xrightarrow{\eta_{\mathfrak{Z}^n 1}} & \mathfrak{Z}^n \mathfrak{Z}^n 1 & \xleftarrow{\mathfrak{Z}^n \eta_1} & \mathfrak{Z}^n 1 \\ & \searrow & \downarrow \mu_1 & \swarrow & \\ & & \mathfrak{Z}^n 1, & & \end{array} \quad \begin{array}{ccc} \mathfrak{Z}^n \mathfrak{Z}^n \mathfrak{Z}^n 1 & \xrightarrow{\mathfrak{Z}^n \mu_1} & \mathfrak{Z}^n \mathfrak{Z}^n 1 \\ \mu_{\mathfrak{Z}^n 1} \downarrow & & \downarrow \mu_1 \\ \mathfrak{Z}^n \mathfrak{Z}^n 1 & \xrightarrow{\mu_1} & \mathfrak{Z}^n 1. \end{array}$$

*Proof.* Straightforward computations. See appendix A for details.  $\square$

**Proposition 4.3.4.** *The cartesian natural transformations  $\mu$  and  $\eta$  give  $\mathfrak{Z}^n$  a structure of p.r.a. monad on  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$ .*

*Proof.* This is a direct consequence of lemmas 4.3.2 and 4.3.3.  $\square$

Clearly, when  $k = 0$ , we recover the usual polynomial monad on  $\text{Set}/\mathbb{O}_n$ . Let  $\text{Alg}^k(\mathfrak{Z}^n)$ , the category of  $k$ -coloured  $n$ -dimensional opetopic algebras, be the Eilenberg–Moore category of  $\mathfrak{Z}^n$  considered as a monad on  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$ . One readily checks the following:

**Proposition 4.3.5.** *Up to equivalence, and for small values of  $k$  and  $n$ , the category  $\text{Alg}^k(\mathfrak{Z}^n)$  is given by the following table:*

$k \setminus n$	0	1	2	3
0	Set	Mon	Op	Comb $_{\mathbb{PT}}$
1		Cat	Op $_{\text{col}}$	Alg $^1(\mathfrak{Z}^3)$
2			Alg $^2(\mathfrak{Z}^2)$	Alg $^2(\mathfrak{Z}^3)$
3				Alg $^3(\mathfrak{Z}^3)$

where  $\text{Set}$  is the category of sets,  $\text{Mon}$  of monoids,  $\text{Cat}$  of small categories,  $\text{Op}$  of non coloured planar operads,  $\text{Op}_{\text{col}}$  of coloured planar operads, and  $\text{Comb}_{\mathbb{PT}}$  of combinads over the combinatorial pattern of planar trees [Lod12]. The lower half of the table is left empty since  $\text{Alg}^k(\mathfrak{Z}^n) = \text{Alg}^n(\mathfrak{Z}^n)$  for  $k \geq n$ .

**4.4.  $\mathfrak{Z}^n$ -cardinals and opetopic shapes.** Following section 4.2, the category of  $\mathfrak{Z}^n$ -cardinals is the full subcategory  $i_0 : \Theta_0 \hookrightarrow \mathcal{Psh}(\mathbb{O}_{n-k,n})$  whose objects are the representables  $\omega \in \mathbb{O}_{n-k,n}$  and the target horns  $\Lambda^t[\nu]$ , for  $\nu \in \mathbb{O}_{n+1}$ . Analogous to equation (4.2.4), we denote the (identity-on-objects, fully faithful) factorisation of  $\mathfrak{Z}^n i_0 : \Theta_0 \hookrightarrow \mathcal{Psh}(\mathbb{O}_{n-k,n}) \rightarrow \text{Alg}^k(\mathfrak{Z}^n)$  by

$$\Theta_0 \xrightarrow{z} \mathbb{A}_{k,n} \xrightarrow{u} \text{Alg}^k(\mathfrak{Z}^n).$$

We call the category  $\mathbb{A}_{k,n}$  of free algebras on the  $\mathfrak{Z}^n$ -cardinals the category of  $(k, n)$ -opetopic shapes.

For the remainder of this section, we fix parameters  $k \leq n \in \mathbb{N}$  once and for all, and suppress them in notation whenever unambiguous, e.g.  $\mathbb{A} := \mathbb{A}_{k,n}$ ,  $\mathfrak{Z} := \mathfrak{Z}^n$ ,  $\text{Alg} := \text{Alg}^k(\mathfrak{Z}^n)$ .

Let  $A[-] : \mathbb{A} \rightarrow \mathcal{Psh}(\mathbb{A})$  denote the Yoneda embedding. For  $\omega \in \mathbb{O}_{n+1}$ , let  $\mathcal{H}_\omega := \mathbb{O}_{n-k,n}/\Lambda^t[\omega]$ . We denote the colimit, in  $\mathcal{Psh}(\mathbb{A})$ , by

$$S[\omega] := \text{colim} \left( \mathcal{H}_\omega \longrightarrow \mathbb{O}_{n-k,n} \xrightarrow{\mathfrak{z}} \mathbb{A} \xrightarrow{A[-]} \mathcal{Psh}(\mathbb{A}) \right),$$

and call it the *spine on  $\omega$* . It is clearly a subobject  $S[\omega] \hookrightarrow A[\mathfrak{z}\Lambda^t[\omega]]$  of the representable on  $\mathfrak{z}\Lambda^t[\omega] \in \mathbb{A}$ . The theory reviewed in section 4.2 has the following immediate consequences.

**Proposition 4.4.1.** (1) *The inclusion  $u : \mathbb{A} \hookrightarrow \mathcal{Alg}$  is dense, i.e., its associated nerve functor  $N_u : \mathcal{Alg} \rightarrow \mathcal{Psh}(\mathbb{A})$  is fully faithful.*

(2) *Any  $X \in \mathcal{Psh}(\mathbb{A})$  is in the essential image of  $N_u$  if and only if  $S \perp X$ , where*

$$S := \{ S[\omega] \hookrightarrow A[\mathfrak{z}\Lambda^t[\omega]] \mid \omega \in \mathbb{O}_{n+1} \} .$$

(3) *The reflective adjunction  $u : \mathcal{Psh}(\mathbb{A}) \xleftarrow{\text{res}} \mathcal{Alg} : N_u$  exhibits  $\mathcal{Alg} \simeq S^{-1}\mathcal{Psh}(\mathbb{A})$  as the localisation of  $\mathcal{Psh}(\mathbb{A})$  at the set of morphisms  $S$ .*

**Example 4.4.2.** The category  $\mathbb{A}_{1,1}$  is the category of simplices  $\Delta$ , and  $\mathbb{A}_{2,1}$  is the planar version of Moerdijk and Weiss's category of dendrices  $\Omega$ . Then proposition 4.4.1 is the well-known fact that  $\mathcal{Cat}$  and  $\mathcal{Op}_{\text{col}}$  have fully faithful nerve functors to  $\mathcal{Psh}(\Delta)$  and to  $\mathcal{Psh}(\Omega)$  respectively, exhibiting them as localisations of the respective presheaf categories at a set of *spine* inclusions.<sup>(9)</sup>

The previous examples may lead one to believe that calling  $\mathbb{A}$  the category of “opetopic” shapes is rather specious. However, our motivation stems from the following remarkable fact: there is a functor  $\dot{h} : \mathbb{O}_{n-k,n+2} \rightarrow \mathbb{A}$  (that we will define below), that is neither full nor faithful (it is, however, *surjective* on objects and on morphisms), but is such that the composite functor  $\mathcal{Alg} \hookrightarrow \mathcal{Psh}(\mathbb{A}) \xrightarrow{\dot{h}^*} \mathcal{Psh}(\mathbb{O}_{n-k,n+2})$  is a fully faithful right adjoint, and moreover exhibits  $\mathcal{Alg}$  as the category of models of a projective sketch on  $\mathbb{O}_{n-k,n+2}^{\text{op}}$ . In addition, the composite fully faithful functor  $\mathbb{A} \hookrightarrow \mathcal{Psh}(\mathbb{O}_{n-k,n+2})$  is simply the nerve associated to  $\dot{h}$  (this says that  $\dot{h}$  is dense), and allows us to view  $\mathbb{A}$  as a full subcategory of  $(n-k, n+2)$ -truncated opetopic sets, justifying the use of the term “opetopic shape”.

The functor  $\dot{h} : \mathbb{O}_{n-k,n+2} \rightarrow \mathbb{A}$  is defined on objects as follows:

$$\begin{aligned} \dot{h} : \mathbb{O}_{n-k,n+2} &\longrightarrow \mathbb{A} \\ \psi \in \mathbb{O}_{\leq n} &\longmapsto \mathfrak{z}O[\psi] \\ \omega \in \mathbb{O}_{n+1} &\longmapsto \mathfrak{z}\Lambda^t[\omega] \\ \xi \in \mathbb{O}_{n+2} &\longmapsto \mathfrak{z}\Lambda^t[t\xi]. \end{aligned}$$

On morphisms,  $\dot{h}$  is the same as the free functor  $\mathfrak{z}$  on  $\mathbb{O}_{n-k,n}$ . Take  $\omega \in \mathbb{O}_{n+1}$  and  $\xi \in \mathbb{O}_{n+2}$ .

(1) Let  $[p] \in \omega^\bullet$ , and  $\dot{h} \left( s_{[p]} \omega \xrightarrow{s_{[p]}} \omega \right) = \mathfrak{z} \left( O[s_{[p]} \omega] \xrightarrow{s_{[p]}} \Lambda^t[\omega] \right)$ .

(2) Let  $\dot{h} \left( t\omega \xrightarrow{t} \omega \right) = \left( \mathfrak{z}O[t\omega] \xrightarrow{\dot{h}t} \mathfrak{z}\Lambda^t[\omega] \right)$  correspond to the cell  $\text{id}_{\Lambda^t[\omega]} \in \mathfrak{z}\Lambda^t[\omega]_{t\omega}$  under the Yoneda embedding.

(3) Let  $\dot{h} \left( t\xi \xrightarrow{t} \xi \right) = \left( \mathfrak{z}\Lambda^t[t\xi] \xrightarrow{\dot{h}t} \mathfrak{z}\Lambda^t[t\xi] \right)$  be the identity map.

(4) Let  $[p] \in \xi^\bullet$ . In order to define  $\dot{h} \left( s_{[p]} \xi \xrightarrow{s_{[p]}} \xi \right) = \left( \mathfrak{z}\Lambda^t[s_{[p]} \xi] \xrightarrow{\dot{h}s_{[p]}} \mathfrak{z}\Lambda^t[t\xi] \right)$ , it is enough to provide a morphism  $\dot{h}s_{[p]} : \Lambda^t[s_{[p]} \xi] \rightarrow \mathfrak{z}\Lambda^t[t\xi]$  in  $\mathcal{Psh}(\mathbb{O}_{n-k,n})$ , which we now construct.

<sup>(9)</sup>Sometimes called “Grothendieck-Segal” colimits.

Using equation (2.4.6),  $\xi$  decomposes as

$$\xi = \zeta \underset{[p]}{\circ} \mathbf{Y}_{\mathfrak{s}_{[p]}\xi} \underset{[[q_i]]}{\circ} \zeta_i,$$

where  $[q_i]$  ranges over  $(\mathfrak{s}_{[p]}\xi)^\bullet$ . The leaves of  $\zeta_i$  are therefore a subset of the leaves of  $\xi$ . Precisely, a leaf address  $[r] \in \zeta_i^!$  corresponds to the leaf address  $[p[q_i]r] \in \xi^!$ , defining an inclusion  $f_i : \Lambda^t[\mathfrak{t}\zeta_i] \hookrightarrow \Lambda^t[\mathfrak{t}\xi]$  that maps the node  $\wp_{\zeta_i}[r] \in (\mathfrak{t}\zeta_i)^\bullet$  to  $\wp_\xi[p[q_i]r] \in (\mathfrak{t}\xi)^\bullet$ .

Note that by definition, each  $f_i$  is an element of  $\mathcal{Psh}(\mathbb{O}_{n-k,n})(\Lambda^t[\mathfrak{t}\zeta_i], \Lambda^t[\mathfrak{t}\xi]) \subseteq \mathfrak{Z}\Lambda^t[\mathfrak{t}\xi]_{\mathfrak{tt}\zeta_i}$ , and since  $\mathfrak{tt}\zeta_i = \mathfrak{ts}_{[]} \zeta_i = \mathfrak{s}_{[q_i]} \mathfrak{s}_{[p]} \xi$  (by **(Glob1)** and **(Inner)**), we have  $f_i \in \mathfrak{Z}\Lambda^t[\mathfrak{t}\xi]_{\mathfrak{s}_{[q_i]} \mathfrak{s}_{[p]} \xi}$ .

Together, the  $f_i$  assemble into the required morphism  $\dot{h}_{\mathfrak{s}_{[p]}\xi} : \Lambda^t[\mathfrak{s}_{[p]}\xi] \rightarrow \mathfrak{Z}\Lambda^t[\mathfrak{t}\xi]$ , that maps the node  $[q_i] \in (\mathfrak{s}_{[p]}\xi)^\bullet$  to  $f_i$ . So in conclusion, we have

$$\begin{aligned} \dot{h}_{\mathfrak{s}_{[p]}\xi} : \Lambda^t[\mathfrak{s}_{[p]}\xi] &\longrightarrow \mathfrak{Z}\Lambda^t[\mathfrak{t}\xi] \\ (\dot{h}_{\mathfrak{s}_{[p]}\xi})([q_i]) : \Lambda^t[\mathfrak{t}\zeta_i] &\longrightarrow \Lambda^t[\mathfrak{t}\xi] \\ \wp_{\zeta_i}[r] &\longmapsto \wp_\xi[p[q_i]r], \end{aligned}$$

for  $[q_i] \in (\mathfrak{s}_{[p]}\xi)^\bullet$  and  $[r] \in \zeta_i^!$ .

This defines  $\dot{h}$  on object and morphisms, and functoriality is straightforward.

**Example 4.4.3.** Consider the case  $(k, n) = (1, 1)$ , so that  $\dot{h} : \mathbb{O}_{0,3} \rightarrow \mathbb{A}_{1,1} \cong \mathbb{A}$ . In low dimensions, we have  $\dot{h}_{1,1}\blacklozenge = [0]$ ,  $\dot{h}_{1,1}\blacksquare = [1]$ , and  $\dot{h}_{1,1}\mathbf{n} = [n]$ , for  $n \in \mathbb{N}$ . Consider now the following 3-opetope  $\xi$ :

$$\xi = \mathbf{Y}_3 \underset{[[*]]}{\circ} \mathbf{Y}_2 \underset{[[**]]}{\circ} \mathbf{Y}_1 = \left( \begin{array}{c} \text{Diagram 1} \\ \Rightarrow \\ \text{Diagram 2} \end{array} \right)$$

Then  $\dot{h}_{1,1}\xi = \mathfrak{Z}^1\Lambda^t[\mathfrak{t}\xi] = [4]$ . This result should be understood as the poset of points of  $\xi$  (represented as dots in the pasting diagram above) ordered by the topmost arrows of  $\xi$ .

Take the face embedding  $\mathfrak{s}_{[]} : \mathbf{3} \rightarrow \xi$ . Then  $\dot{h}_{1,1}\mathfrak{s}_{[]}$  maps points 0, 1, 2, 3 of  $\dot{h}_{1,1}\mathbf{3} = [3]$  to points 0, 1, 3, 4 of  $\dot{h}_{1,1}\xi$ , respectively. In other words, it ‘‘skips’’ point 2, which is exactly what the pasting diagram above depicts: the  $[]$ -source of  $\xi$  does not touch point 2. Likewise, the map  $\dot{h}_{1,1}\mathfrak{s}_{[[**]]} : [1] = \dot{h}_{1,1}\mathbf{1} \rightarrow \dot{h}_{1,1}\xi$  maps 0, 1 to 3, 4, respectively.

Consider now the target embedding  $\mathfrak{t} : \mathbf{4} \rightarrow \xi$ . Since the target face touches all the points of  $\xi$  (this can be checked graphically, but more generally follows from **(Glob2)**),  $\dot{h}_{1,1}\mathfrak{t}$  should be the identity map on  $[4]$ , which is precisely what the definition gives.

We spend the rest of this section proving various (rather technical) facts about the functor  $\dot{h}$ , which will allow us to construct the opetopic nerve functor (and to prove that it is fully faithful) in section 4.5.

**Definition 4.4.4.** Let  $\omega, \omega' \in \mathbb{O}_{n+1}$ . A morphism  $f : \dot{h}\omega \rightarrow \dot{h}\omega'$  in  $\mathbb{A}$  is *diagrammatic* if there exists a  $\xi \in \mathbb{O}_{n+2}$  and a  $[p] \in \xi^\bullet$  such that  $\mathfrak{s}_{[p]}\xi = \omega$ ,  $\mathfrak{t}\xi = \omega'$ , and  $f = \dot{h}\left(\omega \xrightarrow{\mathfrak{s}_{[p]}} \xi\right)$ .

This situation is summarised by the following diagram, called a *diagram of  $f$* .

$$\begin{array}{ccc} & & \xi \\ & \nearrow \mathfrak{s}_{[p]} & \uparrow \mathfrak{t} \\ \omega & & \omega' \\ \hline \dot{h}\omega & \xrightarrow{f} & \dot{h}\omega' \end{array}$$

**Example 4.4.5.** Consider the case  $(k, n) = (1, 1)$  again, and recall that  $\mathbb{A}_{1,1} \cong \mathbb{\Delta}$ . Consider the map  $f : [2] \rightarrow [3]$  mapping 0, 1, and 2 to 0, 2, and 3, respectively (in other words,  $f$  is the *1st simplicial coface map* [Jar06]). Taking  $\xi$  as on the left, we obtain a diagram of  $f$  on the right:

$$\xi = Y_2 \circ_{[[*]]} Y_2 = \left( \begin{array}{c} \text{Diagram 1} \\ \Downarrow \\ \text{Diagram 2} \end{array} \right), \quad \frac{\begin{array}{ccc} & \zeta & \\ s[1] \nearrow & \uparrow t & \\ \mathbf{2} & & \mathbf{2} \end{array}}{[2] \xrightarrow{g} [3]}$$

Consider now a non injective map  $g : [2] \rightarrow [1]$  mapping 0, 1, and 2 to 0, 1, and 1, respectively (in other words,  $g$  is the *1st simplicial codegeneracy map* [Jar06]). Taking  $\zeta$  as on the left, we obtain a diagram of  $g$  on the right:

$$\zeta = Y_2 \circ_{[[*]]} Y_0 = \left( \begin{array}{c} \text{Diagram 1} \\ \Downarrow \\ \text{Diagram 2} \end{array} \right), \quad \frac{\begin{array}{ccc} & \zeta & \\ s[[*]] \nearrow & \uparrow t & \\ \mathbf{2} & & \mathbf{1} \end{array}}{[2] \xrightarrow{g} [1]}$$

On the one hand, lemma 4.4.6 below states that the composite of diagrammatic morphisms remains diagrammatic, onan the other hand, those two examples seem to indicate that all simplicial cofaces and codegeneracies are diagrammatic. One might thus expect all morphisms of  $\mathbb{\Delta}$  to be in the image of  $\dot{h}_{1,1} : \mathbb{O}_{0,3} \rightarrow \mathbb{A}_{1,1} \cong \mathbb{\Delta}$ . This is proved in corollary 4.5.11.

**Lemma 4.4.6.** *If  $f_1$  and  $f_2$  are diagrammatic as on the left, the diagram on the right is well defined, and is a diagram of  $f_2 f_1$ .*

$$\frac{\begin{array}{ccccc} & \xi_1 & & \xi_2 & \\ s[p_1] \nearrow & \uparrow t & s[p_2] \nearrow & \uparrow t & \\ \omega_0 & \omega_1 & & \omega_2 & \end{array}}{\dot{h}\omega_0 \xrightarrow{f_1} \dot{h}\omega_1 \xrightarrow{f_2} \dot{h}\omega_2},} \quad \frac{\begin{array}{ccc} & \xi_2 \square_{[p_2]} \xi_1 & \\ s[p_2 p_1] \nearrow & \uparrow t & \\ \omega_0 & \omega_2 & \end{array}}{\dot{h}\omega_0 \xrightarrow{f_2 f_1} \dot{h}\omega_2}$$

*Proof.* It is a simple but lengthy matter of unfolding the definition of  $\dot{h}$ . See appendix A for details.  $\square$

**Lemma 4.4.7.** (1) *Let  $\omega \in \mathbb{O}_{n+1}$ , and  $\psi = t\omega$ . Then the following is a diagram of  $ht : \dot{h}\psi \rightarrow \dot{h}\omega$ :*

$$\frac{\begin{array}{ccc} & \xi & \\ s[1] \nearrow & \uparrow t & \\ Y_\psi & & \omega \end{array}}{\dot{h}\psi \xrightarrow{ht} \dot{h}\omega}, \quad \xi := Y_{Y_\psi} \circ_{[[\ ]]} Y_\omega.$$

(Note that  $\omega = t\xi$  by lemma 3.2.3)

(2) *Let  $\beta, \omega \in \mathbb{O}_{n+1} = \text{tr } \mathbb{Z}^{n-1}$ , and  $i : \Lambda^t[\beta] \rightarrow \Lambda^t[\omega]$  a morphism of presheaves. Then  $i$  corresponds to an inclusion of  $\mathbb{Z}^{n-1}$  trees  $\beta \hookrightarrow \omega$ , mapping node at address  $[q]$  to  $[pq]$ , where  $[p] = i[ ] \in \omega^\bullet$ .*



Write  $\omega = \bar{\beta} \square_{[p]} \beta$ , for an adequate  $\bar{\beta} \in \mathbb{O}_{n+1}$ . Then following is a diagram of  $\dot{h}i$ :

$$\begin{array}{ccc} & & \xi \\ & \nearrow^{s_{[p]}} & \uparrow t \\ \beta & & \omega \\ \hline \dot{h}\beta & \xrightarrow{\dot{h}i} & \dot{h}\omega, \end{array} \quad \xi := Y_{\bar{\beta}} \circ_{[[p]]} Y_{\beta}.$$

(Note that  $\omega = t\xi$  by lemma 3.2.3)

*Proof.* It is a simple matter of unfolding the definition of  $\dot{h}$ . See appendix A for details.  $\square$

**Lemma 4.4.8** (Diagrammatic lemma). *Let  $\omega, \omega' \in \mathbb{O}_{n+1}$  with  $\omega$  non degenerate, and  $f : \dot{h}\omega \rightarrow \dot{h}\omega'$ . Then  $f$  is diagrammatic.*

*Proof (sketch, see appendix A for details).* The idea is to proceed by induction on  $\omega$ . The case  $\omega = Y_{\psi}$  for some  $\psi \in \mathbb{O}_n$  is fairly simple. In the inductive case ( $\omega = \nu \circ_{[l]} Y_{\psi}$ , for suitable  $\nu, \psi$ , and  $[l]$ ), we essentially show that  $f$  exhibits an inclusion of  $\mathfrak{Z}^n$ -trees  $\omega \hookrightarrow \omega'$  by constructing a  $(n+1)$ -opetope  $\bar{\omega}$  such that  $\omega' = \bar{\omega} \square_{[q]} \omega$ . Thus by lemma 4.4.7, the following is a diagram of  $\dot{h}f$ :

$$\begin{array}{ccc} & & \xi \\ & \nearrow^{s_{[q_1]}} & \uparrow t \\ \omega & & \omega' \\ \hline \dot{h}\omega & \xrightarrow{f} & \dot{h}\omega', \end{array} \quad \xi := Y_{\bar{\omega}} \circ_{[[q_1]]} Y_{\omega}.$$

$\square$

**4.5. The opetopic nerve functor.** This section is entirely devoted to constructing the *opetopic nerve functor*  $N : \mathcal{A}lg \rightarrow \mathcal{P}sh(\mathbb{O})$ , which is a fully faithful right adjoint and which exhibits  $\mathcal{A}lg$  as the category of models of a projective sketch on  $\mathbb{O}^{op}$  (theorem 4.5.10).

Let  $A[-] : \mathbb{A} \rightarrow \mathcal{P}sh(\mathbb{A})$  denote the Yoneda embedding. Recall from corollary 4.2.6 that the reflective adjunction  $\mathcal{P}sh(\mathbb{A}) \rightleftarrows \mathcal{A}lg$  exhibits  $\mathcal{A}lg$  as the localisation of  $\mathcal{P}sh(\mathbb{A})$  at the set of morphisms that we denote

$$\mathbf{S} := \{S[\omega] \hookrightarrow A[\mathfrak{Z}\Lambda^t[\omega]] \mid \omega \in \mathbb{O}_{n+1}\}.$$

Recall the definition of the set  $\mathbf{H}_{n+1, n+2}$  of morphisms in  $\mathcal{P}sh(\mathbb{O})$  from section 3.4. With slight abuse, we overcharge the notation  $\mathbf{H}_{n+1, n+2}$  to denote the image of this set under the truncation functor  $\mathcal{P}sh(\mathbb{O}) \rightarrow \mathcal{P}sh(\mathbb{O}_{n-k, n+2})$ . In corollary 4.5.9, we show an equivalence  $\mathbf{H}_{n+1, n+2}^{-1} \mathcal{P}sh(\mathbb{O}_{n-k, n+2}) \simeq \mathcal{A}lg$ , from which theorem 4.5.10 will follow directly.

**Lemma 4.5.1.** *The functor  $\dot{h}_! : \mathcal{P}sh(\mathbb{O}_{n-k, n+2}) \rightarrow \mathcal{P}sh(\mathbb{A})$  takes  $\mathbf{H}_{n+1}$  to  $\mathbf{S}$  and takes morphisms in  $\mathbf{H}_{n+2}$  to  $\mathbf{S}$ -local isomorphisms.*

*Proof.* (1) We show that  $\dot{h}_! \mathbf{H}_{n+1} = \mathbf{S}$ . Take  $\omega \in \mathbb{O}_{n+1}$ . Then

$$\dot{h}_! \Lambda^t[\omega] = \dot{h}_! \operatorname{colim}_{\psi \in \mathcal{H}_{\omega}} O[\psi] \cong \operatorname{colim}_{\psi \in \mathcal{H}_{\omega}} \dot{h}_! O[\psi] = \operatorname{colim}_{\psi \in \mathcal{H}_{\omega}} A[\dot{h}\psi] = S[\omega].$$

(2) For  $\omega \in \mathbb{O}_{n+2}$ , the inclusion  $\Lambda^t[t\omega] \rightarrow \Lambda^t[\omega]$  is a relative  $\mathbf{H}_{n+1}$ -cell complex by lemma 3.4.9. Since  $\dot{h}_!$  preserves colimits, and since  $\dot{h}_! \mathbf{H}_{n+1} = \mathbf{S}$ , we have that  $\dot{h}_!(\Lambda^t[t\omega] \hookrightarrow \Lambda^t[\omega])$  is a relative

S-cell complex, and thus an S-local isomorphism. In the square below

$$\begin{array}{ccc} \dot{h}_! \Lambda^{\mathfrak{t}}[\mathfrak{t}\omega] & \longrightarrow & \dot{h}_! \Lambda^{\mathfrak{t}}[\omega] \\ \dot{h}_! h_{\mathfrak{t}\omega} \downarrow & & \downarrow \dot{h}_! h_{\omega} \\ \dot{h}_! O[\mathfrak{t}\omega] & \xrightarrow{\dot{h}_! \mathfrak{t}} & \dot{h}_! O[\omega] \end{array}$$

we know that  $\dot{h}_! \mathfrak{t} = O[\dot{h}_! \mathfrak{t}]$  is an isomorphism, and that  $\dot{h}_! h_{\mathfrak{t}\omega} \in \mathbf{S}$  by the previous point. We have just shown that the top arrow is an S-local isomorphism. By 2-for-3, we conclude that  $\dot{h}_! h_{\omega}$  is too.  $\square$

We will prove two crucial lemmas that are key to the proof of theorem 4.5.10. Before doing so, let us make some preliminary remarks that will make the task easier.

**Lemma 4.5.2.** *Let  $\omega \in \mathbb{O}_{n-k, n+2}$ , and let  $X \in \mathbf{H}_{n+1, n+2}^{\perp}$ . Then the following are all spans of isomorphisms.*

- (1)  $\Lambda(\dot{h}\omega, \dot{h}\psi) \times X_{\psi} \xleftarrow{\text{id} \times X_{\mathfrak{t}\mathfrak{t}}} \Lambda(\dot{h}\omega, \dot{h}\psi) \times X_{\mathfrak{t}\psi} \xrightarrow{\Lambda(\dot{h}\omega, \dot{h}\mathfrak{t}\mathfrak{t}) \times \text{id}} \Lambda(\dot{h}\omega, \dot{h}\mathfrak{t}\psi) \times X_{\mathfrak{t}\psi}$ , where  $\psi \in \mathbb{O}_{n-1}$ .
- (2)  $\Lambda(\dot{h}\omega, \dot{h}\psi) \times X_{\psi} \xleftarrow{\text{id} \times X_{\mathfrak{s}[\ ]}} \Lambda(\dot{h}\omega, \dot{h}\psi) \times X_{\mathfrak{Y}\psi} \xrightarrow{\Lambda(\dot{h}\omega, \dot{h}\mathfrak{s}[\ ]) \times \text{id}} \Lambda(\dot{h}\omega, \dot{h}\mathfrak{Y}\psi) \times X_{\mathfrak{Y}\psi}$ , where  $\psi \in \mathbb{O}_n$ .
- (3)  $\Lambda(\dot{h}\omega, \dot{h}\mathfrak{t}\psi) \times X_{\mathfrak{t}\psi} \xleftarrow{\text{id} \times X_{\mathfrak{t}}} \Lambda(\dot{h}\omega, \dot{h}\mathfrak{t}\psi) \times X_{\psi} \xrightarrow{\Lambda(\dot{h}\omega, \dot{h}\mathfrak{t}) \times \text{id}} \Lambda(\dot{h}\omega, \dot{h}\psi) \times X_{\psi}$ , where  $\psi \in \mathbb{O}_{n+2}$

*Proof.* (1) The first map is an isomorphism by corollary 3.4.11 point (1) and the second map is one by definition of  $\dot{h}$ .  
 (2) The first map is an isomorphism by corollary 3.4.11 point (2) and the second is one by definition of  $\dot{h}$ .  
 (3) The first map is an isomorphism by corollary 3.4.10 point (1) and the second is one by definition of  $\dot{h}$ .  $\square$

**Lemma 4.5.3.** *Let  $\omega \in \mathbb{O}_{n-k, n+2}$ . If  $\psi \in \mathbb{O}_{n-k, n-2}$ , then  $\Lambda(\dot{h}\omega, \dot{h}\psi) \cong \mathbb{O}_{n-k, n+2}(\omega, \psi)$ .*

*Proof.* Easy verification.  $\square$

The first of the two crucial propositions will provide us one half of an equivalence between the category  $\mathbf{H}_{n+1, n+2}^{-1} \mathcal{P}\text{sh}(\mathbb{O}_{n-k, n+2})$  and  $\mathcal{A}\text{lg}$ .

**Proposition 4.5.4.** *Let  $X \in \mathcal{P}\text{sh}(\mathbb{O}_{n-k, n+2})$ . If  $\mathbf{H}_{n+1, n+2} \perp X$ , then the unit  $X \longrightarrow \dot{h}^* \dot{h}_! X$  is an isomorphism.*

*Proof.* It suffices to show that for each  $\omega \in \mathbb{O}_{n-k, n+2}$ , the map

$$X_{\omega} \longrightarrow \dot{h}^* \dot{h}_! X_{\omega} = \int^{\psi \in \mathbb{O}_{n-k, n+2}} \Lambda(\dot{h}\omega, \dot{h}\psi) \times X_{\psi}$$

is a bijection. We proceed to construct the required inverse via a cowedge  $\Lambda(\dot{h}\omega, \dot{h}-) \times X_{(-)} \longrightarrow X_{\omega}$ , using a case analysis on  $\omega \in \mathbb{O}_{n-k, n+2}$ .

- (1) Assume  $\omega \in \mathbb{O}_{n-k, n-1}$ . We have  $\Lambda(\dot{h}\omega, \dot{h}-) \cong \mathbb{O}_{n-k, n+2}(\omega, -)$  and this is just the change-of-variable formula.

- (2) Assume  $\omega \in \mathbb{O}_n$ . By lemma 4.5.2 and lemma 4.5.3, it suffices to consider the case  $\psi \in \mathbb{O}_{n+1}$ . We have the sequence of morphisms

$$\begin{aligned} \mathbb{A}(\dot{h}\omega, \dot{h}\psi) \times X_\psi & \cong \left( \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \omega}} \mathcal{Psh}(\mathbb{O}_{n-k, n+2})(\Lambda^{\mathfrak{t}[\nu]}, \Lambda^{\mathfrak{t}[\psi]}) \right) \times \mathcal{Psh}(\mathbb{O}_{n-k, n+2})(\Lambda^{\mathfrak{t}[\psi]}, X) \\ \longrightarrow \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \omega}} \mathcal{Psh}(\mathbb{O}_{n-k, n+2})(\Lambda^{\mathfrak{t}[\nu]}, X) & \cong \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \omega}} X_\nu \\ \xrightarrow{\mathfrak{t}} X_\omega. \end{aligned}$$

It is straightforward to verify that this defines a cowedge whose induced map is the required inverse.

- (3) Assume  $\omega \in \mathbb{O}_{n+1}$ . If  $\omega$  is degenerate, say  $\omega = \mathbf{l}_\phi$  for some  $\phi \in \mathbb{O}_{n-1}$ , then  $\mathbb{A}(\dot{h}\omega, \dot{h}-) \cong \mathbb{A}(\dot{h}\phi, \dot{h}-)$  and we are in a case we have treated before. So let  $\omega$  be non-degenerate. By lemmas 4.5.2 and 4.5.3, we may suppose  $\psi \in \mathbb{O}_{n, n+1}$ . Recall that for every  $f \in \mathbb{A}(\dot{h}\omega, \dot{h}\psi)$ , the diagrammatic lemma 4.4.8 computes a  $\xi \in \mathbb{O}_{n+2}$  and  $[p] \in \xi^\bullet$  such that  $\mathfrak{s}_{[p]}\xi = \omega$ ,  $\mathfrak{t}\xi = \psi$  and  $\dot{h}\mathfrak{s}_{[p]} = f$ . By corollary 3.4.10,  $X_\xi \cong X_\psi$ , and thus this gives a function

$$\begin{aligned} \mathbb{A}(\dot{h}\omega, \dot{h}\psi) \times X_\psi & \longrightarrow X_\omega \\ (f, x) & \longmapsto \mathfrak{s}_{[p]}(x). \end{aligned}$$

It is straightforward to verify that this assignment defines a cowedge, whose associated map is the required inverse.

- (4) Assume  $\omega \in \mathbb{O}_{n+2}$ . Then by definition of  $\dot{h}$ ,  $\mathbb{A}(\dot{h}\omega, \dot{h}-) \cong \mathbb{A}(\dot{h}\mathfrak{t}\omega, \dot{h}-)$ , and this is the case we have just treated.  $\square$

**Corollary 4.5.5.** *If  $\mathbf{H}_{n+1, n+2} \perp X$ , then  $\mathbf{S} \perp \dot{h}_! X$ .*

*Proof.* Recall from lemma 4.5.1 that  $\mathbf{S} = \dot{h}_! \mathbf{H}_{n+1}$ . Let  $\omega \in \mathbb{O}_{n+1}$ . We have

$$\begin{aligned} \mathcal{Psh}(\mathbb{A})(\dot{h}_! \Lambda^{\mathfrak{t}[\omega]}, \dot{h}_! X) & \cong \mathcal{Psh}(\mathbb{O}_{n-k, n+2})(\Lambda^{\mathfrak{t}[\omega]}, \dot{h}^* \dot{h}_! X) && \text{since } \dot{h}_! \dashv \dot{h}^* \\ & \cong \mathcal{Psh}(\mathbb{O}_{n-k, n+2})(\Lambda^{\mathfrak{t}[\omega]}, X) && \text{by proposition 4.5.4} \\ & \cong \mathcal{Psh}(\mathbb{O}_{n-k, n+2})(\omega, X) && \text{since } \mathbf{H}_{n+1} \perp X \\ & \cong \mathcal{Psh}(\mathbb{O}_{n-k, n+2})(\omega, \dot{h}^* \dot{h}_! X) && \text{by proposition 4.5.4} \\ & \cong \mathcal{Psh}(\mathbb{A})(\dot{h}_! \omega, \dot{h}_! X) && \text{since } \dot{h}_! \dashv \dot{h}^*. \end{aligned}$$

$\square$

This second crucial proposition will provide the other half of the equivalence between  $\mathcal{Alg}$  and the localisation  $\mathbf{H}_{n+1, n+2}^{-1} \mathcal{Psh}(\mathbb{O}_{n-k, n+2})$ .

**Proposition 4.5.6.** *Let  $Y \in \mathcal{Psh}(\mathbb{A})$ . If  $\mathbf{S} \perp Y$ , then the counit  $\dot{h}_! \dot{h}^* Y \longrightarrow Y$  is an isomorphism.*

*Proof.* It suffices to prove that for each  $\lambda \in \mathbb{A}$ , the map

$$(\dot{h}_! Y)_\lambda = \int^{\psi \in \mathbb{O}_{n-k, n+2}} \mathbb{A}(\lambda, \dot{h}\psi) \times Y_{\dot{h}\psi} \longrightarrow Y_\lambda \quad (4.5.7)$$

is a bijection. Since the map<sup>(10)</sup>

$$\begin{aligned} Y_\lambda &\longrightarrow \int^\psi \wedge(\lambda, \dot{h}\psi) \times Y_{\dot{h}\psi} \\ y &\longmapsto \text{id} \otimes y \end{aligned}$$

is clearly a section, it is enough to prove that it is surjective. The map is well defined, as  $\dot{h}$  is surjective on objects and it is easy to verify that it is independent of the choice of an antecedent  $\dot{h}\nu = \lambda$ . We need to show that for every  $\psi \in \mathbb{O}_{n-k, n+2}$ , every  $f \otimes y \in \wedge(\lambda, \dot{h}\psi) \times Y_{\dot{h}\psi}$  is equal, in the colimit (4.5.7), to  $\text{id} \otimes y' \in \wedge(\lambda, \lambda) \times Y_\lambda$  for some  $y' \in Y_\lambda$ .

- (1) Assume  $\lambda = \mathfrak{Z}\phi$ , with  $\phi \in \mathbb{O}_{n-k, n-1}$ . Then  $\wedge(\lambda, \dot{h}-) \cong \mathbb{O}_{n-k, n+2}(\phi, -)$  and any pair  $f \otimes y \in \mathbb{O}_{n-k, n+2}(\phi, \psi) \times Y_\psi$  is related via a zig-zag relation

$$f \otimes y \xleftarrow{\sim} \text{id}_\phi \otimes (\dot{h}f)(y)$$

to an element of the required form.

- (2) Assume  $\lambda = \mathfrak{Z}\omega$ , with  $\omega \in \mathbb{O}_n$ . By lemma 4.5.2 and lemma 4.5.3, we may consider only the case where  $\psi \in \mathbb{O}_{n+1}$ . Note that  $\wedge(\lambda, \dot{h}\psi) \cong \wedge(\dot{h}Y_\omega, \dot{h}\psi)$ . Then  $f \otimes y \in \wedge(\dot{h}Y_\omega, \dot{h}-)$  is related via a zig-zag relation

$$f \otimes y \xleftarrow{\mathfrak{s}_{[p]}} \text{id}_{\dot{h}Y_\omega} \otimes (\dot{h}\mathfrak{s}_{[p]})(y)$$

where we use lemma 4.4.8 to obtain  $\mathfrak{s}_{[p]} : Y_\omega \longrightarrow \xi$  such that  $\dot{h}\mathfrak{s}_{[p]} = f$ .

- (3) The case  $\lambda = \mathfrak{Z}\Lambda^\dagger[\omega]$ , with  $\omega \in \mathbb{O}_{n+1}$  identical to the previous one. □

Let the localisation of  $\mathcal{Psh}(\mathbb{O}_{n-k, n+2})$  at the set of horn inclusions  $\mathbf{H}_{n+1, n+2}$  be denoted

$$v : \mathcal{Psh}(\mathbb{O}_{n-k, n+2}) \xleftrightarrow{\perp} \mathbf{H}_{n+1, n+2}^{-1} \mathcal{Psh}(\mathbb{O}_{n-k, n+2}) : N_v$$

On the other hand, recall from proposition 4.4.1 that we have a localisation  $u : \mathcal{Psh}(\wedge) \xleftrightarrow{\perp} \mathcal{Alg} : N_u$ . We are now well-equipped to prove that  $\mathcal{Alg}$  is equivalent to the localised category  $\mathbf{H}_{n+1, n+2}^{-1} \mathcal{Psh}(\mathbb{O}_{n-k, n+2})$ .

**Proposition 4.5.8.** *The adjunction  $\dot{h}_! : \mathcal{Psh}(\mathbb{O}_{n-k, n+2}) \xleftrightarrow{\perp} \mathcal{Psh}(\wedge) : \dot{h}^*$  restricts to an adjunction  $\tilde{h}_! \dashv \tilde{h}^*$ , as shown below.*

$$\begin{array}{ccc} \mathbf{H}_{n+1, n+2}^{-1} \mathcal{Psh}(\mathbb{O}_{n-k, n+2}) & \xleftrightarrow[\tilde{h}^*]{\tilde{h}_!} & \mathcal{Alg} \\ v \downarrow & & \downarrow N_u \\ \mathcal{Psh}(\mathbb{O}_{n-k, n+2}) & \xleftrightarrow[\dot{h}^*]{\dot{h}_!} & \mathcal{Psh}(\wedge). \end{array}$$

*Proof.* For all  $Y \in \mathcal{Alg} \simeq \mathbf{S}^{-1} \mathcal{Psh}(\wedge)$ , by lemma 4.5.1, we have that  $\dot{h}_! \mathbf{H}_{n+1, n+2} \perp N_u Y$ , or equivalently,  $\mathbf{H}_{n+1, n+2} \perp \dot{h}^* N_u Y$ . Thus  $\dot{h}^* N_u$  factors through  $\mathbf{H}_{n+1, n+2}^{-1} \mathcal{Psh}(\mathbb{O}_{n-k, n+2})$ . Next, by corollary 4.5.5,  $\dot{h}_! N_v$  factors through  $\mathcal{Alg}$ . □

**Corollary 4.5.9.** *The adjunction  $\tilde{h}_! : \mathbf{H}_{n+1, n+2}^{-1} \mathcal{Psh}(\mathbb{O}_{n-k, n+2}) \xleftrightarrow{\perp} \mathcal{Alg} : \tilde{h}^*$  is an equivalence.*

*Proof.* This is a direct consequence of propositions 4.5.4 and 4.5.6. □

<sup>(10)</sup>We use the notation  $a \otimes b$  to refer to elements in a coend of sets of the form  $\int^{c \in \mathcal{C}} A_c \times B_c$ , with  $A \in [\mathcal{C}^{\text{op}}, \text{Set}]$  and  $B \in [\mathcal{C}, \text{Set}]$ , our motivation being the tensor product of modules.

With corollary 4.5.9 in hand, let

$$h : \mathcal{Psh}(\mathbb{O}) \xrightleftharpoons{\quad} \mathcal{Alg} : N.$$

be the composite adjunction

$$\mathcal{Psh}(\mathbb{O}) \xrightleftharpoons{\quad} \mathcal{Psh}(\mathbb{O}_{n-k,n+2}) \xrightleftharpoons{v} \mathbf{H}_{n+1,n+2} \mathcal{Psh}(\mathbb{O}_{n-k,n+2}) \xrightleftharpoons{\tilde{h}_1} \mathcal{Alg}.$$

**Theorem 4.5.10** (Nerve theorem for opetopic algebras). *The reflective adjunction  $h : \mathcal{Psh}(\mathbb{O}) \rightarrow \mathcal{Alg} : N$  exhibits  $\mathcal{Alg}$  as the Gabriel–Ulmer localisation of  $\mathcal{Psh}(\mathbb{O})$  at the set of arrows  $\mathbf{A}$ . That is  $\mathcal{Alg} \simeq \mathbf{A}^{-1}\mathcal{Psh}(\mathbb{O})$ .*

*Proof.* By a general fact about composite localisations, the reflective adjunction  $h : \mathcal{Psh}(\mathbb{O}) \rightarrow \mathcal{Alg} : N$  exhibits  $\mathcal{Alg}$  as the localisation of  $\mathcal{Psh}(\mathbb{O})$  at the set  $\mathbf{O}_{<n-k} \cup \mathbf{H}_{n+1,n+2} \cup \mathbf{B}_{>n+2}$ . The result then follows from lemma 3.4.7.  $\square$

**Corollary 4.5.11.** *We have  $\mathbb{A} = h\mathbb{O}_{n-k,n+2}$ , i.e.  $h = \dot{h} : \mathbb{O}_{n-k,n+2} \rightarrow \mathbb{A}$  is surjective on objects (by definition) and on morphisms.*

*Proof.* Let  $\omega, \omega' \in \mathbb{O}_{n-k,n+2}$ .

- (1) If  $\dim \omega, \dim \omega' < n - 1$ , then  $h\omega = \omega$  and  $h\omega' = \omega'$  as presheaves over  $\mathbb{O}_{n-k,n+2}$ , and thus

$$\mathbb{A}(h\omega, h\omega') = h\mathcal{Psh}(\mathbb{O}_{n-k,n+2})(\omega, \omega') = h\mathbb{O}(\omega, \omega').$$

- (2) If  $\dim \omega < n - 1$  and  $\dim \omega' \geq n - 1$ , then since  $h\omega = \omega$  we have

$$\mathbb{A}(h\omega, h\omega') \cong \mathcal{Psh}(\mathbb{O}_{n-k,n+2})(\omega, h\omega') \cong h\mathcal{Psh}(\mathbb{O}_{n-k,n+2})(\omega, \omega') \cong h\mathbb{O}(\omega, \omega'),$$

where the second isomorphism comes from the fact that for  $X \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$ ,  $\mathfrak{Z}^n X_{<n} = X_{<n}$ .

- (3) If  $\dim \omega \geq n - 1$  and  $\dim \omega' < n - 1$ , then  $\mathbb{A}(h\omega, h\omega') = \emptyset$ .

- (4) Lastly, assume  $\dim \omega, \dim \omega' \geq n - 1$ . By corollary 3.4.11, if  $\dim \omega = n - 1$ , then  $h$  maps  $\mathbf{tt} : \omega \rightarrow \mathbf{l}_\omega$  to an isomorphism, and if  $\dim \omega = n$ , then  $h$  maps  $\mathbf{s}_{\square} : \omega \rightarrow \mathbf{Y}_\omega$  to an isomorphism. By corollary 3.4.10, if  $\dim \omega = n + 2$ , then  $h$  maps  $\mathbf{t} : \mathbf{t}\omega \rightarrow \omega$  to an isomorphism as well. Hence, without loss of generality, we may assume that  $\dim \omega = \dim \omega' = n + 1$ . If  $\omega$  is non degenerate, then every morphism in  $\mathbb{A}(h\omega, h\omega')$  is diagrammatic, thus in the image of  $h$ . Otherwise, if  $\omega = \mathbf{l}_\phi$  for some  $\phi \in \mathbb{O}_{n-1}$ , then

$$\mathbb{A}(h\omega, h\omega') \cong \mathbb{A}(h\phi, h\omega') \cong h\mathbb{O}(\phi, \omega').$$

where the first isomorphism comes from corollary 3.4.11.  $\square$

## 5. ALGEBRAIC TROMPE-L'ŒIL

As we saw in section 4, for each  $k, n \geq 1$ , we have a notion of  $k$ -coloured opetopic  $n$ -algebra. For such an algebra  $B \in \mathcal{Alg}^k(\mathfrak{Z}^n)$ , operations are  $n$ -cells (so that their shapes are  $n$ -opetopes), and colours are cells of dimension  $n - k$  to  $n - 1$ , thus the “colour space” is stratified over  $k$  dimensions. Notable examples include

$$\mathcal{Cat} \simeq \mathcal{Alg}^1(\mathfrak{Z}^1), \quad \mathcal{Op}_{\text{col}} \simeq \mathcal{Alg}^1(\mathfrak{Z}^2).$$

But are all  $\mathcal{Alg}^k(\mathfrak{Z}^n)$  fundamentally different?

In this section, we answer this question negatively: in a sense that we make precise, the most “algebraically rich” notion of opetopic algebra is given in the case  $(k, n) = (1, 3)$ . Although opetopes can be arbitrarily complex, the algebraic data can be expressed by much simpler 3-opetopes, a.k.a. trees. We call this phenomenon *algebraic trompe-l'œil*, a french expression that literally translates as “fools-the-eye”. And indeed, the eye is fooled in two ways: by colour (proposition 5.1.4) and shape (proposition 5.2.7). In the former, we argue that the colours of an algebra  $B \in \mathcal{Alg}^k(\mathfrak{Z}^n)$ , expressing how operations may or may not be composed, only need 1 dimension, and thus that cells of dimension less than  $n - 1$  do not bring new algebraic data, only geometrical one. For the latter, recall from section 3.1 that opetopes are

trees of opetopes. In particular, 3-opetopes are just plain trees, and  $\mathbb{O}_3$  already contains all the possible underlying trees of all opetopes. Consequently, operations of  $B$ , which are its  $n$ -cells, may be considered as 3-cells in a very similar 3-algebra  $B_{\dagger}$ . Finally, we combine those two results in theorem 5.2.8, which states that an algebra  $B \in \mathcal{Alg}^k(\mathfrak{Z}^n)$  is exactly a presheaf  $B \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$  with a 1-coloured 3-algebra structure on  $B_{n-1,n,\dagger}$ .

**5.1. Colour.** For  $B \in \mathcal{Alg}^k(\mathfrak{Z}^n)$ , recall that the colours of  $B$  are its cells of dimension  $n - k$  to  $n - 1$ . They express which operations ( $n$ -cells) of  $B$  may or may not be composed. However, since that criterion only depends on  $(n - 1)$ -cells, constraints expressed by lower dimensional cells should be redundant. In proposition 5.1.4, we show that this is indeed the case, in that the algebra structure on  $B$  is completely determined by a 1-coloured  $n$ -algebra structure on  $B_{n-1,n}$ .

**Lemma 5.1.1.** *Let  $k, n \geq 1$ , and  $\nu \in \mathbb{O}_{n+1}$ . Then*

$$\Lambda^{\dagger}[\nu]_{n-k,n} \cong \iota_!(\Lambda^{\dagger}[\nu]_{n-1,n}),$$

where  $\iota_!$  is the left adjoint to the truncation  $\mathcal{Psh}(\mathbb{O}_{n-k,n}) \rightarrow \mathcal{Psh}(\mathbb{O}_{n-1,n})$ .

*Proof.* It follows from the fact that  $\Lambda^{\dagger}[\nu]$  is completely determined by the incidence relation of the  $n$ - and  $(n - 1)$ -faces of  $\nu$ .  $\square$

**Proposition 5.1.2.** *For  $X \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$  we have  $\mathfrak{Z}^n(X_{n-1,n}) \cong (\mathfrak{Z}^n X)_{n-1,n}$ . Consequently, the truncation functor  $(-)_n : \mathcal{Psh}(\mathbb{O}_{n-k,n}) \rightarrow \mathcal{Psh}(\mathbb{O}_{n-1,n})$  lifts as*

$$\begin{array}{ccc} \mathcal{Alg}^k(\mathfrak{Z}^n) & \xrightarrow{(-)_n} & \mathcal{Alg}^1(\mathfrak{Z}^n) \\ \downarrow & & \downarrow \\ \mathcal{Psh}(\mathbb{O}_{n-k,n}) & \xrightarrow{(-)_n} & \mathcal{Psh}(\mathbb{O}_{n-1,n}). \end{array} \quad (5.1.3)$$

*Proof.* First,  $\mathfrak{Z}^n(X_{n-1,n})_{n-1} = X_{n-1} = (\mathfrak{Z}^n X)_{n-1}$ . Then, for  $\psi \in \mathbb{O}_n$ , we have

$$\begin{aligned} \mathfrak{Z}^n(X_{n-1,n})_{\psi} &= \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \psi}} \mathcal{Psh}(\mathbb{O}_{n-1,n})(\Lambda^{\dagger}[\nu], X_{n-1,n}) \\ &\cong \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \psi}} \mathcal{Psh}(\mathbb{O}_{n-1,n})(\iota_!(\Lambda^{\dagger}[\nu]), X) \\ &\cong \sum_{\substack{\nu \in \mathbb{O}_{n+1} \\ \mathfrak{t}\nu = \psi}} \mathcal{Psh}(\mathbb{O}_{n-1,n})(\Lambda^{\dagger}[\nu], X) && \text{by lemma 5.1.1} \\ &= (\mathfrak{Z}^n X)_{\psi}. \end{aligned}$$

$\square$

**Proposition 5.1.4.** *The square (5.1.3) is a pullback. That is, a  $\mathfrak{Z}^n$ -algebra structure on  $X \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$  is completely determined by a  $\mathfrak{Z}^n$ -algebra structure on  $X_{n-1,n}$ .*

*Proof.* Let  $X \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$ . By proposition 5.1.2, a  $\mathfrak{Z}^n$ -algebra structure on  $X$  restricts to one on  $X_{n-1,n}$ . Conversely, since  $(\mathfrak{Z}^n X)_{<n} = X_{<n}$ , a  $\mathfrak{Z}^n$ -algebra structure on  $X_{n-1,n}$  extends to one on  $X$ . Since the truncation functor  $(-)_n : \mathcal{Alg}^k(\mathfrak{Z}^n) \rightarrow \mathcal{Alg}^1(\mathfrak{Z}^n)$  is faithful, it establishes a bijective correspondence between the algebra structures on  $X$  and on  $X_{n-1,n}$ .  $\square$

**5.2. Shape.** We start by defining a functor  $(-)_\dagger : \mathbb{O}_{n-1,n} \rightarrow \mathbb{O}_{2,3}$ , for  $n \geq 1$ , mapping an  $n$ -opetope  $\omega$  to the unique 3-opetope  $\omega_\dagger$  having the same underlying polynomial tree, i.e.  $\langle \omega_\dagger \rangle \cong \langle \omega \rangle$  (see notations of section 2.2).

If  $n = 1$ , then  $(-)_\dagger$  simply maps  $\mathbb{O}_{0,1} = \left( \blacklozenge \xrightarrow{s_*,t} \blacksquare \right)$  to the diagram  $\left( \mathbf{0} \xrightarrow{s[\cdot],t} Y_0 \right)$ .

Assume now that  $n \geq 2$ . Recall that a 3-opetope is a  $\mathfrak{Z}^1$ -tree, where  $\mathfrak{Z}^1$  is given by

$$\{\blacksquare\} \xleftarrow{s} E_2 \xrightarrow{p} \mathbb{O}_2 \xrightarrow{t} \{\blacksquare\},$$

with  $\mathbb{O}_2 = \{\mathbf{n} \mid n \in \mathbb{N}\}$  and  $E_2(\mathbf{n}) = \mathbf{n}^\bullet$ . Let  $f : \mathfrak{Z}^{n-2} \rightarrow \mathfrak{Z}^1$  be given by

$$\begin{array}{ccccccc} \mathbb{O}_{n-2} & \xleftarrow{s} & E_{n-2} & \xrightarrow{p} & \mathbb{O}_{n-1} & \xrightarrow{t} & \mathbb{O}_{n-2} \\ f_0 \downarrow & & \downarrow f_2 & \lrcorner & \downarrow f_1 & & \downarrow f_0 \\ \{\blacksquare\} & \xleftarrow{s} & E_2 & \xrightarrow{p} & \mathbb{O}_2 & \xrightarrow{t} & \{\blacksquare\}, \end{array}$$

where  $f_1(\psi) = \mathbf{m}$ , for  $m = \#\psi^\bullet$  the number of source faces of  $\psi$ , and where  $f_2$  is fiberwise increasing. This morphism of polynomial functors induces a functor  $f_* : \mathbb{O}_n = \text{tr } \mathfrak{Z}^{n-2} \rightarrow \text{tr } \mathfrak{Z}^1 = \mathbb{O}_3$  mapping an  $n$ -opetope to its underlying tree, seen as a 3-opetope. Explicitly,

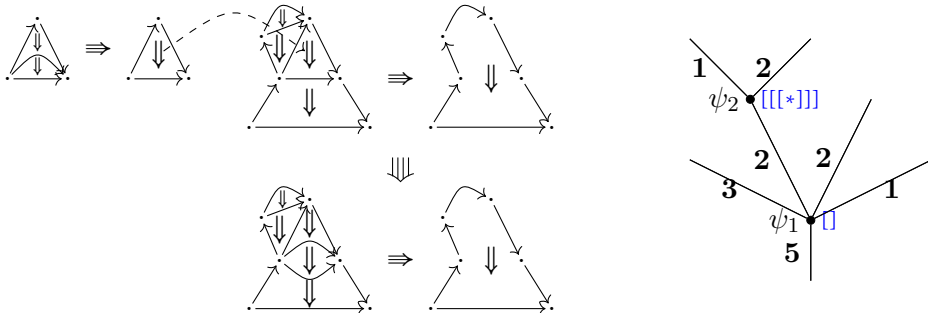
$$f_* l_\phi = l_\bullet, \quad f_* \left( Y_\psi \bigcirc_{[[p_i]]} \nu_i \right) = \mathbf{m} \bigcirc_{[[*^i]]} f_*(\nu_i),$$

where  $\phi \in \mathbb{O}_{n-2}$ ,  $\psi \in \mathbb{O}_{n-1}$ ,  $\psi^\bullet = \{[p_0] < \dots < [p_{m-1}]\}$ , and  $\nu_0, \dots, \nu_{m-1} \in \mathbb{O}_n$ . For  $\omega \in \mathbb{O}_n$ , since  $\omega$  and  $\omega_\dagger$  have the same underlying tree, they have the same number of source faces:  $\#\omega^\bullet = \#\omega_\dagger^\bullet$ , and we write  $a_\omega$  for the unique increasing map  $\omega^\bullet \rightarrow \omega_\dagger^\bullet$  (with respect to the lexicographical order  $<$ ). Intuitively,  $a_\omega$  maps a node of the underlying tree  $\langle \omega \rangle$  of  $\omega$  to that same node in  $\langle \omega_\dagger \rangle$ , but using addresses. Since the source faces of  $\omega$  and  $\omega_\dagger$  are not the same,  $a_\omega$  is not strictly speaking an identity, but rather a conversion of a “walking instruction in the tree  $\omega$ ” (which is what an address is) to one in  $\omega_\dagger$ . Explicitly, a node address  $[[q_1] \dots [q_k]] \in \omega^\bullet$  (with  $[q_{i+1}] \in s_{[[q_1] \dots [q_i]]} \omega$ ) is mapped to  $[f_{2,s[1]} \omega [q_1] \dots f_{2,s[[q_1] \dots [q_{k-1}]]} \omega [q_k]]$ .

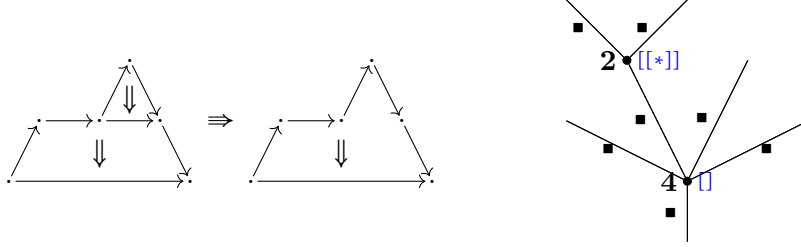
Define now  $(-)_\dagger : \mathbb{O}_{n-1,n} \rightarrow \mathbb{O}_{2,3}$  as follows: for  $\psi \in \mathbb{O}_{n-1}$  and  $\omega \in \mathbb{O}_n$

- (1)  $\psi_\dagger = f_1(\psi)$  as above;
- (2)  $\omega_\dagger = f_*(\omega)$  as above;
- (3) we have  $(t\omega)_\dagger = t\omega_\dagger$ , so let  $(t\omega \xrightarrow{t} \omega)_\dagger = ((t\omega)_\dagger \xrightarrow{t} \omega_\dagger)$ ;
- (4) for  $[p] \in \omega^\bullet$ , we have  $(s_{[p]}\omega)_\dagger = s_{a_\omega[p]}\omega_\dagger$ , so let  $(s_{[p]}\omega \xrightarrow{s_{[p]}} \omega)_\dagger = ((s_{[p]}\omega)_\dagger \xrightarrow{s_{a_\omega[p]}} \omega_\dagger)$ .

**Example 5.2.1.** Consider the 4-opetope  $\omega$ , represented graphically and in tree form below:



where  $\psi_1$  and  $\psi_2$  are the 3-opetopes on the top right and top left hand corner respectively. Then  $\omega_{\dagger}$  is as follows:



Although the graphical representations of  $\omega$  and  $\omega_{\dagger}$  look nothing alike, note that their underlying undecorated trees are identical.

We abuse notations and let  $(-)\dagger : \mathcal{Psh}(\mathbb{O}_{n-1,n}) \longrightarrow \mathcal{Psh}(\mathbb{O}_{2,3})$  be the left Kan extension of  $\mathbb{O}_{n-1,n} \xrightarrow{(-)\dagger} \mathbb{O}_{2,3} \longrightarrow \mathcal{Psh}(\mathbb{O}_{2,3})$  along the Yoneda embedding. Explicitly, for  $X \in \mathcal{Psh}(\mathbb{O}_{n-1,n})$ , we have

$$X_{\dagger, \mathbf{m}} = \sum_{\substack{\psi \in \mathbb{O}_{n-1} \\ \psi_{\dagger} = \mathbf{m}}} X_{\psi}, \quad X_{\dagger, \gamma} = \sum_{\substack{\omega \in \mathbb{O}_{n-1} \\ \omega_{\dagger} = \gamma}} X_{\omega},$$

with  $m \in \mathbb{N}$  and  $\gamma \in \mathbb{O}_3$ . Clearly,  $(-)\dagger$  is faithful, and if  $n \leq 3$ , then  $(-)\dagger$  is also injective on object. Note that this is no longer the case if  $n \geq 4$ , as distinct  $n$ -opetopes may have the same underlying tree.

*Notation 5.2.2.* Let  $\mathcal{C}$  be a small category, and  $X \in \mathcal{Psh}(\mathcal{C})$  be presheaf over  $\mathcal{C}$ . There is a canonical projection  $(-)^{\natural} : \mathcal{C}/X \longrightarrow \mathcal{C}$ , mapping  $x \in X_c$  to  $c \in \mathcal{C}$ . We may then see the category of elements  $\mathcal{C}/X$  of  $X$  as having objects elements of  $\sum_{c \in \mathcal{C}} X_c$ , and a morphism  $f : x \longrightarrow y$  is a morphism  $f : x^{\natural} \longrightarrow y^{\natural}$  in  $\mathcal{C}$  such that  $f(y) = x$ . A morphism  $g : X \longrightarrow Y$  of presheaves over  $\mathcal{C}$  then amounts to a functor  $g : \mathcal{C}/X \longrightarrow \mathcal{C}/Y$  that preserves shapes.

Take  $n \geq 1$ . For  $X \in \mathcal{Psh}(\mathbb{O}_{n-1,n})$ , note that there is a canonical isomorphism  $\mathcal{Psh}(\mathbb{O}_{n-1,n})/X \longrightarrow \mathcal{Psh}(\mathbb{O}_{2,3})/X_{\dagger}$ , which is the identity on objects, maps  $s_{[p]} : x \longrightarrow y$  to  $s_{a_{\omega}[p]} x \longrightarrow y$ , where  $\omega = y^{\natural}$ , and target embeddings to target embeddings.

- Lemma 5.2.3.** (1) For  $\nu \in \mathbb{O}_{n+1}$ , there exists a unique 4-opetope  $\nu' \in \mathbb{O}_4$  such that  $\Lambda^{\natural}[\nu]_{n-1,n,\dagger} \cong \Lambda^{\natural}[\nu']$ .  
 (2) Let  $X \in \mathcal{Psh}(\mathbb{O}_{n-1,n})$ ,  $\nu \in \mathbb{O}_4$ , and  $f : \Lambda^{\natural}[\nu] \longrightarrow X_{\dagger}$ . Then there exists a unique  $\nu' \in \mathbb{O}_{n+1}$  and  $f' : \Lambda^{\natural}[\nu'] \longrightarrow X$  such that  $\Lambda^{\natural}[\nu']_{n-1,n,\dagger} = \Lambda^{\natural}[\nu]$ , and  $f'_{\dagger} = f$ .

*Proof.* (1) If  $\nu = \mathbf{l}_{\phi}$  for  $\phi \in \mathbb{O}_{n-1}$ , let  $\nu' = \mathbf{l}_{\phi_{\dagger}}$ . If  $\nu = \mathbf{Y}_{\omega} \circ_{[[p_i]]} \nu_i$ , let

$$\nu' = \mathbf{Y}_{\omega_{\dagger}} \bigcirc_{[a_{\omega}[p_i]]} \nu'_i,$$

where the  $\nu'_i$  are given by induction. The graftings are well defined since

$$\mathbf{t} s_{[\ ]} \nu'_i = \mathbf{t}(s_{[\ ]} \nu_i)_{\dagger} = (\mathbf{t} s_{[\ ]} \nu_i)_{\dagger} = (s_{[p_i]} \omega)_{\dagger} = s_{a_{\omega}[p_i]} \omega_{\dagger}.$$

The isomorphism  $\Lambda^{\natural}[\nu]_{n-1,n,\dagger} \cong \Lambda^{\natural}[\nu']$  can easily be shown by induction on the structure of  $\nu$  and using lemma 3.4.2.

- (2) For  $\nu^{\bullet} = \{[p_1], \dots, [p_m]\}$ ,  $f$  maps  $[p_i]$  to a cell  $x_i \in X_{\dagger,2} = X_{n-1}$ , and let  $\psi_i \in \mathbb{O}_{n-1}$  be the shape of  $x_i$  as a cell of  $X$ . If  $[p_i] = [p_j[q]]$  for some  $j$  and  $[q]$ , then  $s_{[q]} x_j = \mathbf{t} x_i$  in  $X_{\dagger}$ , so  $s_{a_{\psi_j}^{-1}[q]} x_j = \mathbf{t} x_i$  in  $X$ , and in particular,  $s_{a_{\psi_j}^{-1}[q]} \psi_j = \mathbf{t} \psi_i$ . Consequently, the  $\psi_i$ s may be grafted together into a  $(n+1)$ -opetope  $\nu'$  such that  $\nu'_{\dagger} = \nu$ , and  $s_{a_{\nu'}^{-1}[p_i]} = \psi_i$ . Define  $f' : \Lambda^{\natural}[\nu'] \longrightarrow X$  mapping  $s_{a_{\nu'}^{-1}[p_i]} \nu'$  to  $x_i$ , and observe that  $f'_{\dagger} = f$ .  $\square$



**Proposition 5.2.4.** *For  $X \in \mathcal{Psh}(\mathbb{O}_{n-1,n})$  we have  $\mathfrak{Z}^3(X_{\dagger}) \cong (\mathfrak{Z}^n X)_{\dagger}$ . Consequently, the functor  $(-)_{\dagger}$  lifts as*

$$\begin{array}{ccc} \mathcal{Alg}^1(\mathfrak{Z}^n) & \xrightarrow{(-)_{\dagger}} & \mathcal{Alg}^1(\mathfrak{Z}^3) \\ \downarrow & & \downarrow \\ \mathcal{Psh}(\mathbb{O}_{n-1,n}) & \xrightarrow{(-)_{\dagger}} & \mathcal{Psh}(\mathbb{O}_{2,3}). \end{array} \quad (5.2.5)$$

*Proof.* First,  $\mathfrak{Z}^3(X_{\dagger})_2 = X_{\dagger,2} = X_{n-1} = (\mathfrak{Z}^n X)_{n-1} = (\mathfrak{Z}^n X)_{\dagger,2}$ . Then,

$$\begin{aligned} \mathfrak{Z}^3(X_{\dagger})_3 &= \sum_{\nu \in \mathbb{O}_4} \mathcal{Psh}(\mathbb{O}_{2,3})(\Lambda^{\dagger}[\nu], X_{\dagger}) \\ &\cong \sum_{\nu \in \mathbb{O}_{n+1}} \mathcal{Psh}(\mathbb{O}_{n-1,n})(\Lambda^{\dagger}[\nu], X) && \text{by lemma 5.2.3} \\ &= (\mathfrak{Z}^n X)_n = (\mathfrak{Z}^n X)_{\dagger,3}. \end{aligned}$$

□

**Lemma 5.2.6.** *Let  $X \in \mathcal{Psh}(\mathbb{O}_{n-1,n})$  and  $m : \mathfrak{Z}^n X \rightarrow X$ . Then  $m$  is an algebra structure on  $X$  if and only if  $m_{\dagger} : \mathfrak{Z}^3 X_{\dagger} \rightarrow X_{\dagger}$  is an algebra structure on  $X_{\dagger}$ .*

*Proof.* Clearly,  $(-)_{\dagger}$  maps the multiplication  $\mu^n : \mathfrak{Z}^n \mathfrak{Z}^n \rightarrow \mathfrak{Z}^n$  to  $\mu^3$ , and the unit  $\eta^n : \text{id} \rightarrow \mathfrak{Z}^n$  to  $\eta^3$ . Since  $(-)_{\dagger}$  is faithful, the square on the left commutes if and only if the square on the right commutes

$$\begin{array}{ccc} \mathfrak{Z}^n \mathfrak{Z}^n X & \xrightarrow{\mathfrak{Z}^n m} & \mathfrak{Z}^n X \\ \mu^n \downarrow & & \downarrow m \\ \mathfrak{Z}^n X & \xrightarrow{m} & X, \end{array} \quad \begin{array}{ccc} \mathfrak{Z}^3 \mathfrak{Z}^3 X_{\dagger} & \xrightarrow{\mathfrak{Z}^3 m_{\dagger}} & \mathfrak{Z}^3 X_{\dagger} \\ \mu^3 \downarrow & & \downarrow m_{\dagger} \\ \mathfrak{Z}^3 X_{\dagger} & \xrightarrow{m_{\dagger}} & X_{\dagger}, \end{array}$$

and likewise for the diagram involving  $\eta^n$  and  $\eta^3$ . □

**Proposition 5.2.7.** *The square (5.2.5) is a pullback. That is, a  $\mathfrak{Z}^n$ -algebra structure on  $X \in \mathcal{Psh}(\mathbb{O}_{n-1,n})$  is completely determined by a  $\mathfrak{Z}^3$ -algebra structure on  $X_{\dagger}$ .*

*Proof.* Let  $X \in \mathcal{Psh}(\mathbb{O}_{n-1,n})$ . By proposition 5.2.4, a  $\mathfrak{Z}^n$ -algebra structure on  $X$  induces a  $\mathfrak{Z}^3$ -algebra structure on  $X_{\dagger}$ .

Conversely, let  $m : \mathfrak{Z}^3 X_{\dagger} \rightarrow X_{\dagger}$  be a  $\mathfrak{Z}^3$ -algebra structure on  $X_{\dagger}$ , and define  $m' : \mathfrak{Z}^n X \rightarrow X$  as the identity in dimension  $n-1$ , and mapping  $f : \Lambda^{\dagger}[\nu] \rightarrow X$  to  $m(f_{\dagger}) \in X_{\dagger,2} = X_{n-1}$ . Recall that  $f_{\dagger}$  is a map of the form  $\Lambda^{\dagger}[\nu'] \rightarrow X_{\dagger}$ , for some  $\nu'$  such that  $\mathfrak{t}\nu' = (\mathfrak{t}\nu)_{\dagger}$ , and thus  $m'$  is a map of opetopic sets. By lemma 5.2.6, it is a  $\mathfrak{Z}^n$ -algebra structure on  $X$ .

Since  $(-)_{\dagger}$  is faithful, it establishes a bijective correspondence between the  $\mathfrak{Z}^n$ -algebra structures on  $X$  and the  $\mathfrak{Z}^3$ -algebra structures on  $X_{\dagger}$ . □

**Theorem 5.2.8** (Algebraic trompe-l'œil). *The following square is a pullback:*

$$\begin{array}{ccc} \mathcal{Alg}^k(\mathfrak{Z}^n) & \xrightarrow{(-)_{n-1,n,\dagger}} & \mathcal{Alg}^1(\mathfrak{Z}^3) \\ \downarrow & & \downarrow \\ \mathcal{Psh}(\mathbb{O}_{n-k,n}) & \xrightarrow{(-)_{n-1,n,\dagger}} & \mathcal{Psh}(\mathbb{O}_{2,3}). \end{array} \quad (5.2.9)$$

*In other words, a  $\mathfrak{Z}^n$ -algebra structure on  $X \in \mathcal{Psh}(\mathbb{O}_{n-k,n})$  is completely determined by a  $\mathfrak{Z}^3$ -algebra structure on  $(X_{n-1,n})_{\dagger}$ .*

*Proof.* This is a direct consequence of proposition 5.1.4, proposition 5.2.7, and the pasting lemma for pullbacks.  $\square$

## APPENDIX A. OMITTED PROOFS

*Proof of lemma 4.3.2.* (1) Let  $P$  be the pullback of the cospan  $1 \xrightarrow{\eta_1} \mathfrak{Z}^n 1 \xleftarrow{\mathfrak{Z}^n} \mathfrak{Z}^n X$ . Since  $(\mathfrak{Z}^n X)_{<n} = X_{<n}$ , we trivially have  $P_{<n} = X_{<n}$ . Next, for  $\omega \in \mathbb{O}_n$ , we have

$$P_\omega = \{x \in \mathfrak{Z}^n X \mid \mathfrak{Z}^n!(x) = Y_\omega\} = \mathcal{P}\text{sh}(\mathbb{O}_{n-k,n})(\Lambda^t[Y_\omega], X) = X_\omega$$

as  $\Lambda^t[Y_\omega] = O[\omega]$ .

(2) Let  $P$  be the pullback of the cospan  $\mathfrak{Z}^n \mathfrak{Z}^n 1 \xrightarrow{\mu_1} \mathfrak{Z}^n 1 \xleftarrow{\mathfrak{Z}^n} \mathfrak{Z}^n X$ . As before, since  $(\mathfrak{Z}^n X)_{<n} = X_{<n}$ , we trivially have  $P_{<n} = X_{<n} = (\mathfrak{Z}^n \mathfrak{Z}^n X)_{<n}$ . Recall from lemma 4.3.1 that as a polynomial functor,  $\mathfrak{Z}^n \mathfrak{Z}^n : \text{Set}/\mathbb{O}_n \rightarrow \text{Set}/\mathbb{O}_n$  is given by

$$\mathbb{O}_n \xleftarrow{\mathbf{e}} E \longrightarrow \mathbb{O}_{n+2}^{(2)} \xrightarrow{\mathbf{t}\mathbf{t}} \mathbb{O}_n,$$

where  $\mathbb{O}_{n+2}^{(2)}$  is the set of  $(n+2)$ -opetopes of height at most 2. Then, for  $\omega \in \mathbb{O}_n$ , we have:

$$P_\omega = \{(\xi, x) \mid x : \Lambda^t[\nu] \rightarrow X, \xi \in \mathbb{O}_{n+2}^{(2)}, \mathbf{t}\xi = \nu\} = \{x : \Lambda^t[\mathbf{t}\xi] \mid \xi \in \mathbb{O}_{n+2}^{(2)}\} = \mathfrak{Z}^n \mathfrak{Z}^n X_\omega.$$

$\square$

*Proof of lemma 4.3.3.* For  $X \in \mathcal{P}\text{sh}(\mathbb{O}_{n-k,n})$ ,  $(\mathfrak{Z}^n X)_{<n} = X_{<n}$ , thus all diagrams commute trivially in dimension  $< n$ .

(1) Let  $\omega \in \mathbb{O}_n$  and  $\nu \in \mathfrak{Z}^n 1_\omega$ , i.e.  $\nu \in \mathbb{O}_{n+1}$  such that  $\mathbf{t}\nu = \omega$ . Then

$$\mu_1 \eta_{\mathfrak{Z}^n 1}(\nu) = \mu_1 \left( Y_{Y_{\mathbf{t}\nu}} \circ_{[[\ ]]} Y_\nu \right) = \mathbf{t} \left( Y_{Y_{\mathbf{t}\nu}} \circ_{[[\ ]]} Y_\nu \right) = \nu.$$

(2) Let  $\omega \in \mathbb{O}_n$  and  $\nu \in \mathfrak{Z}^n 1_\omega$ , i.e.  $\nu \in \mathbb{O}_{n+1}$  such that  $\mathbf{t}\nu = \omega$ . Then

$$\mu_1(\mathfrak{Z}^n \eta_1)(\nu) = \mu_1 \left( Y_\nu \circ_{[[p_i]]} Y_{Y_{[p_i]\nu}} \right) = \mathbf{t} \left( Y_\nu \circ_{[[p_i]]} Y_{Y_{[p_i]\nu}} \right) = \nu,$$

where  $[p_i]$  ranges over  $\nu^\bullet$ .

(3) Akin to lemma 4.3.1, one can show that elements of  $\mathfrak{Z}^n \mathfrak{Z}^n \mathfrak{Z}^n 1_\omega$  are  $(n+2)$ -opetopes  $\xi$  of height 3 such that  $\mathbf{t}\mathbf{t}\xi = \omega$ . Let  $\xi$  be such an opetope, and write it as

$$\xi = Y_\alpha \circ_{[[p_i]]} \underbrace{\left( Y_{\beta_i} \circ_{[[q_{i,j}]]} Y_{\gamma_{i,j}} \right)}_{X_i} = \underbrace{\left( Y_\alpha \circ_{[[p_i]]} Y_{\beta_i} \right)}_Y \circ_{[[p_i][q_{i,j}]]} Y_{\gamma_{i,j}}$$

where  $\alpha, \beta_i, \gamma_{i,j} \in \mathbb{O}_n$ ,  $[p_i]$  ranges over  $\alpha^\bullet$  and  $[q_{i,j}]$  over  $\beta_i^\bullet$ . Then

$$\begin{aligned} \mu_1(\mathfrak{Z}^n \mu_1)(\gamma) &= \mathbf{t} \left( Y_\alpha \circ_{[[p_i]]} Y_{\mathbf{t}X_i} \right) \\ &= \mathbf{t} \left( Y_{\mathbf{t}Y} \circ_{[\emptyset_Y][p_i][q_{i,j}]]} Y_{\gamma_{i,j}} \right) \quad \spadesuit \\ &= \mu_1 \mu_{\mathfrak{Z}^n 1}(\gamma), \end{aligned}$$

where  $\spadesuit$  derives from the associativity axiom of the uncolored monad  $\mathfrak{Z}^n$ .

$\square$

*Proof of lemma 4.4.6.* First, note that

$$\begin{aligned} \mathbf{t}(\xi_2 \sqsupset_{[p_2]} \xi_1) &= \mathbf{t}\mathbf{t}(\mathbf{Y}_{\xi_2} \circ_{[[p_2]]} \mathbf{Y}_{\xi_1}) && \text{by lemma 3.2.3} \\ &= \mathbf{t}\mathbf{s}[\ ](\mathbf{Y}_{\xi_2} \circ_{[[p_2]]} \mathbf{Y}_{\xi_1}) && \text{(Glob2)} \\ &= \mathbf{t}\xi_2 = \omega_2. \end{aligned}$$

Using (2.4.6), we write

$$\zeta = \xi_2 \sqsupset_{[p_2]} \xi_1 = \left( \alpha_2 \circ_{[p_2]} \alpha_1 \right) \circ_{[p_2 p_1]} \mathbf{Y}_{\omega_0} \bigcirc_{[[q_i]]} \underbrace{\left( \beta_i \bigcirc_{[l_{i,j}]} \gamma_{i,j} \right)}_{\delta_i}$$

where  $[q_i]$  ranges over  $\omega_0^\bullet$  and  $[l_{i,j}]$  over  $\beta_i^\dagger$ , such that

$$\xi_1 = \alpha_1 \circ_{[p_1]} \mathbf{Y}_{\omega_0} \bigcirc_{[[q_i]]} \beta_i, \quad \xi_2 = \alpha_2 \circ_{[p_2]} \mathbf{Y}_{\omega_1} \bigcirc_{[\wp_{\xi_1}[p_1[q_i]l_{i,j}]]} \gamma_{i,j}$$

Since leaf addresses of  $\xi_1$  are of the form  $[p_1[q_i]l_{i,j}]$  for some  $[q_i] \in \omega_0^\bullet$  and  $[l_{i,j}] \in \beta_i^\dagger$ , and since  $\omega_1 = \mathbf{t}\xi_1$ , the node addresses of  $\omega_1$  are of the form  $\wp_{\xi_1}[p_1[q_i]l_{i,j}]$ , which justifies the decomposition of  $\xi_2$  above.

Applying the definition of  $\dot{h}$  we have, for  $[q_i] \in \omega_0^\bullet$ ,  $[l_{i,j}] \in \beta_i^\dagger$ , and  $[r] \in \gamma_{i,j}$ ,

$$\begin{aligned} \dot{h}\mathbf{s}_{[p_2 p_1]} : \Lambda^\dagger[\omega_0] &\longrightarrow \mathfrak{Z}\Lambda^\dagger[\omega_2] \\ (\dot{h}\mathbf{s}_{[p_2 p_1]})([q_i]) : \Lambda^\dagger[\mathbf{t}\delta_i] &\longrightarrow \Lambda^\dagger[\omega_2] \\ \wp_{\delta_i}[l_{i,j}r] &\longmapsto \wp_\zeta[p_2 p_1[q_i]l_{i,j}r]; && \spadesuit \\ \dot{h}\mathbf{s}_{[p_1]} : \Lambda^\dagger[\omega_0] &\longrightarrow \mathfrak{Z}\Lambda^\dagger[\omega_1] \\ (\dot{h}\mathbf{s}_{[p_1]})([q_i]) : \Lambda^\dagger[\mathbf{t}\beta_i] &\longrightarrow \Lambda^\dagger[\omega_1] \\ \wp_{\beta_i}[l_{i,j}] &\longmapsto \wp_{\xi_1}[p_1[q_i]l_{i,j}]; && \diamond \\ \dot{h}\mathbf{s}_{[p_2]} : \Lambda^\dagger[\omega_1] &\longrightarrow \mathfrak{Z}\Lambda^\dagger[\omega_2] \\ (\dot{h}\mathbf{s}_{[p_2]})(\wp_{\xi_1}[p_1[q_i]l_{i,j}]) : \Lambda^\dagger[\mathbf{t}\gamma_{i,j}] &\longrightarrow \Lambda^\dagger[\omega_2] \\ \wp_{\gamma_{i,j}}[r] &\longmapsto \wp_{\xi_2}[p_2 \wp_{\xi_1}[p_1[q_i]l_{i,j}] r]. && \clubsuit \end{aligned}$$

Thus,

$$\begin{aligned} (\dot{h}\mathbf{s}_{[p_2 p_1]})([q_i])(\wp_{\delta_i}[l_{i,j}r]) &= \wp_\zeta[p_2 p_1[q_i]l_{i,j}r] && \text{by } \spadesuit \\ &= \wp_{\xi_2}[p_2 \wp_{\xi_1}[p_1[q_i]l_{i,j}] r] && \heartsuit \\ &= (\dot{h}\mathbf{s}_{[p_2]})(\wp_{\xi_1}[p_1[q_i]l_{i,j}])(\wp_{\gamma_{i,j}}[r]) && \text{by } \clubsuit \\ &= (\dot{h}\mathbf{s}_{[p_2]})((\dot{h}\mathbf{s}_{[p_1]})([q_i])(\wp_{\beta_i}[l_{i,j}])(\wp_{\gamma_{i,j}}[r])) && \text{by } \diamond \\ &= (\dot{h}\mathbf{s}_{[p_2]} \circ \dot{h}\mathbf{s}_{[p_1]})([q_i])(\wp_{\delta_i}[l_{i,j}r]), && \blacktimes \end{aligned}$$

where equality  $\heartsuit$  comes from the monad structure on  $\mathfrak{Z}$ , and  $\blacktimes$  from the definition of the composition in  $\mathbb{A}$  when considered as the Kleisli category of  $\mathfrak{Z}$ .  $\square$

*Proof of lemma 4.4.7.* (1) Unfolding the definition of  $\dot{h}\mathbf{s}[\ ]$  we get, for  $[q]\omega^\bullet$ :

$$\begin{aligned} \dot{h}\mathbf{s}[\ ] : \Lambda^\dagger[\mathbf{Y}_\psi] &\longrightarrow \mathfrak{Z}\Lambda^\dagger[\omega] \\ (\dot{h}\mathbf{s}[\ ])([ ]) : \Lambda^\dagger[\mathbf{t}\mathbf{Y}_\omega] &\longmapsto \Lambda^\dagger[\omega] \\ \wp_{\mathbf{Y}_\omega}[[q]] &\longmapsto \wp_\xi[[q]]. \end{aligned}$$

Since  $\wp_{Y_\omega}[[q]] = [q] = \wp_\xi[[[q]]]$ ,  $\dot{h}s_{\square}$  corresponds to the cell  $\text{id}_{\Lambda^t[\omega]} \in \mathfrak{Z}\Lambda^t[\omega]_{\mathfrak{t}\omega}$ , thus is equal to  $\dot{h}\mathfrak{t}$  as claimed.

(2) First, graft trivial trees to  $\xi$  so it's in the form of equation (2.4.6):

$$\xi = Y_{\bar{\beta}} \circ_{[[p]]} Y_{\beta} \bigcirc_{[[q_i]]} \mathfrak{I}_{s_{[q_i]}\beta},$$

where  $[q_i]$  ranges over  $\beta^\bullet$ . Unfolding the definition of  $\dot{h}s_{[p]}$  we get, for  $[q]\beta^\bullet$ :

$$\begin{aligned} \dot{h}s_{[p]} : \Lambda^t[\beta] &\longrightarrow \mathfrak{Z}\Lambda^t[\omega] \\ (\dot{h}s_{[p]})([q]) : \Lambda^t[\mathfrak{t}\mathfrak{I}_{s_{[q]}\beta}] &\longrightarrow \Lambda^t[\omega] \\ \square = \wp_{\mathfrak{I}_{s_{[q]}\beta}} \square &\longmapsto \wp_\xi[[p][q]] = [pq], \end{aligned}$$

thus  $\dot{h}s_{[p]} = \dot{h}i$ . □

*Proof of lemma 4.4.8.* We proceed by induction on  $\omega$ .

(1) Assume  $\omega = Y_\psi$  for some  $\psi \in \mathbb{O}_n$ . Then

$$\begin{aligned} \wedge(\dot{h}Y_\psi, \dot{h}\omega') &= \wedge(\mathfrak{Z}\Lambda^t[Y_\psi], \mathfrak{Z}\Lambda^t[\omega']) \\ &\cong (\mathfrak{Z}\Lambda^t[\omega])_\psi. \end{aligned}$$

Thus  $f$  corresponds to a unique morphism  $\tilde{f} : \Lambda^t[\nu] \longrightarrow \Lambda^t[\omega']$ , for some  $\nu \in \mathbb{O}_{n+1}$  such that  $\mathfrak{t}\nu = \psi$ , and  $f$  is the composite

$$\dot{h}Y_\psi = \dot{h}\psi \xrightarrow{\dot{h}\mathfrak{t}} \dot{h}\nu \xrightarrow{\mathfrak{Z}\tilde{f}} \dot{h}\omega'.$$

Those two arrows are diagrammatic by lemma 4.4.7, and thus  $f$  is too by lemma 4.4.6.

(2) By induction, write  $\omega = \nu_1 \circ_{[l]} Y_{\psi_2}$  for some  $\nu_1 \in \mathbb{O}_{n+1}$ ,  $[l] \in \nu_1^\downarrow$ , and  $\psi_2 \in \mathbb{O}_n$ . Write  $\psi_1 = \mathfrak{t}\nu_1$ , and  $\nu_2 = Y_{\psi_2}$ . Then  $f$  restricts as  $f_i$ ,  $i = 1, 2$ , given by the composite  $\dot{h}\nu_i \longrightarrow \dot{h}\omega \xrightarrow{f} \dot{h}\omega'$ .

Let  $[l']$  be the edge address of  $\omega'$  such that  $\mathfrak{e}_{[l']}\omega' = f(\mathfrak{e}_{[l]}\omega)$ . Then  $\omega'$  decomposes as  $\omega' = \beta_1 \circ_{[\nu]}\beta_2$ , for some  $\beta_1, \beta_2 \in \mathbb{O}_{n+1}$  (in particular,  $\beta_1$  and  $\beta_2$  are sub  $\mathfrak{Z}^{n-1}$ -trees of  $\omega'$ ), and  $f_1$  and  $f_2$  factor as on the left

$$\begin{array}{ccc} \dot{h}\nu_i & \xrightarrow{\bar{f}_i} & \dot{h}\beta_i \\ & \searrow f_i & \downarrow u_i \\ & & \dot{h}\omega' \end{array} \qquad \begin{array}{ccc} & & \xi_i \\ & \nearrow s_{[\nu_i]} & \uparrow \mathfrak{t} \\ \nu_i & & \beta_i \\ \hline \dot{h}\nu_i & \xrightarrow{\bar{f}_i} & \dot{h}\beta_i. \end{array}$$

where  $u_i$  correspond to the subtree inclusion  $\beta_i \hookrightarrow \omega'$ . By induction,  $\bar{f}_i$  is diagrammatic, say with the diagram on the right above, and thus  $\beta_i$  can be written as  $\beta_i = \bar{\nu}_i \circ_{[q_i]}\nu_i$ , for some  $\bar{\nu}_i \in \mathbb{O}_{n+1}$  and  $[q_i] \in \bar{\nu}_i^\bullet$ . In the case  $i = 2$ , note that  $\beta_2 = \bar{\nu}_2 \circ_{[q_2]}\nu_2 = \bar{\nu}_2 \circ_{[q_2]} Y_{\psi_2} = \bar{\nu}_2$ .

On the one hand we have

$$\begin{aligned}
e_{[l']}\omega' &= f(e_{[l]}\omega) && \text{by def. of } [l'] \\
&= f_1(e_{[l]}\nu_1) && \text{since } \omega = \nu_1 \circ_{[l]} Y_{\psi_2} \\
&= u_1 \bar{f}_1(e_{[l]}\nu_1) && \text{since } f_1 = u_1 \bar{f}_1 \\
&= u_1(e_{[q_1 l]}\beta_1) && \text{since } \beta_1 = \bar{\nu}_1 \circ_{[q_1]} \nu_1 \\
&= e_{[q_1 l]}\omega,
\end{aligned}$$

showing  $[l'] = [q_1 l]$ , and thus that  $\bar{\nu}_1$  is of the form

$$\bar{\nu}_1 = \mu_1 \circ_{[q_1]} Y_{\psi_1} \bigcirc_{[[r_{1,j}]]} \mu_{1,j}, \quad (\text{A.0.1})$$

where  $[r_{1,j}]$  ranges over  $\psi_1^\bullet - \{\wp_{\nu_1}[l]\}$ , and  $\mu_1, \mu_{1,j} \in \mathbb{O}_{n+1}$ . On the other hand,

$$\begin{aligned}
e_{[l']}\omega' &= f(e_{[l]}\omega) && \text{by def. of } [l'] \\
&= f_2(e_{[ ]}\nu_2) && \text{since } \omega = \nu_1 \circ_{[l]} Y_{\psi_2} \\
&= u_2 \bar{f}_2(e_{[ ]}\nu_2) && \text{since } f_1 = u_2 \bar{f}_2 \\
&= u_2(e_{[q_2]}\beta_2) && \text{since } \beta_2 = \bar{\nu}_2 \circ_{[q_2]} \nu_2 \\
&= e_{[l']}\omega',
\end{aligned}$$

showing  $[q_2] = [ ]$ , and so  $s_{[ ]}\beta_2 = s_{[ ]}\bar{\nu}_2 = \psi_2$ , and we can write  $\beta_2$  as

$$\beta_2 = Y_{\psi_2} \bigcirc_{[[r_{2,j}]]} \mu_{2,j}, \quad (\text{A.0.2})$$

where  $[r_{2,j}]$  ranges over  $\psi_2^\bullet$ , and  $\mu_{2,j} \in \mathbb{O}_{n+1}$ . Finally, we have

$$\begin{aligned}
\omega' &= \beta_1 \circ_{[l']} \beta_2 = (\bar{\nu}_1 \circ_{[q_1]} \nu_1) \circ_{[l']} \beta_2 \\
&= \left( \mu_1 \circ_{[q_1]} \nu_1 \bigcirc_{\wp_{\bar{\nu}_1}^{-1}[r_{1,j}]} \mu_{1,j} \right) \circ_{[l']} \left( Y_{\psi_2} \bigcirc_{[[r_{2,j}]]} \mu_{2,j} \right) && \text{by (A.0.1) and (A.0.2)} \\
&= \left( \left( \mu_1 \circ_{[q_1]} \underbrace{\nu_1 \circ_{[l]} Y_{\psi_2}}_{=\omega} \right) \bigcirc_{[q_1] \cdot \wp_{\bar{\nu}_1}^{-1}[r_{1,j}]} \mu_{1,j} \right) \bigcirc_{[l'][r_{2,j}]} \mu_{2,j} && \text{rearranging terms} \\
&= \bar{\omega} \circ_{[q_1]} \omega,
\end{aligned}$$

for some  $\bar{\omega}' \in \mathbb{O}_{n+1}$ .<sup>(11)</sup> Finally, by lemma 4.4.7, the following is a diagram of  $\dot{h}f$ :

$$\begin{array}{ccc}
 & & \xi \\
 & \nearrow^{s[[q_1]]} & \uparrow t \\
 \omega & & \omega' \\
 \hline
 \dot{h}\omega & \xrightarrow{f} & \dot{h}\omega',
 \end{array}
 \quad \xi := Y_{\bar{\omega}} \circ_{[[q_1]]} Y_{\omega}.$$

□

<sup>(11)</sup>Specifically,

$$\omega' = \mu_1 \circ_{[q_1]} \left( \left( Y_{t\omega} \circ_{[\wp_{\omega}\wp_{v_1}^{-1}][r_{1,j}]} \mu_{1,j} \right) \circ_{[\wp_{\omega}[l'[r_{2,j}]]]} \mu_{2,j} \right) = \left( \left( \mu_1 \circ_{[q_1]} Y_{t\omega} \right) \circ_{[q_1][\wp_{\omega}\wp_{v_1}^{-1}][r_{1,j}]} \mu_{1,j} \right) \circ_{[q_1][\wp_{\omega}[l'[r_{2,j}]]]} \mu_{2,j}.$$

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