

Genuine equivariant operads

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Abstract

We build new algebraic structures, which we call genuine equivariant operads, which can be thought of as a hybrid between equivariant operads and coefficient systems. We then prove an Elmendorf type theorem stating that equivariant operads, with their graph model structure, are equivalent to genuine equivariant operads with their projective model structure.

As an application, we build explicit models for the N_∞ -operads of Blumberg and Hill.

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1 Introduction

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2 Basic definitions

In this section we recall some definitions that will be used throughout.

2.1 Grothendieck constructions

Recall that for a diagram category \mathcal{D} and functor \mathcal{I}_\bullet

$$\begin{aligned} \mathcal{D} &\xrightarrow{\mathcal{I}_\bullet} \mathbf{Cat} \\ d &\longmapsto \mathcal{I}_d \end{aligned} \tag{2.1}$$

the (covariant) Grothendieck construction $\mathcal{D} \ltimes \mathcal{I}_\bullet$ has objects pairs (d, i) with $d \in \mathcal{D}$, $i \in \mathcal{I}_d$ and arrows $(d, i) \rightarrow (d', i')$ given by pairs

$$(f: d \rightarrow d', g: f_*(i) \rightarrow i'),$$

where $f_*: \mathcal{I}_d \rightarrow \mathcal{I}_{d'}$ is a shorthand for the functor $\mathcal{I}_\bullet(f)$.

We now discuss a basic property of over and under categories that will be used in §5.4. TRANSFSIMP SEC

Given $\mathcal{J}, \mathcal{C} \in \mathbf{Cat}$ and $j \in \mathcal{J}$ we will let \mathcal{C}^{lj} denote the Grothendieck construction for the functor

$$\begin{aligned} \mathcal{J} &\longrightarrow \mathbf{Cat} \\ i &\longmapsto \mathcal{C}^{\mathcal{J}(i, j)} \end{aligned}$$

Explicitly, an object of \mathcal{C}^{lj} is a pair $(i, \mathcal{J}(i, j) \xrightarrow{\varphi} \mathcal{C})$ and an arrow $(i, \varphi) \rightarrow (i', \varphi')$ is a pair $(I: i \rightarrow i', \gamma: \varphi \circ I^* \rightarrow \varphi')$.

Lemma 2.2. *Let $\mathcal{J} \in \mathbf{Cat}$ be a small category and $j \in \mathcal{J}$. One then has adjunctions*

$$(- \downarrow j): \mathbf{Cat}_{/\mathcal{J}} \rightleftarrows \mathbf{Cat}: (-)^{lj}, \quad (j \downarrow -): \mathbf{Cat}_{/\mathcal{J}} \rightleftarrows \mathbf{Cat}: (-)^{j\downarrow}.$$

Proof. Since $j \downarrow \mathcal{I} = (\mathcal{I}^{op} \downarrow j)^{op}$ by defining $(\mathcal{C}^{j\downarrow}) = ((\mathcal{C}^{op})^{lj})^{op}$ one reduces to the leftmost adjunction.

Given $\mathcal{I} \xrightarrow{\pi} \mathcal{J}$ and \mathcal{C} we will show that functors $\mathcal{I} \downarrow j \xrightarrow{F} \mathcal{C}$ correspond to functors $\mathcal{I} \xrightarrow{G} \mathcal{C}^{lj}$ over \mathcal{J} .

On objects, F associates to each pair $(i, J: \pi(i) \rightarrow j)$ an object $F(i, J) \in \mathcal{C}$. One thus sets $G(i) = (\pi(i), F(i, -))$ and these are clearly inverse processes.

On arrows F associates to $(i, J' \circ \pi(I)) \xrightarrow{I} (i', J')$ an arrow $F(i, J' \circ \pi(I)) \xrightarrow{F(I)} F(i', J')$. One thus defines

$$G(I) = \left(\pi(i) \xrightarrow{\pi(I)} \pi(i'), F(i, (-) \circ \pi(i)) \xrightarrow{F(I)} F(i', -) \right)$$

and again it is clear that these are inverse processes. Finally, the fact that the associativity and unit conditions for F, G coincide is likewise clear. \square

2.2 Monads

We will make multiple uses of the following straightforward results.

Proposition 2.3. *Let $L: \mathcal{C} \rightleftarrows \mathcal{D}: R$ be an adjunction and T a monad on \mathcal{D} . Then*

- (i) *RTL is a monad and R induces a functor $R: \mathbf{Alg}_T(\mathcal{D}) \rightarrow \mathbf{Alg}_{RTL}(\mathcal{C})$;*
- (ii) *if $LRTL \xrightarrow{\epsilon} TL$ is an isomorphism one further has an induced adjunction*

$$L: \mathbf{Alg}_{RTL}(\mathcal{C}) \rightleftarrows \mathbf{Alg}_T(\mathcal{D}): R.$$

Proposition 2.4. *Let $L: \mathcal{C} \rightleftarrows \mathcal{D}: R$ be an adjunction, T a monad on \mathcal{C} , and suppose further that*

$$LR \xrightarrow{\epsilon} id_{\mathcal{D}}, \quad LT \xrightarrow{\eta} LTRL$$

are natural isomorphisms (so that in particular \mathcal{D} is a reflexive subcategory of \mathcal{C}).

Then

- (i) *LTR is a monad, with multiplication and unit given by*

$$LTRLTR \xrightarrow{\eta^{-1}} LTTR \rightarrow LTR, \quad id_{\mathcal{D}} \xrightarrow{\epsilon^{-1}} LR \rightarrow LTR;$$

- (ii) *$d \in \mathcal{D}$ is a LTR -algebra iff Rd is a T -algebra;*

- (iii) *there is an induced adjunction*

$$L: \mathbf{Alg}_T(\mathcal{C}) \rightleftarrows \mathbf{Alg}_{LTR}(\mathcal{D}): R.$$

3 Planar and tall maps

3.1 Planar structures

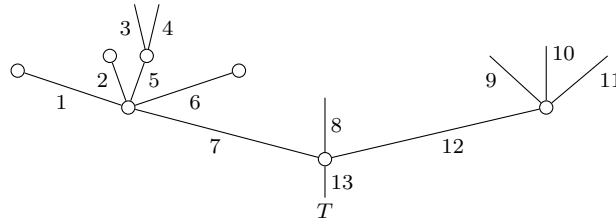
Throughout we will work with trees possessing *planar structures* or, more intuitively, trees embedded into the plane.

Our preferred model for trees will be that of broad posets first introduced by Weiss in [8] and further worked out by the second author in [5]. We now define planar structures in this context.

Definition 3.1. Let $T \in \Omega$ be a tree. A *planar structure* of T is an extension of the descendency partial order \leq_d to a total order \leq_p such that:

- *Planar:* if $e \leq_p f$ and $e \not\leq_d f$ then $g \leq_d f$ implies $e \leq_p g$.

Example 3.2. An example of a planar structure on a tree T follows, with \leq_r encoded by the number labels.



(3.3)

PLANAREX EQ

Intuitively, given a planar depiction of a tree T , $e \leq_d f$ holds when the downward path from e passes through f and $e \leq_p f$ holds if either $e \leq_d f$ or if the downward path from e is to the left of the downward path from f (as measured at the node where the paths intersect).

Intuitively, a planar depiction of a tree amounts to choosing a total order for each of the sets of *input edges* of each node (i.e. those edges immediately above that node).

While we will not need to make this last statement precise, we will nonetheless find it convenient to show that Definition 3.1 is equivalent to such choosing total orders for each of the sets of input edges. To do so, we first introduce some notation.

Notation 3.4. Let $T \in \Omega$ be a tree and $e \in T$ and edge. We will denote

$$I(e) = \{f \in T : e \leq_d f\}$$

and refer to this poset as the *input path* of e .

We will repeatedly use the following, which is a consequence of [Pe16b, Cor. 5.26].

Lemma 3.5. *If $e \leq_d f$, $e \leq_d f'$, then f, f' are \leq_d -comparable.*

Proposition 3.6. *Let $T \in \Omega$ be a tree. Then*

- (a) *for any $e \in T$ the finite poset $I(e)$ is totally ordered;*
- (b) *the poset (T, \leq_d) has all joins, denoted \vee . In fact, $\bigvee_i e_i = \min(\bigcap_i I(e_i))$.*

Proof. (a) is immediate from Lemma 3.5. To prove (b) we note that $\min(\bigcap_i I(e_i))$ exists by (a), and that this is clearly the join $\bigvee e_i$. \square

Notation 3.7. Let $T \in \Omega$ be a tree and suppose that $e <_d b$. We will denote by $b_e^\dagger \in T$ the predecessor of b in $I(e)$.

Proposition 3.8. *Suppose e, f are \leq_d -incomparable edges of T and write $b = e \vee f$. Then*

- (a) *$e <_d b$, $f <_d b$ and $b_e^\dagger \neq b_f^\dagger$;*
- (b) *$b_e^\dagger, b_f^\dagger \in b^\dagger$. In fact $\{b_e^\dagger\} = I(e) \cap b^\dagger$, $\{b_f^\dagger\} = I(f) \cap b^\dagger$;*
- (c) *if $e' \leq_d e$, $f' \leq_d f$ then $b = e' \vee f'$ and $b_{e'}^\dagger = b_e^\dagger$, $b_{f'}^\dagger = b_f^\dagger$.*

Proof. (a) is immediate: the condition $e = g$ (resp. $f = g$) would imply $f \leq_d e$ (resp. $e \leq_d f$) while the condition $b_e^\dagger = b_f^\dagger$ would provide a predecessor of b in $I(e) \cap I(f)$.

For (b), note that any relation $a <_d b$ factors as $a \leq_d b_a^* <_d b$ for some unique $b_a^* \in b^\dagger$, where uniqueness follows from Lemma 3.5. Choosing $a = e$ implies $I(e) \cap b^\dagger = \{b_e^*\}$ and letting a range over edges such that $e \leq_d a <_d b$ shows that b_e^* is in fact the predecessor of b .

To prove (c) one reduces to the case $e' = e$, in which case it suffices to check $I(e) \cap I(f') = I(e) \cap I(f)$. But if it were otherwise there would exist an edge a satisfying $f' \leq_d a <_d f$ and $e \leq_d a$, and this would imply $e \leq_d f$, contradicting our hypothesis. \square

Proposition 3.9. *Let $c = e_1 \vee e_2 \vee e_3$. Then $c = e_i \vee e_j$ iff $c_{e_i}^\dagger \neq c_{e_j}^\dagger$.*

Therefore, all ternary joins in (T, \leq_d) are binary, i.e.

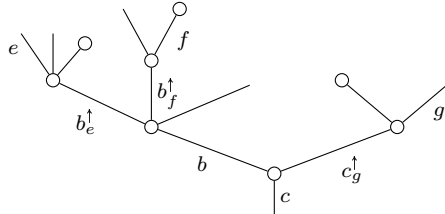
$$c = e_1 \vee e_2 \vee e_3 = e_i \vee e_j \tag{3.10}$$

for some $1 \leq i < j \leq 3$, and (3.10) fails for at most one choice of $1 \leq i < j \leq 3$.

Proof. If $c_{e_i}^\dagger \neq c_{e_j}^\dagger$, then $c = \min(I(e_i) \cap I(e_j)) = e_i \vee e_j$, whereas the converse follows from Proposition 3.8(a).

The “therefore” part follows by noting that $c_{e_1}^\dagger, c_{e_2}^\dagger, c_{e_3}^\dagger$ can not all coincide, or else c would not be the minimum of $I(e_1) \cap I(e_2) \cap I(e_3)$. \square

Example 3.11. In the following example $b = e \vee f$, $c = e \vee f \vee g$, $c_e^\dagger = c_f^\dagger = b$.



Notation 3.12. Given a set S of size n we write $\text{Ord}(S) \simeq \text{Iso}(S, \{1, \dots, n\})$. We will usually abuse notation by regarding its objects as pairs (S, \leq) where \leq is a total order in S .

Proposition 3.13. Let $T \in \Omega$ be a tree. There is a bijection

$$\begin{aligned} \{\text{planar structures } (T, \leq_p)\} &\longrightarrow \prod_{(a^\dagger \leq a) \in V(T)} \text{Ord}(a^\dagger) \\ \leq_p &\longmapsto (\leq_p \mid_{a^\dagger}) \end{aligned} \quad (3.14) \quad \text{PLANAR EQ}$$

Proof. We will keep the setup of Proposition 3.8 throughout: e, f are \leq_d -incomparable edges and we write $b = e \vee f$.

We first show that (3.14) is injective, i.e. that the restrictions $\leq_p \mid_{a^\dagger}$ determine if $e <_p f$ holds or not. If $b_e^\dagger <_p b_f^\dagger$, the relations $e \leq_d b_e^\dagger <_p b_f^\dagger \geq_d f$ and Definition 3.1 imply it must be $e <_p f$. Dually, if $b_f^\dagger <_p b_e^\dagger$ then $f <_p e$. Thus $b_e^\dagger <_p b_f^\dagger \Leftrightarrow e <_p f$ and hence (3.14) is indeed injective.

To check that (3.14) is surjective, it suffices (recall that e, f are assumed \leq_d -incomparable) to check that defining $e \leq_p f$ to hold iff $b_e^\dagger < b_f^\dagger$ holds in b^\dagger yields a planar structure.

Antisymmetry and the total order conditions are immediate, and it thus remains to check the transitivity and planar conditions. Transitivity of \leq_p in the case $e' <_p e <_p f$ and the planar condition, which is the case $e <_p f \geq_d f'$, follow from Proposition 3.8(c). Transitivity of \leq_p in the case $e <_p f \leq_d f'$ follows since either $e <_p f'$ or else e, f' are \leq_d -incomparable, in which case one can apply 3.8(c) with the roles of f, f' reversed.

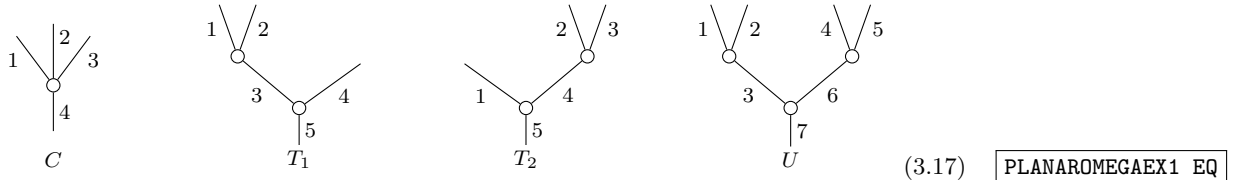
It remains to check transitivity in the hardest case, that of $e <_p f <_p g$ with e, f, g incomparable. We write $c = e \vee f \vee g$. By the “therefore” part of Proposition 3.9, either (i) $e \vee f <_d c$, in which case Proposition 3.9 implies $c_e^\dagger = c_f^\dagger$ and transitivity follows; (ii) $f \vee g <_d c$, which follows just as (i); (iii) $e \vee f = f \vee g = c$, in which case $c_e^\dagger < c_f^\dagger < c_g^\dagger$ in c^\dagger so that $c_e^\dagger \neq c_g^\dagger$ and by Proposition 3.9 it is also $e \vee g = c$ and transitivity follows. \square

Remark 3.15. Definition 3.1 readily extends to forests $F \in \Phi$. The analogue of Proposition 3.13 then states that the data of a planar structure is equivalent to total orderings of the nodes of F together with a total ordering of its set of roots. Indeed, this follows by either adapting the proof above or by noting that planar structures on F are clearly in bijection with planar structures on the join tree $F \star \eta$ (cf. [5, Def. 7.44]), which adds a single edge η to F , serving as the (unique) root of $F \star \eta$.

When discussing the substitution procedure in §3.3 we will find it convenient to work with a model for the category Ω that possesses exactly one representative of each possible planar structure on each tree or, more precisely, such that the only isomorphisms preserving the planar structures are the identities. On the other hand, using such a model for Ω throughout would, among other issues, make the discussion of faces in §3.2 rather awkward. We now outline our conventions to address such issues.

Let Ω^p , the category of *planarized trees*, denote the category with objects pairs $T_{\leq_p} = (T, \leq_p)$ of trees together with a planar structure and morphisms the *underlying* maps of trees (so that the planar structures are ignored). There is a full subcategory $\Omega^s \hookrightarrow \Omega^p$, whose objects we call *standard models*, of those T_{\leq_p} whose underlying set is one of the sets $\underline{n} = \{1, 2, \dots, n\}$ and for which \leq_p coincides with the canonical order.

Example 3.16. Some examples of standard models, i.e. objects of Ω^s , follow (further, (3.3) can also be interpreted as such an example).



Here T_1 and T_2 are isomorphic to each other but not isomorphic to any other standard model in Ω^s while both C and U are the unique objects in their isomorphism classes.

Given $T_{\leq_p} \in \Omega^p$ there is an obvious standard model $T_{\leq_p}^s \in \Omega^s$ given by replacing each edge by its order following \leq_p . Indeed, this defines a retraction $(-)^s: \Omega^p \rightarrow \Omega^s$ and a natural transformation $\sigma: id \Rightarrow (-)^s$ given by isomorphisms preserving the planar structure (in fact, the pair $((-)^s, \sigma)$ is clearly unique).

Convention 3.18. From now on, we will write simply Ω, Ω_G to denote the categories Ω^s, Ω_G^s of standard models (where planar structures are defined in the underlying forest as in Remark 3.15). Similarly \mathcal{O}_G will denote the model \mathcal{O}_G^s for the orbital category whose objects are the orbital G -sets whose underlying set is one of the sets $\underline{n} = \{1, 2, \dots, n\}$.

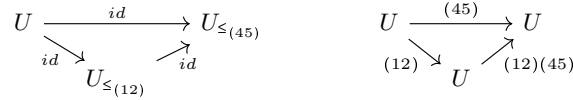
Therefore, whenever one of our constructions produces an object/diagram in $\Omega^p, \Omega_G^p, \mathcal{O}_G^p$ (of trees, G -trees, orbital G -sets with a planarization/total order) we will hence implicitly reinterpret it by using the standardization functor $(-)^s$.

Example 3.19. To illustrate our convention, we consider the trees in Example 3.16.

One has subfaces $F_1 \subset F_2 \subset U$ where F_1 is the subtree with edge set $\{1, 2, 6, 7\}$ and F_2 is the subtree with edge set $\{1, 2, 3, 6, 7\}$, both with inherited tree and planar structures. Applying $(-)^s$ to the inclusion diagram on the left below then yields a diagram as on the right.

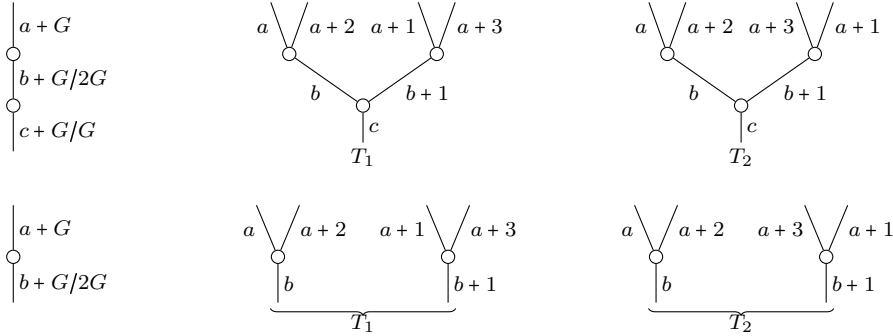


Similarly, let $\leq_{(12)}$ and $\leq_{(45)}$ denote alternate planar structures for U exchanging the orders of the pairs 1, 2 and 4, 5, so that one has objects $U_{\leq_{(12)}}, U_{\leq_{(45)}}$ in Ω^p . Applying $(-)^s$ to the diagram of underlying identities on the left yields the permutation diagram on the right.



Example 3.20. An additional reason to leave the use of $(-)^s$ implicit is that when depicting G -trees it is preferable to choose edge labels that describe the action rather than the planarization (which is already implicit anyway).

For example, when $G = \mathbb{Z}/4$, in both diagrams below the orbital representation on the left represents the isomorphism class consisting of the two trees $T_1, T_2 \in \Omega_G$ on the right.



Definition 3.21. A morphism $S \xrightarrow{\varphi} T$ in Ω that is compatible with the planar structures \leq_p is called a *planar map*.

More generally, a morphism $F \rightarrow G$ in the categories Φ, Φ^G, Ω^G of forests, G -forests, G -trees is called a *planar map* if it is an independent map (cf. [5, Def. 5.28]) compatible with the planar structures \leq_p .

Remark 3.22. The need for the independence condition is justified by [Pe16b, Lemma 5.33] and its converse, since non independent maps do not reflect \leq_d inequalities.

We note that in the Ω_G case a map φ is independent iff φ does not factor through a non trivial quotient iff φ is injective on each edge orbit.

Proposition 3.23. *Let $F \xrightarrow{\varphi} G$ be an independent map in Φ (or Ω , Ω_G , Φ_G). Then there is a unique factorization*

$$F \xrightarrow{\sim} \bar{F} \rightarrow G$$

such that $F \xrightarrow{\sim} \bar{F}$ is an isomorphism and $\bar{F} \rightarrow G$ is planar.

Proof. We need to show that there is a unique planar structure $\leq_{\bar{F}}$ on the underlying forest of F making the underlying map a planar map. Simplicity of G ensures that for any vertex $e^\dagger \leq e$ of F the edges in $\varphi(e^\dagger)$ are all distinct while independence of φ likewise ensures that the edges in $\varphi(e^\dagger)$ are distinct. The result now follows from (the forest version of) Proposition 3.13: one simply orders each set e^\dagger and \underline{r}_F according to its image.

not quite complete... maybe that \leq_p is the closure of \leq_d and the vertex relations under transitivity and the planar condition \square

Remark 3.24. Proposition 3.23 says that planar structures can be pulled back along independent maps. However, they can not always be pushed forward. As an example, in the notation of (3.17), consider the map $C \rightarrow T_1$ defined by $1 \mapsto 1$, $2 \mapsto 4$, $3 \mapsto 2$, $4 \mapsto 5$.

Remark 3.25. Given any tree $T \in \Omega$ there is a unique corolla $\text{lr}(T) \in \Sigma$ and planar tall map $\text{lr}(T) \rightarrow T$. Explicitly, the number of leaves of $\text{lr}(T)$ matches that of T , together with the inherited order.

3.2 Outer faces and tall maps

In preparation for our discussion of the substitution operation in §3.3, we now recall some basic notions and results concerning outer subtrees and tree grafting, as in [5, §5].

Definition 3.26. Let $T \in \Omega$ be a tree and $e_1 \cdots e_n = \underline{e} \leq e$ a broad relation in T .

We define the *planar outer face* $T_{\underline{e} \leq e}$ to be the subtree with underlying set those edges $f \in T$ such that

$$f \leq_d e, \quad \forall_i e_i \not\leq_d f, \quad (3.27)$$

generating broad relations the relations $f^\dagger \leq f$ for f satisfying (3.27) and $\forall_i f \neq e_i$, and planar structure pulled back from T .

Remark 3.28. If one forgoes the requirement that $T_{\underline{e} \leq e}$ be equipped with the pullback planar structure, the inclusion $T_{\underline{e} \leq e} \rightarrow T$ is usually called simply an *outer face*.

We now recap some basic results.

Proposition 3.29. *Let $T \in \Omega$ be a tree.*

- (a) $T_{\underline{e} \leq e}$ is a tree with root e and edge tuple \underline{e} ;
- (b) there is a bijection

$$\{\text{planar outer faces of } T\} \leftrightarrow \{\text{broad relations of } T\};$$

- (c) if $R \rightarrow S$ and $S \rightarrow T$ are outer face maps then so is $R \rightarrow T$;
- (d) any pair of broad relations $\underline{g} \leq v$, $\underline{f}v \leq e$ induces a grafting pushout diagram

$$\begin{array}{ccc} \eta & \xrightarrow{v} & T_{\underline{g} \leq v} \\ v \downarrow & & \downarrow \\ T_{\underline{f}v \leq e} & \longrightarrow & T_{\underline{f}g \leq v} \end{array} \quad (3.30)$$

Proof. We first show (a). That $T_{\underline{e} \leq e}$ is indeed a tree is the content of [Pe16b, Prop. 5.20]: more precisely, $T_{\underline{e} \leq e} = (T^{\leq e})_{< \underline{e}}$ in the notation therein. That the root of $T_{\underline{e} \leq e}$ is e is clear and that the root tuple is \underline{e} follows from [Pe16b, Remark 5.23].

(b) follows from (a), which shows that $\underline{e} \leq e$ can be recovered from $T_{\underline{e} \leq e}$.

(c) follows from the definition of outer face together with [Pe16b, Lemma 5.33], which states that the \leq_d relations on S, T coincide.

Since by (c) both $T_{\underline{g} \leq v}$ and $T_{\underline{f}v \leq e}$ are outer faces of $T_{\underline{fg} \leq v}$, (d) is a restatement of [Pe16b, Prop. 5.15]. \square

Definition 3.31. A map $S \xrightarrow{\varphi} T$ in Ω is called a *tall map* if

$$\varphi(l_S) = l_T, \quad \varphi(rs) = r_T,$$

where $l_{(-)}$ denotes the leaf tuple and $r_{(-)}$ the root.

The following is a restatement of [Pe16b, Cor. 5.24]

Proposition 3.32. Any map $S \xrightarrow{\varphi} T$ in Ω has a factorization, unique up to unique isomorphism,

$$S \xrightarrow{\varphi^t} U \xrightarrow{\varphi^u} T$$

as a tall map followed by an outer face (in fact, $U = T_{\varphi(l_S) \leq r_S}$).

We recall that a face $F \rightarrow T$ is called inner if it is obtained by iteratively removing inner edges, i.e. edges other than the root or the leaves. In particular, it follows that a face is inner iff it is tall. The usual face-degeneracy decomposition thus combines with Corollary 3.32 to give the following.

Corollary 3.33. Any map $S \xrightarrow{\varphi} T$ in Ω has a factorization, unique up to unique isomorphisms,

$$S \xrightarrow{\varphi^-} U \xrightarrow{\varphi^i} V \xrightarrow{\varphi^u} T \tag{3.34}$$

as a degeneracy followed by an inner face followed by an outer face.

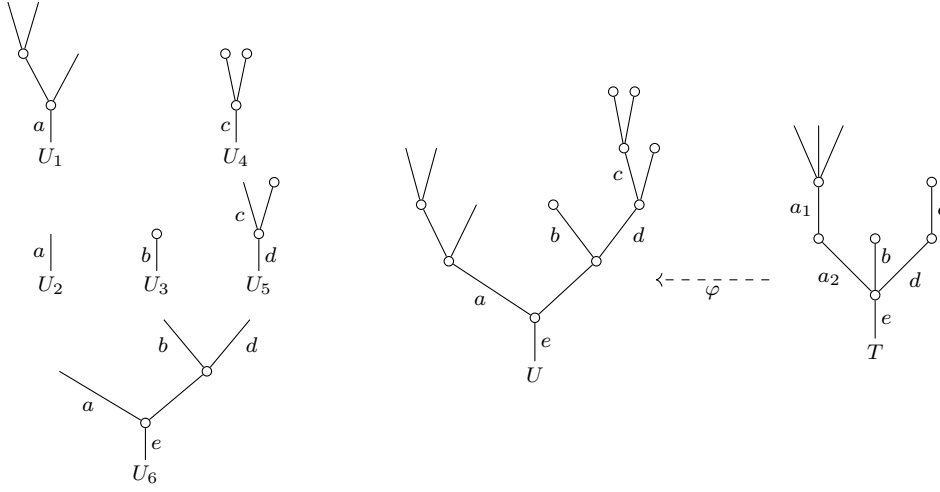
Proof. The factorization (3.34) can be built by first performing the degeneracy-face decomposition and then performing the tall-outer decomposition on the face map. \square

3.3 Substitution

One of the key ideas needed to describe operads is that of substitution of tree nodes, a process that we will prefer to repackage in terms of maps of trees. We start by discussing an example, focusing on the related notion of iterated graftings of trees (as described in (3.30)).

Example 3.35. The trees U_1, U_2, \dots, U_6 on the left below can be grafted into the tree U in the middle. More precisely (among other possible grafting orders), one has

$$U = (((((U_6 \sqcup_a U_2)) \sqcup_a U_1) \sqcup_b U_3) \sqcup_d U_5) \sqcup_c U_4 \tag{3.36}$$

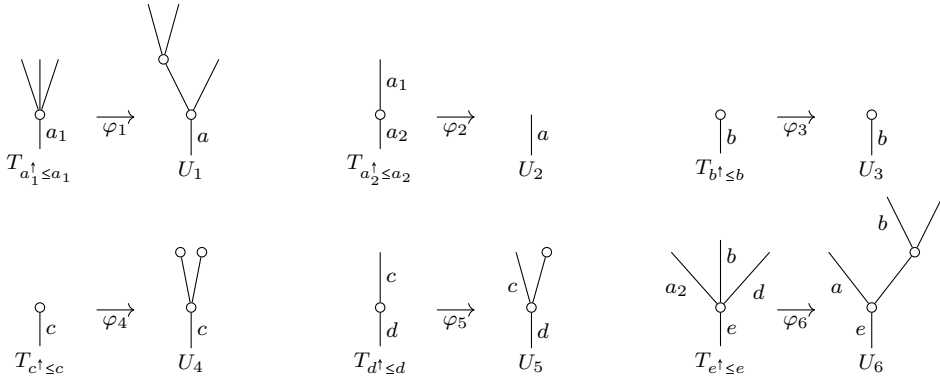


(3.37)

SUBSDATUMTREES EQ

We now consider the tree T , which is built by converting each U_i into the corolla $\text{lr}(U_i)$ (cf. Remark 3.25), and then performing the same grafting operations as in (3.36). T can then be regarded as encoding the combinatorics of the iterated grafting in (3.36), with alternative ways to reorder operations in (3.36) in bijection with ways to assemble T out of its nodes.

One can now therefore think of the iterated grafting (3.36) as being instead encoded by the tree T together with the (unique) planar tall maps φ_i below.



(3.38)

SUBSDATUMTREES2 EQ

From this perspective, U can now be thought as obtained from T by substituting each of its nodes with the corresponding U_i . Moreover, the φ_i assemble to a planar tall map $\varphi: T \rightarrow U$ (such that $a_i \mapsto a, b \mapsto b, \dots, e \mapsto e$), which likewise encodes the same information.

Our perspective will then be that data for substitution of tree nodes such as in (3.38) can equivalently be repackaged using planar tall maps.

Definition 3.39. Let $T \in \Omega$ be a tree.

A T -substitution datum is a tuple $\{U_{e \mapsto e}\}_{(e \mapsto e) \in V(T)}$ together with tall maps $T_{e \mapsto e} \rightarrow U_{e \mapsto e}$.

Further, a map of planar T -substitution data $\{U_{e \mapsto e}\} \rightarrow \{V_{e \mapsto e}\}$ is a tuple of tall maps $\{U_{e \mapsto e} \rightarrow V_{e \mapsto e}\}$ compatible with the chosen maps.

Lastly, a substitution datum is called a *planar T -substitution datum* if the chosen maps are planar (so that $\text{lr}(U_{e \mapsto e}) = T_{e \mapsto e}$) and a morphism of planar data is called a planar morphism if it consists of a tuple of planar maps.

Definition 3.40. Let $T \in \Omega$.

The *Segal core poset* $\mathbf{Sc}(T)$ is the poset with objects the edge subtrees η_e and vertex subtrees $T_{e^\dagger \leq e}$. The order relation is given by inclusion.

Remark 3.41. Note that the only maps in $\mathbf{Sc}(T)$ are inclusions of the form $\eta_a \subset T_{e^\dagger \leq e}$. In particular, there are no pairs of composable non-identity relations in $\mathbf{Sc}(T)$.

Given a T -substitution datum $\{U_{\{e^\dagger \leq e\}}\}$ we abuse notation by writing

$$U_{(-)} : \mathbf{Sc}(T) \rightarrow \Omega$$

for the functor $\eta_a \mapsto \eta$, $T_{e^\dagger \leq e} \mapsto U_{e^\dagger \leq e}$ and sending the inclusions $\eta_a \subset T_{e^\dagger \leq e}$ to the composites

$$\eta \xrightarrow{a} T_{e^\dagger \leq e} \rightarrow U_{e^\dagger \leq e}.$$

Proposition 3.42. *Let $T \in \Omega$ be a tree. There is an isomorphism of categories*

$$\begin{aligned} \mathbf{Sub}_p(T) &\xleftarrow{\quad} \Omega_{T|}^{\text{pt}} \\ \{U_{e^\dagger \leq e}\} &\longmapsto (T \rightarrow \text{colim}_{\mathbf{Sc}(T)} U_{(-)}) \\ \{U_{\varphi(e^\dagger) \leq \varphi(e)}\} &\longleftarrow (T \xrightarrow{\varphi} U) \end{aligned} \tag{3.43}$$

where $\mathbf{Sub}_p(T)$ denotes the category of planar T -substitution data and $\Omega_{T|}^{\text{pt}}$ the category of planar tall maps under T .

Proof. We first claim that (i) the $\text{colim}_{\mathbf{Sc}(T)} U_{(-)}$ indeed exists; (ii) for the canonical datum $\{T_{e^\dagger \leq e}\}$, it is $T = \text{colim}_{\mathbf{Sc}(T)} T_{(-)}$; (iii) the induced map $T \rightarrow \text{colim}_{\mathbf{Sc}(T)} U_{(-)}$ is planar tall.

The argument is by induction on the number of vertices of T , with the base cases of T with 0 or 1 vertices being immediate, since then T is the terminal object of $\mathbf{Sc}(T)$. Otherwise, one can choose a non trivial grafting decomposition so as to write $T = R \sqcup_e S$, resulting in identifications $\mathbf{Sc}(R) \subset \mathbf{Sc}(T)$, $\mathbf{Sc}(S) \subset \mathbf{Sc}(T)$ so that $\mathbf{Sc}(R) \cup \mathbf{Sc}(S) = \mathbf{Sc}(T)$ and $\mathbf{Sc}(R) \cap \mathbf{Sc}(S) = \{\eta_e\}$. The existence of $\text{colim}_{\mathbf{Sc}(T)} U_{(-)}$ is thus equivalent to the existence of the pushout below.

$$\begin{array}{ccc} \eta & \longrightarrow & \text{colim}_{\mathbf{Sc}(R)} U_{(-)} \\ \downarrow & & \downarrow \\ \text{colim}_{\mathbf{Sc}(S)} U_{(-)} & \dashrightarrow & \text{colim}_{\mathbf{Sc}(T)} U_{(-)} \end{array} \tag{3.44}$$

By induction, the top right and bottom left colimits exist for any $U_{(-)}$, equal R and S in the case $U_{(-)} = T_{(-)}$, and the maps $R \rightarrow \text{colim}_{\mathbf{Sc}(R)} U_{(-)}$, $S \rightarrow \text{colim}_{\mathbf{Sc}(S)} U_{(-)}$ are planar tall. But it now follows that (3.44) is a grafting pushout diagram, so that the pushout indeed exists. The conditions that $T = \text{colim}_{\mathbf{Sc}(T)} T_{(-)}$ and $T \rightarrow \text{colim}_{\mathbf{Sc}(T)} U_{(-)}$ is planar tall follow.

The fact that the two functors in (3.43) are inverse to each other is clear by the same inductive argument. \square

Corollary 3.45. *Let $T \in \Omega$ be a tree. There is an isomorphism of categories*

$$\mathbf{Sub}(T) \xleftarrow{\quad} \Omega_{T|}^{\text{t}} \tag{3.46}$$

where $\mathbf{Sub}(T)$ denotes the category of T -substitution data and $\Omega_{T|}^{\text{t}}$ the category of tall maps under T .

Proof. This is a consequence of Proposition 3.23 together with the previous result, with the functor $\mathbf{Sub}(T) \rightarrow \Omega_{T|}^{\text{t}}$ given by the same formula. Indeed, Proposition 3.13 can be restated as saying that isomorphisms $T \rightarrow T'$ are in bijection with substitution data consisting of isomorphisms, and thus bijectiveness reduces to that in the previous result. \square

VERTEXDECOMP REM

Remark 3.47. It follows from the previous proof that, writing $U = \text{colim}_{\text{sc}(T)} U_{(-)}$, one has

$$V(U) = \coprod_{(e^\dagger \leq e) \in V(T)} V(U_{e^\dagger \leq e}). \quad (3.48)$$

VERTEXDECOMP EQ

Alternatively, (3.48) can be regarded as a map $f^*: V(U) \rightarrow V(T)$ induced by the planar tall map $f: T \rightarrow U$. Explicitly, $f^*(U_{u^\dagger \leq u})$ is the unique $T_{t^\dagger \leq t}$ such that $U_{u^\dagger \leq u} \subset U_{t^\dagger \leq t}$. We note that f^* is indeed contravariant in the tall planar map f .

The following is a converse of sorts to Proposition 3.42.

SUBDATAUNDERPLAN PROP

Proposition 3.49. *Let $U \in \Omega$ be a tree. Then:*

- (i) *given non stick outer subtrees U_i such that $V(U) = \coprod_i V(U_i)$ there is a unique tree T and planar tall map $T \rightarrow U$ such that $\{U_i\} = \{U_{e^\dagger \leq e}\}$;*
- (ii) *given multiplicities $m_e \geq 1$ for each edge $e \in U$, there is a unique planar degeneracy $\rho: T \rightarrow U$ such that $\rho^{-1}(e)$ has m_e elements;*
- (iii) *planar tall maps $T \rightarrow U$ are in bijection with collections $\{U_i\}$ of outer subtrees such that $V(U) = \coprod_i V(U_i)$ and U_j is not an inner edge of any U_i whenever $U_j \simeq \eta$ is a stick.*

Proof. We first show (i) by induction on the number of subtrees U_i . The base case $\{U_i\} = \{U\}$ is immediate, setting $T = \text{lr}(U)$. Otherwise, letting e be edge that is both an inner edge of U and a root of some U_i , and one can form a pushout diagram

$$\begin{array}{ccc} \eta & \xrightarrow{e} & V \\ e \downarrow & & \downarrow \\ W & \longrightarrow & U \end{array} \quad (3.50)$$

DECOMPPROOF EQ

inducing a nontrivial partition $\{U_i\} = \{U_i | U_i \hookrightarrow V\} \sqcup \{U_i | U_i \hookrightarrow W\}$. Existence of $T \rightarrow U$ now follows from the induction hypothesis. For uniqueness, the condition that no U_i is a stick guarantees that T possesses a single inner edge mapping to e , and thus admits a compatible decomposition as in (3.50), and thus uniqueness too follows by the induction hypothesis.

For (ii), we argue existence by nested induction on the number of vertices $|V(U)|$ and the sum of the multiplicities m_e . The base case $|V(U)| = 0$, i.e. $U = \eta$ is immediate. Otherwise, writing $m_e = m'_e + 1$, one can form a decomposition (3.50) where either $|V(V)|, |V(W)| < |V(U)|$ or one of V, W is η , so that $T \rightarrow U$ can be built via the induction hypothesis. For uniqueness, note first that by [5, Lemma 5.33] each pre-image $\rho^{-1}(e)$ is linearly ordered and by the “further” claim in [5, Cor. 5.39] the remaining broad relations are precisely the pre-image of the non-identity relations in U , showing that the tree T is uniquely determined.

(iii) follows by combining (i) and (ii). Indeed, any planar tall map $T \rightarrow U$ has a unique decomposition $T \twoheadrightarrow \bar{T} \hookrightarrow U$ as a planar degeneracy followed by a planar inner face, and each of these maps is classified by the data in (b) and (a). \square

Lemma 3.51. *Suppose $T_1, T_2 \hookrightarrow T$ are two outer faces with at least one common edge e . Then there exists a unique outer face $T_1 \cup T_2$ such that $V(T_1 \cup T_2) = V(T_1) \cup V(T_2)$.*

Proof. If either of T_1, T_2 is the root or a leaf the result is obvious. Otherwise, one can necessarily choose e to be an inner edge of T , in which case all of T_1, T_2, T admit compatible decompositions (3.50) and the result follows by induction on $|V(T)|$. \square

DECOMPPROOF EQ

TERFACEUNION LEM

4 The genuine equivariant operad monad

We now turn to the task of building the monad encoding genuine equivariant operads.

4.1 Wreath product over finite sets

In what follows we will let \mathbf{F} denote the usual skeleton of the category of finite sets and all set maps. Explicitly, its objects are the finite sets $\{1, 2, \dots, n\}$ for $n \geq 0$. However, much as in the discussion in Convention 3.18 we will often find it more convenient to regard the elements of \mathbf{F} as equivalence classes of finite sets equipped with total orders.

Definition 4.1. For a category \mathcal{C} , we let $\mathbf{F} \wr \mathcal{C}$ denote the opposite of the Grothendieck construction for the functor

$$\begin{aligned} \mathbf{F}^{op} &\longrightarrow \mathbf{Cat} \\ I &\longmapsto \mathcal{C}^I \end{aligned}$$

Explicitly, the objects of $\mathbf{F} \wr \mathcal{C}$ are tuples $(c_i)_{i \in I}$ and a map $(c_i)_{i \in I} \rightarrow (d_j)_{j \in J}$ consists of a pair

$$(\phi: I \rightarrow J, (f_i: c_i \rightarrow d_{\phi(i)})_{i \in I}),$$

henceforth abbreviated as $(\phi, (f_i))$.

The following is immediate.

Proposition 4.2. Suppose \mathcal{C} has all finite coproducts. One then has a functor as on the left below. Dually, if \mathcal{C} has all finite products, one has a functor as on the right below.

$$\begin{array}{ccc} \mathbf{F} \wr \mathcal{C} & \xrightarrow{\Pi} & \mathcal{C} \\ (c_i)_{i \in I} & \longmapsto & \coprod_{i \in I} c_i \end{array} \qquad \begin{array}{ccc} (\mathbf{F} \wr \mathcal{C}^{op})^{op} & \xrightarrow{\Pi} & \mathcal{C} \\ (c_i)_{i \in I} & \longmapsto & \prod_{i \in I} c_i \end{array}$$

Lemma 4.3. Suppose that \mathcal{E} is a bicomplete category such that coproducts commute with limits in each variable. If the leftmost diagram

$$\begin{array}{ccc} \mathcal{C} & \xrightarrow{F} & \mathcal{E} \\ k \downarrow & \nearrow \eta & \uparrow G \\ \mathcal{D} & & \end{array} \qquad \begin{array}{ccccc} \mathbf{F} \wr \mathcal{C} & \xrightarrow{\mathbf{F} \wr F} & \mathbf{F} \wr \mathcal{E} & \xrightarrow{\Pi} & \mathcal{E} \\ \mathbf{F} \wr k \downarrow & \nearrow \mathbf{F} \wr \eta & \nearrow \mathbf{F} \wr G & \searrow \Pi \circ \mathbf{F} \wr G & \\ \mathbf{F} \wr \mathcal{D} & & & & \end{array} \quad (4.4) \quad \boxed{\text{WRRAN EQ}}$$

is a right Kan extension diagram then so is the composite of the rightmost diagram.

Dually, if in \mathcal{E} products commute with colimits in each variable, and the leftmost diagram

$$\begin{array}{ccc} \mathcal{C}^{op} & \xrightarrow{F} & \mathcal{E} \\ k \downarrow & \nearrow \epsilon & \uparrow G \\ \mathcal{D}^{op} & & \end{array} \qquad \begin{array}{ccccc} (\mathbf{F} \wr \mathcal{C})^{op} & \xrightarrow{(\mathbf{F} \wr F)^{op}} & (\mathbf{F} \wr \mathcal{E})^{op} & \xrightarrow{\Pi} & \mathcal{E} \\ (\mathbf{F} \wr k)^{op} \downarrow & \nearrow & \nearrow (\mathbf{F} \wr G)^{op} & \searrow \Pi \circ (\mathbf{F} \wr G)^{op} & \\ (\mathbf{F} \wr \mathcal{D})^{op} & & & & \end{array} \quad (4.5) \quad \boxed{\text{WRLAN EQ}}$$

is a left Kan extension diagram then so is the composite of the rightmost diagram.

Proof. Unpacking definitions using the pointwise formula for Kan extensions ([McL, X.3.1]), the claim concerning (4.4) amounts to showing that for each $(d_i) \in \mathbf{F} \wr \mathcal{D}$ one has natural isomorphisms

$$\lim_{((d_i) \rightarrow (kc_j)) \in ((d_i) \downarrow \mathbf{F} \wr \mathcal{C})} \left(\coprod_j F(c_j) \right) \simeq \prod_i \lim_{(d_i \rightarrow kc_i) \in d_i \downarrow \mathcal{C}} (F(c_i)). \quad (4.6) \quad \boxed{\text{POINTKAN EQ}}$$

Noting that the canonical factorizations of each $(\varphi, (f_i)): (d_i)_{i \in I} \rightarrow (kc_j)_{j \in J}$ as

$$(d_i)_{i \in I} \rightarrow (c_{\phi(i)})_{i \in I} \rightarrow (kc_j)_{j \in J}$$

exhibit $\prod_i (d_i \downarrow \mathcal{C})$ as a coreflexive subcategory of $(d_i) \downarrow \mathbf{F} \wr \mathcal{C}$, we see that it is an initial subcategory. Therefore

$$\lim_{((d_i) \rightarrow (kc_j)) \in ((d_i) \downarrow \mathbf{F} \wr \mathcal{C})} \left(\coprod_j F(c_j) \right) \simeq \lim_{((d_i) \rightarrow (kc_i)) \in \prod_i (d_i \downarrow \mathcal{C})} \left(\coprod_i F(c_i) \right)$$

and hence ^{POINTKAN EQ} (4.6) now follows from the assumption that coproducts commute with limits in each variable. \square

Notation 4.7. Using the coproduct functor $F^{i2} = F^{i\{0,1\}} = F \wr F \xrightarrow{\sqcup} F$ (where $\coprod_{i \in I} J_i$ is ordered lexicographically) and the simpleton $\{1\} \in F$ one can regard the collection of categories $F^{i\{0,\dots,n\}} \wr \mathcal{C} = F^{in} \wr \mathcal{C}$ as a coaugmented cosimplicial object in \mathbf{Cat} . As such, we will denote by

$$\delta^i: F^{in-1} \wr \mathcal{C} \rightarrow F^{in} \wr \mathcal{C}, \quad 0 \leq i \leq n$$

the cofaces obtained by inserting simpletons $\{1\} \in F$ and by

$$\sigma^i: F^{in+1} \wr \mathcal{C} \rightarrow F^{in} \wr \mathcal{C}, \quad 0 \leq i \leq n$$

the codegeneracies obtained by applying the coproduct $F^{i2} \xrightarrow{\sqcup} F$ to adjacent F coordinates.

4.2 Equivariant leaf-root and vertex functors

Definition 4.8. A morphism $T \xrightarrow{\varphi} S$ in Ω_G is called a *quotient* if the underlying morphism of forests

$$\coprod_{[g] \in G/H} T_{[g]} \rightarrow \coprod_{[h] \in G/K} S_{[h]}$$

maps each tree component (or, equivalently, some tree component) isomorphically onto its image component.

We denote the subcategory of G -trees and quotients by Ω_G^q .

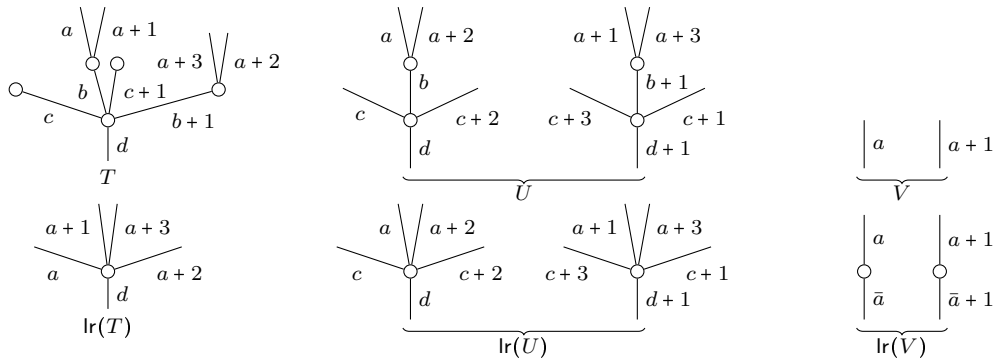
Definition 4.9. The *G -symmetric category*, which we will also call the *category of G -corollas*, is the full subcategory $\Sigma_G \subset \Omega_G^q$ of those G -trees that are corollas, i.e. G -trees such that each edge is either a root or a leaf (but not both).

Definition 4.10. The *leaf-root functor* is the functor $\Omega_G^q \xrightarrow{\text{lr}} \Sigma_G$ defined by

$$\text{lr}(T) = \{\text{leaves of } T\} \sqcup \{\text{roots of } T\}$$

with a broad relation $l_1 \dots l_n \leq r$ holding in $\text{lr}(T)$ iff its image holds in T and similarly for the planar structure \leq_p .

Remark 4.11. Generalizing Remark 3.25, ^{UNIQCOR REM} $\text{lr}(T)$ can alternatively be characterized as being the *unique G -corolla* which admits an also unique (tree-wise) tall planar map $\text{lr}(T) \rightarrow T$. Moreover, $\text{lr}(T)$ can usually be regarded as the “smallest inner face” of T , obtained by removing all the inner edges, although this characterization fails when $T = G \cdot_H \eta$ is a stick G -tree. Some examples with $G = \mathbb{Z}/4$ follow.



Remark 4.12. One consequence of the fact that planarizations can not be pushed forward along tree maps (cf. Remark 3.24) ^{PULLPLANAR REM} is that $\text{lr}: \Omega_G^q \rightarrow \Sigma_G$ is not a categorical fibration. **maybe add to this.**

VG DEF

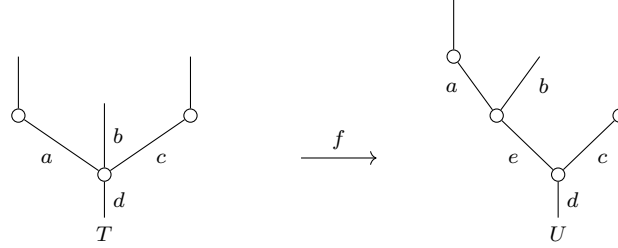
Definition 4.13. Given $T \in \Omega_G$ we define the set $V_G(T)$ of G -vertices of T to be the orbit set $V(T)/G$, i.e. the quotient of the vertex set $V(T)$ by its G -action.

Furthermore, we will regard $V_G(T)$ as an object in \mathbf{F} by equipping it with its lexicographic order: i.e. vertex equivalence classes $[e^\dagger \leq e]$ are ordered according to the planar order \leq_p of the smallest representative ge , $g \in G$.

VERTEXDECOMP REM

Remark 4.14. Following Remark 3.47, a planar tall map $f: T \rightarrow U$ of G -trees induces a G -equivariant map $f^*: V(U) \rightarrow V(T)$ and thus also a map of orbits $f^*: V_G(U) \rightarrow V_G(T)$. We note, however, that f^* is not in general compatible with the order on V_G , as is indeed the case even in the non-equivariant case.

A minimal example follows.



In $V(T)$ the vertices are ordered as $a < c < d$ while in $V(U)$ they are ordered as $a < e < c < d$ but the map $f^*: V(U) \rightarrow V(T)$ is given by $a \mapsto a, c \mapsto c, d \mapsto d, e \mapsto d$.

Note that each element of $V_G(T)$ corresponds to an unique edge orbit Ge for e not a leaf. As such, we will represent the corresponding G -vertex by $v_{Ge} = (Ge)^\dagger \leq Ge$ (which we interpret as the concatenation of the relations $f^\dagger \leq f$ for $f \in Ge$) and write

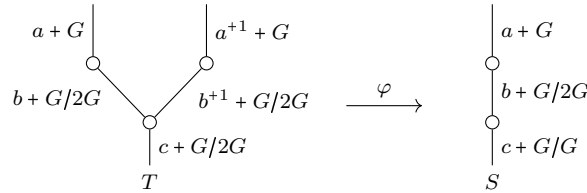
$$T_{v_{Ge}} = T_{(Ge)^\dagger \leq Ge} = \coprod_{f \in Ge} T_{f^\dagger \leq f}.$$

We note that $T_{v_{Ge}}$ is always a G -corolla. Indeed, noting that a quotient map $\varphi: T \rightarrow S$ induces quotient maps $T_{v_{ge}} \rightarrow S_{v_{G\varphi(e)}}$ one obtains a functor

$$\begin{aligned} \Omega_G^q &\xrightarrow{V_G} \mathbf{F} \wr \Sigma_G \\ T &\longmapsto (T_{v_{Ge}})_{v_{Ge} \in V_G(T)}. \end{aligned} \tag{4.15}$$

VFUNCTOR EQ

Remark 4.16. The need to introduce the $\mathbf{F} \wr \mathcal{C}$ categories comes from the fact that general quotient maps do not preserve the number of G -vertices. For a simple example, let $G = \mathbb{Z}/4$ and consider the quotient map



sending edges labeled a, b, c to the edges with the same name and the edges a^{+1}, b^{+1} to the edges $a + 1, b + 1$. We note that T has three G -vertices $v_{Gc}, v_{Gb}, v_{Gb^{+1}}$ while S has only two G -vertices v_{Gc} and v_{Gb} . $V(\phi)$ then maps the two corollas $T_{v_{Gb}}$ and $T_{v_{Gb^{+1}}}$ isomorphically onto $T_{S_{Gb}}$ and the corolla $T_{v_{Gc}}$ non-isomorphically onto $S_{v_{Gc}}$.

Definition 3.39 now immediately generalizes. Here a map is called *rooted* if it induces an ordered isomorphism on the root orbit.

TUTIONDATUMG DEF

Definition 4.17. Let $T \in \Omega_G$ be a G -tree.

A *rooted (resp. planar) T -substitution datum* is a tuple $\{U_{v_{Ge}}\}_{v_{Ge} \in V_G(T)}$ together with rooted (resp. planar) tall maps $T_{v_{Ge}} \rightarrow U_{v_{Ge}} = T_{v_{Ge}}$.

Further, a map of rooted (resp. planar) T -substitution data $\{U_{v_{Ge}}\} \rightarrow \{V_{v_{Ge}}\}$ is a tuple of rooted (resp. planar) tall maps $\{U_{v_{Ge}} \rightarrow V_{v_{Ge}}\}$.

UBSDATUMCONV REM

Remark 4.18. To establish the equivariant analogue of Proposition 3.42 we will prefer to repackage equivariant substitution data in terms of non-equivariant terms.

Noting that there are decompositions $U_{v_{Ge}} = \coprod_{ge \in G_e} U_{ge^\dagger \leq ge}$ and letting $G \ltimes V(T)$ denote the Grothendieck construction for the action of G on the non-equivariant vertices $V(T)$ (often called the action groupoid), it is immediate that an equivariant T -substitution datum is the same as a functor $G \ltimes V(T) \rightarrow \Omega$ whose restriction to $V(T) \subset G \ltimes V(T)$ is a (non-equivariant) substitution datum.

AUNDERPLANG PROP

Proposition 4.19. Let $T \in \Omega_G$ be a G -tree. There are isomorphisms of categories

$$\begin{aligned} \text{Sub}_p(T) &\xleftarrow{\quad} \Omega_{G,T}^{\text{pt}} & \text{Sub}_r(T) &\xleftarrow{\quad} \Omega_{G,T}^{\text{rt}} \\ \{U_{v_{Ge}}\} &\longmapsto (T \rightarrow \text{colim}_{\text{Sc}(T)} U_{(-)}) & \{U_{v_{Ge}}\} &\longmapsto (T \rightarrow \text{colim}_{\text{Sc}(T)} U_{(-)}) \end{aligned} \quad (4.20)$$

SUBDATAUNDERPLANG EQ

Proof. This is a minor adaptation of the non-equivariant analogues Proposition 4.19 and Corollary 3.45. Since $\text{Sc}(T)$ inherits a G action, one can form the Grothendieck construction $G \ltimes \text{Sc}(T)$ and by Remark 4.18 equivariant substitution data $\{U_{v_{Ge}}\}$ therefore induce functors $U_{(-)}: G \ltimes \text{Sc}(T) \rightarrow \Omega$. It is then immediate that $\text{colim}_{\text{Sc}(T)} U_{(-)}$ inherits a G -action, provided it exists. The key observation is then that, since $\text{Sc}(T)$ is now a disconnected poset, this colimit is to be interpreted as taken in the category Φ of forests rather than in Ω .

Additionally, we note that the need to use rooted data comes from the fact that rooted isomorphisms $T \rightarrow T'$ are in bijection with rooted substitution data that are given by isomorphisms, a statement that fails in the absence of the rooted condition. \square

Remark 4.21. We will need to know that in the planar case each of the maps

$$U_{v_{Ge}} \rightarrow U = \text{colim}_{\text{Sc}(T)} U_{(-)}$$

induced by the previous proof is a planar map of G -trees. This requires two observations: (i) the restrictions to each of the constituent non-equivariant trees $U_{ge^\dagger \leq ge}$ is planar by Proposition 4.19; (ii) the restriction to the roots of $U_{v_{Ge}}$ is injective and order preserving since it matches the inclusion of the roots of $T_{v_{Ge}}$, and the map $T \rightarrow U$ is a planar map of G -trees.

PULLCOMP REM

Remark 4.22. The isomorphisms in Proposition 4.19 are compatible with root pullback of trees. More concretely, any pullback $\pi: S = \varphi^* T \rightarrow T$ induces pullbacks $\pi_{Ge}: S_{v_{Ge}} \rightarrow T_{v_{Ge}}$ for $v_{Ge} \in V_G(S)$ and one has commutative diagrams

$$\begin{array}{ccc} \text{Sub}_p(S) &\xleftarrow{\quad} \Omega_{G,S}^{\text{pt}} & \text{Sub}_r(S) &\xleftarrow{\quad} \Omega_{G,S}^{\text{rt}} \\ (\pi_{Ge})^\uparrow &\uparrow \pi^* & (\pi_{Ge})^\uparrow &\uparrow \pi^* \\ \text{Sub}_p(T) &\xleftarrow{\quad} \Omega_{G,T}^{\text{pt}} & \text{Sub}_r(T) &\xleftarrow{\quad} \Omega_{G,T}^{\text{rt}} \end{array} \quad (4.23)$$

SUBDATAUNDERPLANG2 EQ

PLANARSTRING SEC

4.3 Planar strings

The leaf-root and vertex functors will allow us to reinterpret our results concerning substitution.

Definition 4.24. The category $\Omega_{G,n}$ of *substitution n -strings* is the category whose objects are strings

$$T_0 \xrightarrow{f_1} T_1 \xrightarrow{f_2} \dots \xrightarrow{f_n} T_n$$

where $T_i \in \Omega_G$ and the f_i are tall planar maps, and arrows are commutative diagrams

$$\begin{array}{ccccccc} T_0 & \xrightarrow{f_1} & T_1 & \xrightarrow{f_2} & \cdots & \xrightarrow{f_n} & T_n \\ q_0 \downarrow & & q_1 \downarrow & & & & q_n \downarrow \\ T'_0 & \xrightarrow{f'_1} & T'_1 & \xrightarrow{f'_2} & \cdots & \xrightarrow{f'_n} & T'_n \end{array} \quad (4.25) \quad \text{PTNARROW EQ}$$

where each q_i is a quotient map.

Notation 4.26. Since compositions of planar tall arrows are planar tall and identity arrows are planar tall it follows that $\Omega_{G,\bullet}$ forms a simplicial object in \mathbf{Cat} , with faces given by composing and degeneracies by inserting identities.

Noting that $\Omega_{G,0} = \Omega_G^q$ and setting $\Omega_{G,-1} = \Sigma_G$, the leaf-root functor $\Omega_G^q \xrightarrow{\text{lr}} \Sigma_G$ makes $\Omega_{G,\bullet}^q$ into an augmented simplicial object and, furthermore, the maps $s_{-1}: \Omega_{G,n}^q \rightarrow \Omega_{G,n+1}^q$ sending $T_0 \rightarrow T_1 \rightarrow \cdots \rightarrow T_n$ to $\text{lr}(T_0) \rightarrow T_0 \rightarrow T_1 \rightarrow \cdots \rightarrow T_n$ equip it with extra degeneracies.

Notation 4.27. We extend the vertex functor to a functor $V_G: \Omega_{G,n+1} \rightarrow \mathbf{F} \wr \Omega_{G,n}$ by

$$V_G(T_0 \rightarrow T_1 \rightarrow \cdots \rightarrow T_n) = (T_{1,v_{Ge}} \rightarrow \cdots \rightarrow T_{n,v_{Ge}})_{v_{Ge} \in V_G(T_0)} \quad (4.28) \quad \text{VGDEF EQ}$$

where we abuse notation by writing $T_{i,v_{Ge}}$ for $T_{i,(f_1 \circ \cdots \circ f_i)(v_{Ge})}$.

The following is a reinterpretation of Proposition 4.19.

Proposition 4.29. *The diagram*

$$\begin{array}{ccc} \Omega_{G,n+1} & \xrightarrow{V_G} & \mathbf{F} \wr \Omega_{G,n} \\ d_{1,\dots,n+1} \downarrow & & \downarrow \text{Fid}_{0,\dots,n} \\ \Omega_{G,0} & \xrightarrow{V_G} & \mathbf{F} \wr \Sigma_G \end{array} \quad (4.30) \quad \text{PTPULL EQ}$$

is a pullback diagram in \mathbf{Cat} .

Proof. An object in the pullback (4.30) over $T \in \Omega_{G,0} = \Omega_G^q$ is precisely the same as a n -string in $\mathbf{Sub}(T)$, and thus by Proposition 4.19 equivalent to a $n+1$ planar tall string starting at T .

The case of arrows is slightly more subtle. A quotient map $\pi: T \rightarrow T'$ induces a G -equivariant poset map $\pi_*: \mathbf{Sc}(T) \rightarrow \mathbf{Sc}(T')$ (or equivalently, a map of Grothendieck constructions $G \ltimes \mathbf{Sc}(T) \rightarrow G \ltimes \mathbf{Sc}(T')$) and diagrams as on the left below (where v_{Ge} ranges over $V_G(T)$ and $e' = \varphi(e)$) induce diagrams (of functors $\mathbf{Sc}(T) \rightarrow \Omega$) as on the right below.

$$\begin{array}{ccc} T_{v_{Ge}} \rightarrow T_{1,v_{Ge}} \rightarrow \cdots \rightarrow T_{n,v_{Ge}} & T_{(-)} \longrightarrow T_{1,(-)} \longrightarrow \cdots \longrightarrow T_{n,(-)} \\ \downarrow & \downarrow & \downarrow \\ T'_{v_{Ge'}} \rightarrow T'_{1,v_{Ge'}} \rightarrow \cdots \rightarrow T'_{n,v_{Ge'}} & T'_{(-)} \circ \pi_* \rightarrow T'_{1,(-)} \circ \pi_* \rightarrow \cdots \rightarrow T'_{n,(-)} \circ \pi_* \end{array} \quad (4.31) \quad \text{PTNARROWLOC EQ}$$

Passing to colimits then gives the desired commutative diagram (4.25). Moreover, diagrams of the form (4.25) clearly induce diagrams as in (4.31) and it is straightforward to check that these are inverse processes. \square

Remark 4.32. The diagrams (with back and lower slanted faces instances of (4.30))

$$\begin{array}{ccc} \Omega_{G,n+2} & \xrightarrow{\quad} & \mathbf{F} \wr \Omega_{G,n+1} \\ & \searrow d_{i+1} & \downarrow \text{Fid}_i \\ & \Omega_{G,n+1} & \xrightarrow{\quad} & \mathbf{F} \wr \Omega_{G,n} \\ & \downarrow & \downarrow & \downarrow \\ \Omega_{G,0} & \xrightarrow{\quad} & \mathbf{F} \wr \Sigma_G \end{array} \quad \begin{array}{ccc} \Omega_{G,n+1} & \xrightarrow{\quad} & \mathbf{F} \wr \Omega_{G,n} \\ & \searrow s_i & \downarrow \text{Fid}_{i-1} \\ & \Omega_{G,n+2} & \xrightarrow{\quad} & \mathbf{F} \wr \Omega_{G,n+1} \\ & \downarrow & \downarrow & \downarrow \\ \Omega_{G,0} & \xrightarrow{\quad} & \mathbf{F} \wr \Sigma_G \end{array}$$

commute whenever defined (i.e. $0 \leq i \leq n+1$).

INDVNG NOT

Notation 4.33. We will let

$$V_{G,n}: \Omega_{G,n} \rightarrow \mathbf{F} \wr \Sigma_G$$

be inductively defined by $V_{G,n} = \sigma_0 \circ V_{G,n-1} \circ V_G$.

Remark 4.34. When $n = 2$, $V_{G,2}$ is thus the composite

$$\Omega_{G,2} \xrightarrow{V_G} \mathbf{F} \wr \Omega_{G,1} \xrightarrow{V_G} \mathbf{F} \wr \mathbf{F} \wr \Omega_{G,0} \xrightarrow{V_G} \mathbf{F} \wr \mathbf{F} \wr \mathbf{F} \wr \Sigma_G \xrightarrow{\sigma^0} \mathbf{F} \wr \mathbf{F} \wr \Sigma_G \xrightarrow{\sigma^0} \mathbf{F} \wr \Sigma_G$$

In light of Remarks 3.47 and 4.14, $V_{G,n}(T_0 \rightarrow \dots \rightarrow T_n)$ is identified with the tuple

$$(T_n, v_{Ge})_{v_{Ge} \in V_G(T_n)}, \quad (4.35)$$

VGNISO EQ

though this requires changing the total order in $V_G(T_n)$. Rather than using the order induced by T_n , one instead equips $V_G(T_n)$ with the order induced lexicographically from the maps $V_G(T_n) \rightarrow V_G(T_{n-1}) \rightarrow \dots \rightarrow V_G(T_0)$, i.e., for $v, w \in V_G(T_n)$ the condition $v < w$ is determined by the lowest i such that the images of $v, w \in V_G(T_i)$ are distinct.

4.4 A monad on spans

WSPAN DEF

Definition 4.36. We will write $\mathbf{WSpan}^l(\mathcal{C}, \mathcal{D})$ (resp. $\mathbf{WSpan}^r(\mathcal{C}, \mathcal{D})$), which we call the category of *left weak spans* (resp. *right weak spans*), to denote the category with objects the spans

$$\mathcal{C} \xleftarrow{k} A \xrightarrow{F} \mathcal{D},$$

arrows the diagrams as on the left (resp. right) below

$$\begin{array}{ccc} & A_1 & \\ k_1 \swarrow & & \searrow F_1 \\ \mathcal{C} & & \mathcal{D} \\ k_2 \swarrow & i \downarrow & \nearrow \varphi \\ & A_2 & \\ & \nearrow F_2 & \end{array} \quad \begin{array}{ccc} & A_1 & \\ k_1 \swarrow & & \searrow F_1 \\ \mathcal{C} & & \mathcal{D} \\ k_2 \swarrow & i \downarrow & \nearrow \varphi \\ & A_2 & \\ & \nearrow F_2 & \end{array} \quad (4.37)$$

TWISTEDARROWRIGHT EQ

which we write as $(i, \varphi): (k_1, F_1) \rightarrow (k_2, F_2)$, and composition given in the obvious way.

Remark 4.38. There are natural isomorphisms

$$\mathbf{WSpan}^r(\mathcal{C}, \mathcal{D}) \simeq \mathbf{WSpan}^l(\mathcal{C}^{op}, \mathcal{D}^{op}). \quad (4.39)$$

LRSPANISO EQ

Remark 4.40. The terms *left/right* are motivated by the existence of adjunctions (which are seen to be equivalent by using (4.39))

$$\mathbf{Lan}: \mathbf{WSpan}^l(\mathcal{C}, \mathcal{D}) \rightleftarrows \mathbf{Fun}(\mathcal{C}, \mathcal{D}): \iota$$

$$\iota: \mathbf{Fun}(\mathcal{C}, \mathcal{D}) \rightleftarrows \mathbf{WSpan}^r(\mathcal{C}, \mathcal{D})^{op}: \mathbf{Ran}$$

where the functors ι denote the obvious inclusions (note the need for the $(-)^{op}$ in the second adjunction) and $\mathbf{Lan}/\mathbf{Ran}$ denote the left/right Kan extension functors.

We will mainly be interested in the span categories $\mathbf{WSpan}^l(\Sigma_G^{op}, \mathcal{V}) \simeq \mathbf{WSpan}^r(\Sigma_G, \mathcal{V}^{op})$.

Notation 4.41. Given a functor $\pi: A \rightarrow \Sigma_G$, we let $\Omega_{G,n}^{(A)}$ denote the pullback (in \mathbf{Cat})

$$\begin{array}{ccc} \Omega_{G,n}^{(A)} & \xrightarrow{V_{G,n}^{(A)}} & \mathbf{F} \wr A \\ \downarrow & & \downarrow \\ \Omega_{G,n} & \xrightarrow{V_{G,n}} & \mathbf{F} \wr \Sigma_G \end{array}$$

Explicitly, the objects of $\Omega_{G,n}^{(A)}$ are pairs

$$(T_0 \rightarrow \dots \rightarrow T_n, (a_{e^\dagger \leq e})_{(e^\dagger \leq e) \in V_G(T_n)}) \quad (4.42)$$

OMEGAGNA EQ

such that $\pi(a_{e^\dagger \leq e}) = T_{n, e^\dagger \leq e}$.

OMEGAGNA NOT

Remark 4.43. Our primary interest here will be in the $\Omega_{G,0}^{(A)}$ construction. Importantly, the composite maps $\Omega_{G,0}^{(A)} \rightarrow \Omega_{G,0} \rightarrow \Sigma_G$ allow us to iterate the $\Omega_{G,0}^{(-)}$ construction. In practice, the role of higher strings $\Omega_{G,n}^{(A)}$ will then be to provide more convenient models for iterated $\Omega_{G,0}^{(-)}$ constructions.

Indeed, the content of Proposition 4.29 is then that there are compatible identifications $\Omega_{G,0}^{(\Omega_{G,n}^{(A)})} \simeq \Omega_{G,n+1}$ which identify $V_G^{(\Omega_{G,n}^{(A)})}$ with V_G .

Moreover, since all squares in the diagram

$$\begin{array}{ccccccc}
 \Omega_{G,n+1}^{(A)} & \xrightarrow{V_G^{(A)}} & F \wr \Omega_{G,n}^{(A)} & \xrightarrow{F \wr V_G^{(A)}} & F \wr F \wr A & \xrightarrow{\sigma^0} & F \wr A \\
 \downarrow & & \downarrow & & \downarrow & & \downarrow \\
 \Omega_{G,n+1} & \xrightarrow{V_G} & F \wr \Omega_{G,n} & \xrightarrow{F \wr V_G} & F \wr F \wr \Sigma_G & \xrightarrow{\sigma^0} & F \wr \Sigma_G \\
 \downarrow & & \downarrow & & & & \\
 \Omega_{G,0} & \longrightarrow & F \wr \Sigma_G & & & &
 \end{array} \tag{4.44}$$

ALLSQUARES EQ

are pullback squares (the top center square is so by induction, the top right square by direct verification, the total top square by definition of $\Omega_{G,n+1}^{(A)}$ and the bottom left square by Proposition 4.29), we likewise obtain identifications $\Omega_G^{(\Omega_{G,n}^{(A)})} \simeq \Omega_{G,n+1}^{(A)}$.

Proposition 4.45. For any $A \rightarrow \Sigma_G$ there are functors $d_0^{(A)}: \Omega_{G,1}^{(A)} \rightarrow \Omega_G^{(A)}$ and natural isomorphisms

$$\begin{array}{ccc}
 \Omega_{G,1}^{(A)} & \xrightarrow{V_G} & F \wr \Omega_G^{(A)} \xrightarrow{F \wr V_G} F \wr F \wr A \\
 d_0^{(A)} \downarrow & \nearrow \pi^{(A)} & \downarrow \sigma^0 \\
 \Omega_G^{(A)} & \xrightarrow{V_G} & F \wr A,
 \end{array} \tag{4.46}$$

SHUFFLEPERMA EQ

both natural in $A \rightarrow \Sigma$. Here naturality of $\pi^{(-)}$ means that for a functor $H: A \rightarrow B$ with corresponding diagram

$$\begin{array}{ccccccc}
 \Omega_{G,1}^{(A)} & \xrightarrow{V_G^{(A)}} & F \wr \Omega_{G,0}^{(A)} & \xrightarrow{F \wr V_G^{(A)}} & F \wr F \wr A & \xrightarrow{\sigma^0} & F \wr A \\
 \downarrow \Omega_{G,1}^{(H)} & \searrow d_0^{(A)} & \downarrow & \nearrow \pi^{(A)} & \downarrow & & \downarrow \\
 \Omega_{G,1}^{(B)} & \xrightarrow{V_G^{(B)}} & F \wr \Omega_{G,0}^{(B)} & \xrightarrow{F \wr V_G^{(B)}} & F \wr F \wr B & \xrightarrow{\sigma^0} & F \wr B \\
 \downarrow \Omega_{G,1}^{(H)} & \searrow d_0^{(B)} & \downarrow & \nearrow \pi^{(B)} & \downarrow & & \downarrow \\
 \Omega_{G,1}^{(H)} & \xrightarrow{V_G^{(H)}} & F \wr \Omega_{G,0}^{(H)} & \xrightarrow{F \wr V_G^{(H)}} & F \wr F \wr H & \xrightarrow{\sigma^0} & F \wr H
 \end{array} \tag{4.47}$$

PICUBOIDAB EQ

one has an equality

$$(F \wr H) \pi^{(A)} = \pi^{(B)} \Omega_{G,1}^{(H)}$$

(i.e. the two natural isomorphisms between the two distinct functors $\Omega_{G,1}^{(A)} \Rightarrow F \wr B$ coincide).

Proof. Informally, using the object description in (4.42), $d_0^{(A)}$ is simply given by the formula

$$d_0^{(A)}(T_0 \rightarrow T_1, (a_{e^\dagger \leq e})_{(e^\dagger \leq e) \in V_G(T_1)}) = (T_1, (a_{e^\dagger \leq e})_{(e^\dagger \leq e) \in V_G(T_1)}), \tag{4.48}$$

though one must note that since in (4.42) the order in $V_G(T_1)$ is induced lexicographically from the string, the two orders for $V_G(T_1)$ in each side of (4.48) do not coincide.

It now follows that the composites $\sigma^0 \circ (F \wr V_G^{(A)}) \circ V_G^{(A)}$ and $V_G^{(A)} \circ d_0^{(A)}$ differ by the natural automorphism $\pi^{(A)}$ given by the tuple permutations interchanging the two orders in $V_G(T_1)$ for each $T_0 \rightarrow T_1$.

The commutativity of (4.47) is clear. \square

Definition 4.49. Suppose \mathcal{V} has finite products.

We define an endofunctor N of $\mathbf{Wspan}^r(\Sigma_G, \mathcal{V}^{op})$ by letting $N(\Sigma_G \leftarrow A \rightarrow \mathcal{V}^{op})$ be the span $\Sigma_G \leftarrow \Omega_G^{(A)} \rightarrow \mathcal{V}^{op}$ given composition along the diagram

$$\begin{array}{ccccc} \Omega_{G,0}^{(A)} & \longrightarrow & F \wr A & \longrightarrow & F \wr \mathcal{V}^{op} \xrightarrow{\Pi^{op}} \mathcal{V}^{op} \\ \downarrow & & \downarrow & & \\ \Omega_{G,0} & \longrightarrow & F \wr \Sigma_G & & \\ \downarrow & & & & \\ \Sigma_G & & & & \end{array}$$

and defined on maps of spans in the obvious way.

One has a multiplication $\mu: N \circ N \Rightarrow N$ given by the natural isomorphisms

$$\begin{array}{ccccccc} \Sigma & \longleftarrow & \Omega_{G,1}^{(A)} & \xrightarrow{V_G} & F \wr \Omega_G^{(A)} & \xrightarrow{F \wr V_G} & F \wr F \wr A \longrightarrow F \wr F \wr \mathcal{V}^{op} \longrightarrow F \wr \mathcal{V}^{op} \longrightarrow \mathcal{V}^{op} \\ \parallel & & \downarrow d_0^{(A)} & & \swarrow \pi^{(A)} & \downarrow \sigma^0 & \downarrow \sigma^0 & \swarrow \alpha & \parallel \\ \Sigma & \longleftarrow & \Omega_G^{(A)} & \xrightarrow{V_G} & F \wr A & \longrightarrow & F \wr \mathcal{V}^{op} & \longrightarrow & \mathcal{V}^{op} \end{array} \quad (4.50)$$

MULTDEFSpan EQ

where α is an associativity isomorphism for the product Π . We note that naturality of μ follows from the commutativity of (4.47).

Lastly, there is a unit $\eta: id \Rightarrow N$ given by the strictly commutative diagrams

$$\begin{array}{ccccccc} \Sigma & \longleftarrow & A & \xlongequal{\quad} & A & \longrightarrow & \mathcal{V}^{op} \xlongequal{\quad} \mathcal{V}^{op} \\ \parallel & & \downarrow s_{-1}^{(A)} & & \downarrow & & \downarrow & \parallel \\ \Sigma & \longleftarrow & \Omega_G^{(A)} & \xrightarrow{V_G} & F \wr A & \longrightarrow & F \wr \mathcal{V}^{op} & \longrightarrow \mathcal{V}^{op}. \end{array} \quad (4.51)$$

UNITSpan EQ

MONSPAN PROP

Proposition 4.52. (N, μ, η) form a monad on $\mathbf{Wspan}^r(\Sigma_G, \mathcal{V}^{op})$.

Proof. The natural transformation component of $\mu \circ (N\mu)$ is given by the composite diagram

$$\begin{array}{ccccccccccc} \Omega_{G,2}^{(A)} & \rightarrow & F \wr \Omega_{G,1}^{(A)} & \rightarrow & F^{i2} \wr \Omega_G^{(A)} & \rightarrow & F^{i3} \wr A & \rightarrow & F^{i3} \wr \mathcal{V}^{op} & \rightarrow & F^{i2} \wr \mathcal{V}^{op} & \rightarrow & F \wr \mathcal{V}^{op} & \rightarrow & \mathcal{V}^{op} \\ d_1^{(A)} \downarrow & & \downarrow & & \swarrow F \wr \pi^{(A)} & & \downarrow \sigma^1 & & \downarrow \sigma^1 & & \swarrow F \wr \alpha & & \parallel & & \parallel \\ \Omega_{G,1}^{(A)} & \rightarrow & F \wr \Omega_G^{(A)} & \rightarrow & F^{i2} \wr A & \rightarrow & F^{i2} \wr \mathcal{V}^{op} & \rightarrow & F \wr \mathcal{V}^{op} & \rightarrow & \mathcal{V}^{op} \\ d_0^{(A)} \downarrow & & \swarrow \pi^{(A)} & & \downarrow \sigma^0 & & \downarrow \sigma^0 & & \swarrow \alpha & & \parallel \\ \Omega_G^{(A)} & \rightarrow & F \wr A & \rightarrow & F \wr \mathcal{V}^{op} & \rightarrow & \mathcal{V}^{op} \end{array} \quad (4.53)$$

ASSOCSPAN1 EQ

whereas the natural transformation component of $\mu \circ (\mu N)$ is given by

$$\begin{array}{ccccccccccc}
\Omega_{G,2}^{(A)} & \rightarrow & F\wr\Omega_{G,1}^{(A)} & \rightarrow & F^{i2}\wr\Omega_G^{(A)} & \rightarrow & F^{i3}\wr A & \rightarrow & F^{i3}\wr \mathcal{V}^{op} & \rightarrow & F^{i2}\wr \mathcal{V}^{op} & \rightarrow & F\wr \mathcal{V}^{op} & \rightarrow & \mathcal{V}^{op} \\
d_0^{(A)} \downarrow & & \nearrow & & \downarrow & & \downarrow \sigma^0 & & \downarrow \sigma^0 & & \downarrow & & \nearrow \alpha & & \parallel \\
\Omega_{G,1}^{(A)} & \xrightarrow{\pi(\Omega_G^{(A)})} & F\wr\Omega_G^{(A)} & \rightarrow & F^{i2}\wr A & \rightarrow & F^{i2}\wr \mathcal{V}^{op} & \rightarrow & F\wr \mathcal{V}^{op} & \xrightarrow{\alpha} & \mathcal{V}^{op} & & & & \\
d_0^{(A)} \downarrow & & \nearrow & & \downarrow \sigma^0 & & \downarrow \sigma^0 & & \downarrow & & \nearrow \alpha & & & & \parallel \\
\Omega_G^{(A)} & \xrightarrow{\pi(A)} & F\wr A & \rightarrow & F\wr \mathcal{V}^{op} & \xrightarrow{\alpha} & \mathcal{V}^{op} & & & & & & & &
\end{array} \tag{4.54}$$

ASSOCSPAN2 EQ

That the rightmost sections of (4.53) and (4.54) coincide follows from compatibility of the associativity isomorphisms for Π^{op} .

For the leftmost sections, note first that, in either diagram, the top right and bottom left paths $\Omega_{G,2}^{(A)} \rightarrow F\wr A$ differ only by the induced order on $V_G(T_2)$ for each string $T_0 \rightarrow T_1 \rightarrow T_2$. More explicitly, the top right paths use the order induced lexicographically from the string $T_0 \rightarrow T_1 \rightarrow T_2$ while the bottom left paths use the order induced exclusively by T_2 . The two left sections then coincide since are both given by the permutation interchanging these orders, the only difference being that the intermediate stage of (4.53) uses the order induced lexicographically from $T_0 \rightarrow T_2$ while (4.54) uses the order induced lexicographically from $T_1 \rightarrow T_2$.

As for unit conditions, $\mu \circ (N\eta)$ is represented by

$$\begin{array}{ccccccc}
\Omega_G^{(A)} & \longrightarrow & F\wr A & = & F\wr A & \longrightarrow & F\wr \mathcal{V}^{op} = F\wr \mathcal{V}^{op} \longrightarrow \mathcal{V}^{op} \\
s_0^{(A)} \downarrow & & \downarrow & & \downarrow \delta^1 & & \downarrow \delta^1 & & \parallel & & \parallel \\
\Omega_{G,1}^{(A)} & \rightarrow & F\wr\Omega_G^{(A)} & \rightarrow & F^{i2}\wr A & \rightarrow & F^{i2}\wr \mathcal{V}^{op} & \rightarrow & F\wr \mathcal{V}^{op} & \rightarrow & \mathcal{V}^{op} \\
d_0^{(A)} \downarrow & & \nearrow & & \downarrow \sigma^0 & & \downarrow \sigma^0 & & \nearrow \alpha & & \parallel \\
\Omega_G^{(A)} & \xrightarrow{\pi(A)} & F\wr A & \longrightarrow & F\wr \mathcal{V}^{op} & \xrightarrow{\alpha} & \mathcal{V}^{op} & & & &
\end{array} \tag{4.55}$$

UNITSPAN1 EQ

while $\mu \circ (\eta N)$ is represented by

$$\begin{array}{ccccccc}
\Omega_G^{(A)} & = & \Omega_G^{(A)} & \longrightarrow & F\wr A & \longrightarrow & F\wr \mathcal{V}^{op} \longrightarrow \mathcal{V}^{op} = \mathcal{V}^{op} \\
s_{-1}^{(A)} \downarrow & & \downarrow & & \downarrow \delta^0 & & \downarrow \delta^0 & & \parallel & & \parallel \\
\Omega_{G,1}^{(A)} & \rightarrow & F\wr\Omega_G^{(A)} & \rightarrow & F\wr F\wr A & \rightarrow & F\wr F\wr \mathcal{V}^{op} & \rightarrow & F\wr \mathcal{V}^{op} & \rightarrow & \mathcal{V}^{op} \\
d_0^{(A)} \downarrow & & \nearrow & & \downarrow \sigma^0 & & \downarrow \sigma^0 & & \nearrow \alpha & & \parallel \\
\Omega_G^{(A)} & \xrightarrow{\pi(A)} & F\wr A & \longrightarrow & F\wr \mathcal{V}^{op} & \xrightarrow{\alpha} & \mathcal{V}^{op} & & & &
\end{array} \tag{4.56}$$

UNITSPAN2 EQ

It is straightforward to check that the composites of the left and right sections of both (4.55) and (4.56) are strictly commutative diagrams, and thus that (4.55) and (4.56) coincide. \square

4.5 The free genuine operad monad

Recalling that $\mathbf{Wspan}^r(\Sigma_G, \mathcal{V}^{op}) \simeq \mathbf{Wspan}^l(\Sigma_G^{op}, \mathcal{V})$, Proposition 4.52 and Remark 4.40 give an adjunction

$$\mathbf{Lan}: \mathbf{Wspan}^l(\Sigma_G^{op}, \mathcal{V}) \rightleftarrows \mathbf{Fun}(\Sigma_G^{op}, \mathcal{V}): \iota \tag{4.57}$$

LANIOTAADJ EQ

together with a monad N in the leftmost category $\mathbf{Wspan}^l(\Sigma_G^{op}, \mathcal{V})$. We now turn to showing that, under reasonable hypothesis on \mathcal{V} , the composite $\mathbf{Lan} \circ N \circ \iota$ inherits a monad structure from N . The key will be to show that under such conditions the map $\mathbf{Lan} \circ N \Rightarrow \mathbf{Lan} \circ N \circ \iota \circ \mathbf{Lan}$ is a natural isomorphism.

Recall that following Convention PLANARCONV CON 3.18 our model for \mathbf{O}_G consists of totally ordered sets. One therefore has *root functors*

$$\Omega_G^q \xrightarrow{r} \mathbf{O}_G, \quad \Sigma_G \xrightarrow{r} \mathbf{O}_G$$

sending each planar G -tree to its ordered orbital G -set of roots.

Root functors are compatible with the leaf-root functor and the inclusion, i.e. the following commute.

$$\begin{array}{ccc} \Omega_G^q & \xrightarrow{lr} & \Sigma_G \\ & \searrow r & \downarrow r \\ & & \mathbf{O}_G \end{array} \quad \begin{array}{ccc} \Sigma_G & \xrightarrow{\quad} & \Omega_G^q \\ & \searrow r & \downarrow r \\ & & \mathbf{O}_G \end{array} \quad (4.58) \quad \boxed{\text{ROOTLEAFTROOTCOM EQ}}$$

Moreover, the diagrams ROOTLEAFTROOTCOM EQ (4.58) possess some extra structure we will need to make use of. Indeed, both functors are split Grothendieck fibrations: given a map $\varphi: A \rightarrow B$ in \mathbf{O}_G and G -tree T such that $r(T) = B$ we can build a cartesian arrow $\varphi^*(T) \rightarrow T$ by letting $\varphi^*(T)$ to be the pullback G -tree together with the planar structure on roots given by A and on non-equivariant nodes given by their image via $\varphi^*(T) \rightarrow T$.

It now follows that ROOTLEAFTROOTCOM EQ (4.58) are diagrams of split Grothendieck fibrations.

One advantage of split Grothendieck fibrations (in general) is the following initiality condition on overcategories.

Definition 4.59. Suppose we have two split fibrations $r: \mathcal{C} \rightarrow \mathcal{E}$ and $r: \mathcal{D} \rightarrow \mathcal{E}$ and a map of fibrations f as below.

$$\begin{array}{ccc} \mathcal{C} & \xrightarrow{f} & \mathcal{D} \\ & \searrow r & \swarrow r \\ & \mathcal{E} & \end{array}$$

For any $d \in \mathcal{D}$, let $d \downarrow_r \mathcal{C}$ denote the subcategory of $d \downarrow \mathcal{C}$ of just those maps $d \rightarrow f(c)$ which map to the identity under r .

Lemma 4.60. *In the above scenario, $d \downarrow_r \mathcal{C}$ is initial in $d \downarrow \mathcal{C}$.*

Proof. We must show that the appropriate iterated overcategories are non-empty and connected. To that end, suppose we have a map $\phi: d \rightarrow f(c)$ in \mathcal{D} , and let $q := r(\phi): r(d) \rightarrow r(c)$. Since \mathcal{C} is fibrant over \mathcal{E} , we have a Cartesian arrow $q': c' \rightarrow c$ lifting $q: r(d) = r(c') \rightarrow r(c)$. Thus we have diagrams in \mathcal{E} and \mathcal{D} of the form

$$\begin{array}{ccc} r(d) & \xrightarrow{id} & r(c') \\ & \searrow r(\phi) & \downarrow q \\ & & r(c) \end{array} \quad \begin{array}{ccc} d & \xrightarrow{\exists!} & f(c') \\ & \searrow \phi & \downarrow f(q') \\ & & f(c) \end{array}$$

As f preserves Cartesian arrows, $f(q')$ is Cartesian, and hence we have a unique lifting $p(\phi): d \rightarrow f(c')$ of $r(d) = r(c')$. Thus the iterated overcategory is inhabited.

To show it is connected, any other factorization $d \xrightarrow{\psi} f(c'') \rightarrow f(c)$ such that $r(\psi) = id$, we can again use the fact that q' is Cartesian to produce a lift $f(c';) \rightarrow f(c')$ of $r(c'') = r(c')$; by uniqueness of the map $d \rightarrow f(c')$, we have that the diagram below commutes, finishing the proof.

$$\begin{array}{ccccc} & & d & & \\ & \swarrow \exists! & & \searrow \psi & \\ f(c') & & & & f(c'') \\ & \swarrow f(q') & & \searrow & \\ & & f(c) & & \end{array}$$

□

Remark 4.61. The above proof can be easily modified to show that $d \downarrow \mathcal{C}$ is in fact a coreflective subcategory of $d \downarrow \mathcal{C}$, with $\phi \mapsto p(\phi)$ the reflection.

Luis: to actually show this would take just as long - functoriality and the fact that the inclusion is a left adjoint both require unique liftings/factorizations

Definition 4.62. A split Grothendieck fibration $A \xrightarrow{r} \mathbf{O}_G$ is called a *root fibration* and a split Grothendieck fibration diagram

$$\begin{array}{ccc} A & \longrightarrow & B \\ & \searrow r & \downarrow r \\ & & \mathbf{O}_G \end{array}$$

is called a *root fibration functor*.

The relevance of root fibrations is given by the following couple of lemmas.

Lemma 4.63. If $A \rightarrow \Sigma_G$ is a root fibration functor then so is $\Omega_G^{(A)} \rightarrow \Omega_G$, naturally in A .

Proof. We consider the pullback diagram below.

$$\begin{array}{ccc} \Omega_{G,0}^{(A)} & \xrightarrow{V_G^{(A)}} & \mathbf{F} \wr A \\ \downarrow & & \downarrow \\ \Omega_{G,0} & \xrightarrow{V_G} & \mathbf{F} \wr \Sigma_G \end{array} \quad (4.64) \quad \text{ROOTIMPLIESROOT EQ}$$

The hypothesis that $A \rightarrow \Sigma_G$ is root fibration implies that the rightmost map in (4.64) is a ROOTIMPLIESROOT EQ map of split Grothendieck fibrations over $\mathbf{F} \wr \mathbf{O}_G$.

Since the map V_G sends the chosen cartesian arrows in $\Omega_{G,0}$ (over \mathbf{O}_G) to chosen cartesian arrows of $\mathbf{F} \wr \Sigma_G$ (over $\mathbf{F} \wr \mathbf{O}_G$), the result follows. \square

Example 4.65. Let $G = \mathbb{Z}_{/8}$. The following exemplifies a pull back along the twist map $\varphi: G/2G \rightarrow G/2G$ (i.e., accounting for order, φ is the permutation (12)), with the topmost representation of φ^*T maintaining the chosen generators for each edge orbit from T and the bottom representation choosing instead the generators to be minimal with regard to the planar structure.

(4.66)

We note that $(\varphi^*(T))_{v_{Ge}} = \psi^*(T_{v_{Gb}})$ for ψ the permutation (13)(24) encoded by the composite identifications $\{1, 2, 3, 4\} \simeq \{e, e+2, e+3, e+1\} \simeq \{b+1, b+3, b, b+2\} \simeq \{3, 4, 1, 2\}$.

LANPULLCOMA LEM

Lemma 4.67. Suppose that \mathcal{V} is complete and that $A \rightarrow \Sigma_G$ is a root fibration. If the rightmost triangle in

$$\begin{array}{ccccc} \Omega_{G,0}^{(A)} & \xrightarrow{V_G^{(A)}} & F \wr A & \longrightarrow & \mathcal{V} \\ \downarrow & & \downarrow & \nearrow & \\ \Omega_{G,0} & \xrightarrow{V_G} & F \wr \Sigma_G & & \end{array} \quad (4.68)$$

is a right Kan extension diagram then so is the composite diagram.

Proof. Unpacking definitions using the pointwise formula for right Kan extensions ([McL, X.3.1]), it suffices to check that for each $T \in \Omega_{G,0}$ the functor

$$T \downarrow \Omega_{G,0}^{(A)} \rightarrow V_G(T) \downarrow F \wr A \quad (4.69)$$

LANPULLCOMA EQ

is initial. In the course of the proof of Lemma 4.3 it was shown that the subcategory

$$\prod_{v_{Ge} \in V_G(T)} T_{v_{Ge}} \downarrow A$$

is initial in the $V_G(T) \downarrow F \wr A$.

On the other hand, since $\Omega_G^{(A)} \rightarrow \Omega_G$ is a root fibration functor, $T \downarrow \Omega_G^{(A)}$ has an initial subcategory $T \downarrow_{r,\simeq} \Omega_G^{(A)}$ with objects $(S \in \Omega_G^{(A)}, T \rightarrow u(S))$ such that $T \rightarrow u(S)$ is a quotient map that induces an ordered isomorphism on roots. Note that this can be restated as saying that $T \rightarrow u(S)$ is an isomorphism preserving the order of the roots.

The result now follows from the natural isomorphism

$$T \downarrow_{r,\simeq} \Omega_G^{(A)} \simeq \prod_{v_{Ge} \in V_G(T)} T_{v_{Ge}} \downarrow_{r,\simeq} A. \quad (4.70)$$

TDOWNISOA EQ

To see this, we focus first on the case $A = \Sigma_G$. In that case, the left hand side of (4.70) encodes replanarizations of T that preserve the root order. On the other hand, the right hand side encodes replanarizations of all the G -vertices that preserve the order of their roots, or, equivalently, replanarizations of the non-equivariant vertices of T . That these are equivalent is the content of Proposition 3.13.

Note that $(T \rightarrow S) \in (T \downarrow_{r,\simeq} \Omega_G)$ is then encoded by a tuple $(T_{v_{Ge}} \rightarrow \varphi_{v_{Ge}}^* S_{v_{Ge}})_{v_{Ge} \in V_G(T)}$ where the pullbacks $\varphi_{v_{Ge}}^*$ are needed to correct the root order.

The case of general A follows likewise, using the corresponding pullbacks $\varphi_{v_{Ge}}^*$.

Note: an addendum is needed to show that (4.70) suffices, since $T \downarrow_{r,\simeq} \Omega_G^{(A)}$ is not sent directly to $\prod_{v_{Ge} \in V_G(T)} T_{v_{Ge}} \downarrow_{r,\simeq} A$ □

Lemma 4.63 can be interpreted as saying that, if one defines a category $\mathbf{Wspan}_r^l(\Sigma_G^{op}, \mathcal{V})$ of *rooted spans*

$$\Sigma_G^{op} \leftarrow A^{op} \rightarrow \mathcal{V}$$

where $A \rightarrow \Sigma_G$ is a root fibration functor, the monad N built in Proposition 4.52 lifts to a monad N_r in $\mathbf{Wspan}_r^l(\Sigma_G^{op}, \mathcal{V})$, and likewise for the adjunction (4.57).

Corollary 4.71. Suppose that finite products in \mathcal{V} commute with colimits in each variable. The functors

$$\mathbf{Lan} \circ N_r \Rightarrow \mathbf{Lan} \circ N_r \circ \iota \circ \mathbf{Lan}, \quad \mathbf{Lan} \circ \iota \Rightarrow id$$

are natural isomorphisms.

Proof. This follows by combining Lemma 4.67 with Lemma 4.3. □

Definition 4.72. The *genuine equivariant operad monad* is the monad \mathbb{F}_G on $\text{Fun}(\Sigma_G^{op}, \mathcal{V})$ given by

$$\mathbb{F}_G = \text{Lan} \circ N_r \circ \iota$$

and with multiplication and unit given by the composites

$$\begin{aligned} \text{Lan} \circ N_r \circ \iota \circ \text{Lan} \circ N_r \circ \iota &\stackrel{\simeq}{\leftarrow} \text{Lan} \circ N_r \circ N_r \circ \iota \Rightarrow \text{Lan} \circ N_r \circ \iota \\ id &\stackrel{\simeq}{\leftarrow} \text{Lan} \circ \iota \Rightarrow \text{Lan} \circ N_r \circ \iota. \end{aligned}$$

Remark 4.73. The functor $\text{Lan} \circ N_r \circ \iota$ is isomorphic to $\text{Lan} \circ N \circ \iota$, and this isomorphism is compatible with the multiplication and unit in Definition 4.72, and we will henceforth simply write N rather than N_r .

From this point of view, the role of root fibrations is to guarantee that $\text{Lan} \circ N \circ \iota$ is indeed a monad, but unnecessary to describe the monad structure itself.

Remark 4.74. Since a map

$$\mathbb{F}_G X = \text{Lan} \circ N_r \circ \iota X \rightarrow X$$

is adjoint to a map

$$N_r \circ \iota X \rightarrow \iota X$$

one easily verifies that X is a genuine equivariant operad, i.e. a \mathbb{F}_G -algebra, iff ιX is a N -algebra. Moreover, the bar resolution

$$\mathbb{F}_G^{\bullet+1} X$$

is isomorphic to

$$\text{Lan}(N^{\bullet+1} \iota X).$$

4.6 Comparison with (regular) equivariant operads

We start by noting that in the case $G = *$, genuine operads simply recover the usual notion of symmetric operads, i.e. $\text{Sym}_*(\mathcal{V}) \simeq \text{Sym}(\mathcal{V})$ and $\text{Op}_*(\mathcal{V}) \simeq \text{Op}(\mathcal{V})$, and in what follows we will adopt the notations $\text{Sym}^G(\mathcal{V})$ and $\text{Op}^G(\mathcal{V})$ for the corresponding categories of G -objects. Our goal will be to relate these to the categories $\text{Sym}_G(\mathcal{V})$ and $\text{Op}_G(\mathcal{V})$ of genuine equivariant sequences and genuine operads.

We will throughout this section fix a total order of G such that the identity e is the first element, though we note that the exact order is unimportant, as any other such choice would lead to unique isomorphisms between the constructions in this section.

We thus have an inclusion functor

$$\begin{aligned} \iota: G \times \Sigma &\hookrightarrow \Sigma_G \\ C &\longmapsto G \cdot C \end{aligned}$$

where $G \cdot C$ is planarized so that the roots inherit the order of G and each of the individual copies of C inherits the planarization of C . Moreover, letting $\Sigma_G^{\text{fr}} \hookrightarrow \Sigma_G$ denote the full subcategory of G -free corollas, there is an induced retraction $\rho: \Sigma_G^{\text{fr}} \rightarrow G \times \Sigma$ defined by $\rho(u_{1 \leq i \leq |G|} C_i) = G \cdot C_1$ together with isomorphisms $C \simeq \rho(C)$ uniquely determined by the condition that they are the identity on the first tree component C_1 .

We now consider the associated adjunctions.

$$\begin{array}{ccc} & \xleftarrow{\iota_!} & \\ \text{Sym}_G(\mathcal{V}) & \xrightarrow{\iota^*} & \text{Sym}^G(\mathcal{V}) \\ & \xleftarrow{\iota_*} & \end{array}$$

(4.75) TWOADJOINTS EQ

Explicitly, we have the formulas

$$\iota_! Y(\sqcup_i C_i) = \begin{cases} Y(C_1), & \sqcup_i C_i \in \Sigma_G^{\text{fr}} \\ \emptyset, & \sqcup_i C_i \notin \Sigma_G^{\text{fr}} \end{cases}, \quad \iota^* X(C) = X(G \cdot C), \quad \iota_* Y(\sqcup_i C_i) = \left(\prod_i Y(C_i) \right)^G,$$

where we note that in the formula for $\iota_*(-)$ the action of G interchanges factors according to the action on the indexing set, i.e. the root orbit of $\sqcup_i C_i$. As a side note, we note that the formulas for $\iota_!$ and ι_* are independent of the chosen order of G .

There is an obvious natural transformation $\beta: \iota_! \Rightarrow \iota_*$ which for $\sqcup_i C_i \in \Sigma_G^{\text{fr}}$ sends $Y(C_1)$ to the “ G -twisted diagonal” of $\prod_i Y(C_i)$. Moreover, letting $\eta_!, \epsilon_!$ (resp. η_*, ϵ_*) denote the unit and counit of the $(\iota_!, \iota^*)$ adjunction (resp. (ι^*, ι_*) adjunction) it is straightforward to check that the following diagram commutes.

$$\begin{array}{ccc} \iota_! \iota^* \iota_* & \xrightarrow{\epsilon_!} & \iota_* \\ \epsilon_* \downarrow \simeq & \nearrow \beta & \simeq \downarrow \eta_! \\ \iota_! & \xrightarrow{\eta_*} & \iota_* \iota^* \iota_! \end{array} \quad (4.76) \quad \boxed{\text{BETADEFSQUARE EQ}}$$

Remark 4.77. An exercise in adjunctions shows that any outer square as in $\boxed{\text{BETADEFSQUARE EQ}}$ commutes provided at least one of the adjunctions in $\boxed{\text{BETADEFSQUARE EQ}}$ is (co)reflexive, so that $\boxed{\text{BETADEFSQUARE EQ}}$ can be regarded as an alternative definition of β .

Proposition 4.78. *One has the following*

- (i) the map $\iota^* \mathbb{F}_G \xrightarrow{\eta_*} \iota^* \mathbb{F}_{G \iota_*} \iota^*$ is an isomorphism, and thus (cf. Prop. $\boxed{\text{MONADADJ PROP 2.4}}$) $\iota^* \mathbb{F}_{G \iota_*}$ is a monad;
- (ii) the map $\iota^* \mathbb{F}_G \iota_! \xrightarrow{\beta} \iota^* \mathbb{F}_{G \iota_*}$ is an isomorphism of monads;
- (iii) the map $\iota_! \iota^* \mathbb{F}_G \iota_! \xrightarrow{\epsilon_!} \mathbb{F}_G \iota_!$ is an isomorphism;
- (iv) there is a natural isomorphism of monads $\alpha: \mathbb{F} \rightarrow \iota^* \mathbb{F}_G \iota_!$.

Proof. We first show (i), starting with some notation. In analogy with Σ_G^{fr} , we write $\Omega_{G,0}^{\text{fr}}$ for the subcategory of free trees and note that the leaf-root and vertex functors then restrict to functors $\text{lr}: \Omega_{G,0}^{\text{fr}} \rightarrow \Sigma_G^{\text{fr}}$, $V_G: \Omega_{G,0}^{\text{fr}} \rightarrow \mathbf{F} \wr \Sigma_G^{\text{fr}}$. Moreover, for each $C \in \Sigma_G^{\text{fr}}$ one has an equality of rooted undercategories between $C \downarrow_{\text{r}} \Omega_{G,0}$ and $C \downarrow_{\text{r}} \Omega_{G,0}^{\text{fr}}$, and thus $\iota^* \mathbb{F}_G X$ is computed by the Kan extension of the following diagram.

$$\begin{array}{ccccc} \Omega_{G,0}^{\text{fr}} & \longrightarrow & \mathbf{F} \wr \Sigma_G^{\text{fr}} & \xrightarrow{\text{F} \wr X} & \mathbf{F} \wr \mathcal{V}^{op} \longrightarrow \mathcal{V}^{op} \\ \downarrow & & & & \\ \Sigma_G^{\text{fr}} & & & & \end{array} \quad (4.79) \quad \boxed{\text{IFGI EQ}}$$

(i) now follows by noting that $X \rightarrow \iota_* \iota^* X$ is an isomorphism when restricted to Σ_G^{fr} .

For (ii), to show that $\iota^* \mathbb{F}_G \iota_! \rightarrow \iota^* \mathbb{F}_{G \iota_*}$ is an isomorphism one just repeats the argument in the previous paragraph by noting that $\iota_! \rightarrow \iota_*$ is an isomorphism when restricted to Σ_G^{fr} . To check that this is a map of monads, we recall first that the monad structure on $\iota^* \mathbb{F}_{G \iota_*}$ is given as described in Proposition $\boxed{\text{MONADADJ PROP 2.4}}$. Unpacking definitions, compatibility with multiplication reduces to showing that the composite $\iota_! \iota^* \xrightarrow{\epsilon_!} id \xrightarrow{\eta_*} \iota_* \iota^*$ coincides with $\beta \iota^*$ while compatibility with units reduces to showing that the composite $id \xrightarrow{\eta_!} \iota^* \iota_! \xrightarrow{\iota^* \beta} \iota^* \iota_* \xrightarrow{\epsilon_*} id$ is the identity. Both of these are a consequence of $\boxed{\text{BETADEFSQUARE EQ}}$ (4.76), following from the diagrams below (where the top composites are identities).

$$\begin{array}{ccc} \iota_! \iota^* & \xrightarrow{\iota_! \iota^* \eta_*} & \iota_! \iota^* \iota_* \iota^* \xrightarrow{\iota_! \epsilon_* \iota^*} \iota_! \iota^* \\ \epsilon_! \downarrow & \searrow \epsilon_! \iota_* \iota^* \downarrow & \swarrow \beta \iota^* \\ id & \xrightarrow{\eta_*} & \iota_* \iota^* \end{array} \quad \begin{array}{ccc} \iota^* \iota_* & \xrightarrow{\eta_! \iota^* \iota_*} & \iota^* \iota_! \iota^* \iota_* \xrightarrow{\iota^* \epsilon_! \iota_*} \iota^* \iota_* \\ \epsilon_* \downarrow \simeq & \searrow \iota^* \iota_! \epsilon_* \downarrow \simeq & \swarrow \iota^* \beta \\ id & \xrightarrow[\eta_!]{\simeq} & \iota^* \iota_! \end{array} \quad (4.80)$$

(iii) amounts to showing that if $X(C) = \emptyset$ whenever $C \notin \Sigma_G^{\text{fr}}$ then it is also $\mathbb{F}_G X(C) = \emptyset$. But since for such $C \notin \Sigma_G^{\text{fr}}$ the undercategory $C \downarrow \Omega_{G,0}$ consists of trees with at least one non-free vertex, the composite

$$C \downarrow \Omega_{G,0} \xrightarrow{V} \mathbb{F} \wr \Sigma_G \xrightarrow{\mathbb{F}X} \mathbb{F} \wr \mathcal{V}^{op} \xrightarrow{\Pi} \mathcal{V}^{op}$$

is constant equal to \emptyset , and (iii) follows.

Finally, we show (iv). We will slightly abuse notation by writing $G \times \Sigma \hookrightarrow \Sigma_G$ for the image of ι and similarly $G \times \Omega_0 \hookrightarrow \Omega_{G,0}$ for the image of the obvious analogous functor $\iota: G \times \Omega_0 \rightarrow \Omega_{G,0}$. The map $\alpha: \mathbb{F} \rightarrow \iota^* \mathbb{F}_G \iota$ is the adjoint to the map $\mathbb{F} \iota^* \rightarrow \iota^* \mathbb{F}_G$ encoded by the following diagram.

$$\begin{array}{ccccccc} G \times \Omega_0 & \longrightarrow & \mathbb{F} \wr (G \times \Sigma_0) & \xrightarrow{\iota^* X} & \mathbb{F} \wr \mathcal{V}^{op} & \longrightarrow & \mathcal{V}^{op} \\ \downarrow & & \downarrow & & \downarrow & \searrow & \searrow \\ & & \Omega_{G,0} & \longrightarrow & \mathbb{F} \wr \Sigma_G & \xrightarrow{X} & \mathbb{F} \wr \mathcal{V}^{op} \rightarrow \mathcal{V}^{op} \\ \downarrow & & \downarrow & & & & \\ G \times \Sigma & & \Sigma_G & & & & \end{array} \quad (4.81) \quad \boxed{\text{MONADEQUIV DEF}}$$

That α is a natural isomorphism follows by the previous identifications $C \downarrow \Omega_{G,0} \simeq C \downarrow \Omega_{G,0}^{\text{fr}}$ for $C \in G \times \Sigma$ together with the fact that the retraction $\rho: \Omega_{G,0}^{\text{fr}} \rightarrow G \times \Omega_0$ (built just as the retraction $\rho: \Sigma_G^{\text{fr}} \rightarrow G \times \Sigma$) retracts $C \downarrow \Omega_{G,0}^{\text{fr}}$ to the undercategory $C \downarrow G \times \Omega_0$, which is thus initial (as well as final), and the claim that α is an isomorphism follows.

Intuitively, the final claim that α is a map of monads follows from the fact that the composite $\mathbb{F} \mathbb{F} \rightarrow \iota^* \mathbb{F}_G \iota \iota^* \mathbb{F}_G \iota \rightarrow \iota^* \mathbb{F}_G \mathbb{F}_G \iota$ is encoded by the analogous natural transformation of diagrams for strings $G \times \Omega_1 \hookrightarrow \Omega_{G,1}^{\text{fr}}$. However, since the presence of left Kan extensions in the definitions of \mathbb{F} , \mathbb{F}_G can make a rigorous direct proof of this last claim fairly cumbersome, we sketch here a workaround argument. We first consider the adjunction $\iota: \mathbf{WSpan}^l((G \times \Sigma)^{op}, \mathcal{V}) \rightleftarrows \mathbf{WSpan}^l(\Sigma_G^{op}, \mathcal{V}): \iota^*$ where ι is composition with ι and ι^* is the pullback of spans. Writing N, N_G for the monads on the span categories, mimicking (4.81) yields a map $\tilde{\alpha}: N \rightarrow \iota^* N_G \iota$ encoded by the diagram (where the front and back squares are pullbacks).

$$\begin{array}{ccccccc} (G \times \Omega)^{(\iota^* A)} & \longrightarrow & \mathbb{F} \wr \iota^* A & \longrightarrow & \mathbb{F} \wr \mathcal{V}^{op} & \longrightarrow & \mathcal{V}^{op} \\ \downarrow & & \downarrow & & \downarrow & \searrow & \searrow \\ & & \Omega_{G,0}^{(A)} & \longrightarrow & \mathbb{F} \wr A & \longrightarrow & \mathbb{F} \wr \mathcal{V}^{op} \rightarrow \mathcal{V}^{op} \\ \downarrow & & \downarrow & & \downarrow & & \\ G \times \Omega_0 & \dashrightarrow & \mathbb{F} \wr (G \times \Sigma) & \dashrightarrow & \mathbb{F} \wr \Sigma_G & & \\ \downarrow & & \downarrow & & \downarrow & & \\ G \times \Sigma & \longrightarrow & \Sigma_G & & & & \end{array}$$

The claim that $\tilde{\alpha}$ is a map of monads is then straightforward. Writing

$$\text{Lan}: \mathbf{WSpan}^l((G \times \Sigma)^{op}, \mathcal{V}) \rightleftarrows \mathbf{Fun}((G \times \Sigma)^{op}, \mathcal{V}): j \quad \text{Lan}_G: \mathbf{WSpan}^l(\Omega_G^{op}, \mathcal{V}) \rightleftarrows \mathbf{Fun}(\Omega_G^{op}, \mathcal{V}): j_G$$

for the span functor adjunctions, $\alpha: \mathbb{F} \rightarrow \iota^* \mathbb{F}_G \iota$ can then be written as the composite

$$\text{Lan} N j \rightarrow \text{Lan} \iota^* N_G \iota j \rightarrow \iota^* \text{Lan}_G N_G j_G \iota$$

where the first map is the isomorphism of monads induced by $\tilde{\alpha}$ and the second map can be shown directly to be a monad map by unpacking the monad structures in Propositions 2.3 and 2.4. \square

Combining the previous result with Propositions ~~MONADADJ PROP~~ 2.3 and 2.4 now gives the following.
Corollary 4.82. ~~TWOADJOINTS EQ~~ *The adjunctions (4.75) extends to adjunctions*

$$\begin{array}{ccc} & \xleftarrow{\iota_!} & \\ \text{Op}_G(\mathcal{V}) & \xrightarrow{\iota_*} & \text{Op}^G(\mathcal{V}). \\ & \xleftarrow{\iota_*} & \end{array} \quad (4.83)$$

TWOADJOINTSOP EQ

In particular, ι_* identifies Op^G as a reflexive subcategory of Op_G .

Remark 4.84. The image of ι_* consists of genuine equivariant operads whose mapping spaces for non-free G -trees are suitable fixed points of the mapping spaces for free G -trees.

By contrast, if one uses $\iota_!$ to regard Op^G as a coreflexive subcategory of Op_G , one obtains the far less interesting subcategory of genuine equivariant operads whose mapping spaces are empty for non-free trees.

The isomorphism $\iota_! \iota^* \mathbb{F}_G \iota_! \xrightarrow{\epsilon_!} \mathbb{F}_G \iota_!$ then shows that \mathbb{F}_G essentially preserves the image of $\iota_!$, and can thus be identified with \mathbb{F} over it.

However, the analogous statement fails for ι_* , i.e., one does not always have that

$$\mathbb{F}_G \iota_* \xrightarrow{\eta_*} \iota_* \iota^* \mathbb{F}_G \iota_* \quad (4.85)$$

KEYNONISO EQ

is an isomorphism. In fact, showing that (4.85) ~~KEYNONISO EQ~~ does become an isomorphism when restricted to suitably cofibrant objects is one of the key technical ingredients for our ~~COFIB SEC~~ proof of the Quillen equivalence between $\text{Op}_G(\mathcal{V})$ and $\text{Op}^G(\mathcal{V})$, and will be the subject of §7.

For now, we end this section with a minimal counterexample to the more general claim.

Let $G = \mathbb{Z}/2$ and $Y = * \in \text{Sym}^G(\mathcal{V})$ be the simpleton.

When evaluating $\mathbb{F}_G Y$ at the G -fixed stump corolla $G/G \cdot C_0$, the two G -trees T_1 and T_2 below encode two distinct points (since T_1, T_2 are not isomorphic as objects under $G/G \cdot T_0$).

$$\begin{array}{ccc} \begin{array}{c} \circ \\ | \\ r + G/G \\ G/G \cdot C_0 \end{array} & \begin{array}{c} \circ \\ | \\ a + G \\ \circ \\ | \\ r + G/G \\ T_1 \end{array} & \begin{array}{c} \circ \quad \circ \\ \diagdown \quad \diagup \\ \circ \\ | \\ r + G/G \\ T_2 \end{array} \\ & & \end{array} \quad (4.86)$$

However, when pulling these points back to the G -free stump corolla $G \cdot C_0$ one obtains the same point, namely that encoded by the G -tree T below.

$$\begin{array}{ccc} \begin{array}{c} \circ \\ | \\ r + G \\ G \cdot C_0 \end{array} & & \begin{array}{c} \circ \quad \circ \\ \diagdown \quad \diagup \\ \circ \\ | \\ r + G \\ T \end{array} \\ & & \end{array} \quad (4.87)$$

Moreover, it is not hard to modify the example above to produce similar examples when evaluating $\mathbb{F}_G Y$ at non-empty corollas.

However, such counter-examples all require the use of trees with stumps. Indeed, it can be shown that (4.85) ~~KEYNONISO EQ~~ is an isomorphism whenever evaluated at a Y such that $Y(0) = \emptyset$.

5 Free extensions

Our overall goal in this section will be to produce a description of free genuine operad pushouts, i.e. pushouts of the form

$$\begin{array}{ccc} \mathbb{F}_G A & \longrightarrow & X \\ \downarrow & & \downarrow \\ \mathbb{F}_G B & \longrightarrow & Y \end{array}$$

in the category \mathbf{Op}_G of genuine equivariant operads.

5.1 Extensions over general monads

Any monad T on \mathcal{C} one obtains induced monads $T^{\times l}$ on $\mathcal{C}^{\times l}$, and we will make use of several standard relations between these. In particular, any map $\alpha: \underline{l} \rightarrow \underline{m}$ induces a forgetful functor such that for the forgetful functor $\alpha^*: \mathcal{C}^{\times l} \rightarrow \mathcal{C}^{\times n}$ one has $T^{\times l} \alpha^* \simeq \alpha^* T^{\times m}$.

Indeed, we will need to make use of a slightly more general setup. Letting I denote the identity monad on \mathcal{C} , and $K \subset \underline{m}$ be a subset, there is a monad $T^{\times K} \times I^{\times(\underline{m}-K)}$ on $\mathcal{C}^{\times m}$, which we abusively denote simply as $T^{\times K}$. Identities then determine maps of monads $T^J \rightarrow T^{\times K}$ whenever $J \subset K$ and, moreover, there are identifications $T^{\times \alpha^{-1}(K)} \alpha^* \simeq \alpha^* T^{\times K}$. One then has the following.

Proposition 5.1. *The functor*

$$T^{\times \alpha^{-1}(K)} \Rightarrow \alpha^* T^{\times K} \alpha_! \quad (5.2)$$

MONADFUNCTORALPHA EQ

adjoint to the identification $T^{\times \alpha^{-1}(K)} \alpha^* \simeq \alpha^* T^{\times K}$ is a map of monads on $\mathcal{C}^{\times n}$.

Proof. We first note that there are identifications of functors $(FG)^{\times K} \simeq F^{\times K} G^{\times K}$ which are compatible with the identifications $F^{\times \alpha^{-1}(K)} \alpha^* \simeq \alpha^* F^{\times K}$ in the sense that the identification $(FG)^{\times \alpha^{-1}(K)} \circ \alpha^* \simeq \alpha^* (FG)^{\times K}$ matches the composite identification $F^{\times \alpha^{-1}(K)} G^{\times \alpha^{-1}(K)} \alpha^* \simeq F^{\times \alpha^{-1}(K)} \alpha^* G^{\times K} \simeq \alpha^* F^{\times K} G^{\times K}$.

Letting η, ϵ denote the unit and counit for the $(\alpha_!, \alpha^*)$ adjunction, (5.2) is then the composite

$$T^{\times \alpha^{-1}(K)} \xrightarrow{\eta} T^{\times \alpha^{-1}(K)} \alpha^* \alpha_! \simeq \alpha^* T^{\times K} \alpha_!.$$

That this is a monad map is the condition that the following multiplication and unit diagrams commute.

$$\begin{array}{ccc} T^{\times \alpha^{-1}(K)} \circ T^{\times \alpha^{-1}(K)} & \longrightarrow & \alpha^* T^{\times K} \alpha_! \circ \alpha^* T^{\times K} \alpha_! \\ \downarrow & & \downarrow \\ T^{\times \alpha^{-1}(K)} & \longrightarrow & \alpha^* T^{\times K} \alpha_! \end{array} \quad \begin{array}{ccc} I^{\times n} & & \\ \downarrow & \searrow & \\ T^{\times \alpha^{-1}(K)} & \longrightarrow & \alpha^* T^{\times K} \alpha_! \end{array}$$

We argue only the case of the leftmost multiplication diagram, with commutativity of the unit diagram following by a similar but simpler argument. Since the precomposition $(-) \circ \alpha^*$ is the left adjoint to the precomposition $(-) \circ \alpha_!$ this follows from the following diagram.

$$\begin{array}{ccccc} T^{\times \alpha^{-1}(K)} T^{\times \alpha^{-1}(K)} \alpha^* & \xrightarrow{\simeq} & T^{\times \alpha^{-1}(K)} \alpha^* T^{\times K} & \xrightarrow{\eta} & T^{\times \alpha^{-1}(K)} \alpha^* \alpha_! \alpha^* T^{\times K} & \xrightarrow{\simeq} & \alpha^* T^{\times K} \alpha_! \alpha^* T^{\times K} \\ \downarrow & & \searrow & & \downarrow \epsilon & & \downarrow \epsilon \\ & & T^{\times \alpha^{-1}(K)} \alpha^* T^{\times K} & \xrightarrow{\simeq} & \alpha^* T^{\times K} T^{\times K} & & \downarrow \\ T^{\times \alpha^{-1}(K)} \alpha^* & \xrightarrow{\simeq} & & & \alpha^* T^{\times K} & & \end{array}$$

□

Remark 5.3. Since $T^{\times K} \alpha_!$ is a right $\alpha^* T^{\times K} \alpha_!$ -module, Proposition 5.1 implies that it is also a right $T^{\times \alpha^{-1}(K)}$ -module or, moreover, a right $T^{\times J}$ -module whenever $\alpha(J) \subset K$.

Remark 5.4. Combining the precomposition and postcomposition adjunctions, the identification $T^{\times \alpha^{-1}(K)} \alpha^* \simeq \alpha^* T^{\times K}$ is then adjoint to a functor $\alpha_! T^{\times \alpha^{-1}(K)} \rightarrow T^{\times K} \alpha_!$ which is readily checked to be a map of right $T^{\times \alpha^{-1}(K)}$ -modules.

EXTGENMON SEC

MONADICFUN PROP

TALPHAKMOD REM

COMPOSTCOMP REM

More generally, for $\alpha(J) \subset K$, the composite $T^{\times J} \alpha^* \rightarrow T^{\times \alpha^{-1}(K)} \alpha^* \simeq \alpha^* T^{\times K}$ is thus adjoint to a map of right $T^{\times J}$ -modules

$$\alpha_! T^{\times J} \rightarrow T^{\times K} \alpha_!. \quad (5.5)$$

RIGHTMODULETMAP EQ

We now unpack the content of (5.5) when $\alpha: \underline{l} \rightarrow *$ is the unique map to the singleton $* = \underline{1}$. In this case we can instead write $\alpha_! = \coprod$, $\alpha^* = \Delta$, and we thus have commutative diagrams

$$\begin{array}{ccc} \coprod_J TTA_j \sqcup \coprod_{\underline{n}-J} A_j & \longrightarrow & T(\coprod_J TA_j \sqcup \coprod_{\underline{n}-J} A_j) \\ \downarrow & & \downarrow \\ \coprod_J TA_j \sqcup \coprod_{\underline{n}-J} A_j & \longrightarrow & T(\coprod_J A_j \sqcup \coprod_{\underline{n}-J} A_j) \end{array} \quad (5.6)$$

RIGHTMODULETMAPAUX EQ

where the vertical maps come from the right $T^{\times J}$ -module structure. Writing \sqcup^a for the coproduct of T -algebras and recalling the canonical identifications $\coprod_K^a(TA_k) \simeq T(\coprod_K A_k)$, (5.6) in fact shows that the right $T^{\times J}$ -module structure on $T \circ \coprod$ in fact codifies the multiplication maps

$$\coprod_J^a TTA_j \sqcup^a \coprod_{\underline{l}-J}^a TA_j \rightarrow \coprod_J^a TA_j \sqcup^a \coprod_{\underline{l}-J}^a TA_j.$$

5.2 Labeled planar strings

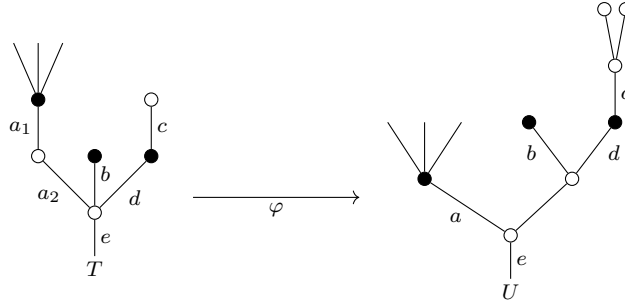
We now translate the results in the previous section to the context of the monad N on $\mathbf{WSpan}^l(\Sigma^{op}, \mathcal{V})$. In analogy to the planar string models $\Omega_{G,n}^{(A)}$ for iterations $N^{\circ n+1}$ of the monad N , we will find it convenient to build similar string models $\Omega_{G,n}^{(\underline{A}_J)}$ for $N \circ \coprod \circ (N^{\times J})^{\circ n}$.

Definition 5.7. A l -node labeled G -tree (or just l -labeled G -tree) G -tree is a pair $(T, V_G(T) \rightarrow \{1, \dots, l\})$ with $T \in \Omega_G$, which we think of as a G -tree together with G -vertices labels in $1, \dots, l$.

Further, a tall map $\varphi: T \rightarrow S$ between l -labeled trees is called a *label map* if for each G -vertex v_{Ge} of T with label j , the vertices of the subtree $S_{v_{Ge}}$ are all labeled by j .

Lastly, given a subset $J \subset \underline{l}$, a planar label map $\varphi: T \rightarrow S$ is said to be J -inert if for every G -vertex v_{Ge} of T with label $j \in J$ it is $S_{v_{Ge}} = T_{v_{Ge}}$.

Example 5.8. Consider the 2-labeled trees below (for $G = *$ the trivial group), with black nodes (\bullet) denoting labels by the number 1 and white nodes (\circ) labels by the number 2. The planar map φ (sending $a_i \mapsto a$, $b \mapsto b$, $c \mapsto c$, $d \mapsto d$, $e \mapsto e$) is a label map which is $\{1\}$ -inert.



(5.9)

SUBSDATUMTREESLAB EQ

Definition 5.10. Let $0 \leq s \leq n$ and $J \subset \underline{l}$ be a subset.

We define $\Omega_{G,n,s}^J$ to have as objects n -planar strings

$$T_0 \xrightarrow{f_1} T_1 \xrightarrow{f_2} \dots \xrightarrow{f_s} T_s \xrightarrow{f_{s+1}} T_{s+1} \xrightarrow{f_{s+2}} \dots \xrightarrow{f_n} T_n \quad (5.11)$$

NSTRINGLAB EQ

together with l -labelings of T_s, T_{s+1}, \dots, T_n such that the $f_r, r > s$ are $(\underline{l} - J)$ -inert label maps.

Arrows in $\Omega_{G,n,s}^J$ are quotients of strings $(q_r: T_r \rightarrow T_r')$ such that $q_r, r \leq s$ are label maps.

Informally, $\Omega_{G,n,s}^l$ consists of n -strings such that trees and maps after T_s are l -labeled.

Remark 5.12. Our main case of interest will that of $s = 0$, in which case we abbreviate $\Omega_{G,n}^J = \Omega_{G,n,0}^J$. Indeed, such strings will suffice to build models for $N \circ \coprod (N^{\times J})^{\text{on}}$.

However, to unpack the right $N^{\times J}$ -module structure as in Remark 5.3 one further needs to encode composites $NN \circ \coprod (N^{\times J})^{\text{on}-1}$, a role played by strings $\Omega_{G,n,1}^J$.

Notation 5.13. We will further write

$$\Omega_{G,n,-1}^J = \coprod_J \Omega_{G,n} \sqcup \coprod_{l=J} \Sigma_G, \quad \Omega_{G,n,n+1}^J = \Omega_{G,n}^J \quad (5.14)$$

OMEGAMINUSONE EQ

To justify this convention, we note that a string as in (5.11) can be extended by prepending to it the map $\text{lr}(T_0) = T_{-1} \xrightarrow{f_0} T_0$. If one then attempts to define $\Omega_{G,n,-1}^J$ by insisting that T_{-1} also be labeled, it follows that all node labels in each string must coincide, resulting in the coproduct decomposition in (5.14).

There are a number of obvious functors relating the $\Omega_{G,n,s}^J$ categories, which we now make explicit. Given $s \leq s'$ or $J \subset J'$ there are forgetful functors

$$\Omega_{G,n,s}^J \rightarrow \Omega_{G,n,s'}^J \quad \Omega_{G,n,s}^J \rightarrow \Omega_{G,n,s}^{J'} \quad (5.15)$$

NKNFGT EQ

The simplicial operators in Notation 4.26 generalize to operators (where $0 \leq i \leq n$, $-1 \leq j \leq n$)

$$\begin{aligned} d_i: \Omega_{G,n,s}^J &\rightarrow \Omega_{G,n-1,s-1}^J & i < s & & s_j: \Omega_{G,n,s}^J &\rightarrow \Omega_{G,n+1,s+1}^J & j < s \\ d_i: \Omega_{G,n,s}^J &\rightarrow \Omega_{G,n-1,s}^J & s \leq i & & s_j: \Omega_{G,n,s}^J &\rightarrow \Omega_{G,n+1,s}^J & s \leq j \end{aligned}$$

which are compatible with the forgetful functors in the obvious way.

Remark 5.16. For $J \subset J'$ the forgetful functor in (5.15) is a fully faithful inclusion. However, and somewhat subtly, this is not the case for the $s \leq s'$ forgetful functors. Indeed, regarding $T \rightarrow U$ in Examples 5.8 as an object in $\Omega_{*,n,0}^2$, changing the label of the $a_1 \leq a_2$ vertex of T from a \circ -label to a \bullet -label yields an alternate object $\bar{T} \rightarrow U$ of $\Omega_{*,n,0}^2$ forgetting to the same object of $\Omega_{*,n,1}^2$, yet $T \rightarrow U$ and $\bar{T} \rightarrow U$ are not isomorphic.

We note that this is a consequence of the fact that substitution data can replace unary nodes by stumps, which have no nodes.

Generalizing Notation 4.33 there is a commutative diagram

$$\begin{array}{ccc} \Omega_{G,n,s}^J & \xrightarrow{V_{G,n}} & \text{F} \wr \Sigma_G^{\text{ul}} \\ \downarrow & & \downarrow \\ \Omega_{G,n} & \xrightarrow{V_{G,n}} & \text{F} \wr \Sigma_G \end{array}$$

where for a labeled string it is $V_G(T_0 \rightarrow \dots \rightarrow T_n) = (T_{n,v_{Ge}})_{V_G(T_n)}$, where we regard $T_{n,v_{Ge}} \in \Sigma_G^{\text{ul}} \simeq \Omega_{G,-1,-1}^l$ by using the label in $1 \dots l$.

We now expand Notation 4.41.

Notation 5.17. Let \underline{A} denote a l -tuple $(\pi_j: A_j \rightarrow \Sigma_G)_l$ of categories over Σ_G . We define $\Omega_{G,n,s}^{(\underline{A}),J}$ by the pullback diagram

$$\begin{array}{ccc} \Omega_{G,n,s}^{(\underline{A}),J} & \xrightarrow{V_{G,n}^{(\underline{A})}} & \text{F} \wr \coprod A_j \\ \downarrow & & \downarrow \\ \Omega_{G,n,s}^J & \xrightarrow{V_{G,n}} & \text{F} \wr \Sigma_G^{\text{ul}} \end{array} \quad (5.18)$$

LTUPLEAPULL EQ

Explicitly, an object of $\Omega_{G,n,s}^{(\underline{A}),J}$ consists of a labeled string $T_0 \rightarrow \dots \rightarrow T_n$ as in (5.11) together with a tuple $(a_{v_{Ge}})_{V_G(T_n)}$ such that $a_{v_{Ge}} \in A_j$ if v_{Ge} has label j and $\pi_j(a_{v_{Ge}}) = T_{n,v_{Ge}}$.

The reader may have noticed a certain asymmetry between our definition of the $V_{G,n}$ functors here versus their analogues in §4.3, where they were defined iteratively in terms of simpler functors V_G . This is because of the possibility that $s = -1$, in which case (5.14) applies and some caution is needed in that the following result fails.

Proposition 5.19. *Suppose $0 \leq s \leq n$. One has a diagram of pullback squares (generalizing (4.44))*

$$\begin{array}{ccccc}
 \Omega_{G,n,s}^{(A),J} & \xrightarrow{V_G^{(A)}} & F \wr \Omega_{G,n-1,s-1}^{(A),J} & \xrightarrow{F \wr V_{G,n}^{(A)}} & F \wr F \wr \coprod A_j & \xrightarrow{\sigma^0} & F \wr \coprod A_j \\
 \downarrow & & \downarrow & & \downarrow & & \downarrow \\
 \Omega_{G,n,s}^J & \xrightarrow{V_G} & F \wr \Omega_{G,n-1,s-1}^J & \xrightarrow{F \wr V_{G,n}} & F \wr F \wr \Sigma_G^{\text{ul}} & \xrightarrow{\sigma^0} & F \wr \Sigma_G^{\text{ul}} \\
 \downarrow & & \downarrow & & & & \\
 \Omega_{G,0} & \xrightarrow{V_G} & F \wr \Sigma_G & & & &
 \end{array} \quad (5.20)$$

such that the composite of the top squares is (5.18).

Proof. The V_G functors are defined just as in (4.28) via the formula

$$V_G(T_0 \rightarrow T_1 \rightarrow \cdots \rightarrow T_n) = (T_{1,v_{Ge}} \rightarrow \cdots \rightarrow T_{n,v_{Ge}})_{v_{Ge} \in V_G(T_0)}$$

with the strings $T_{1,v_{Ge}} \rightarrow \cdots \rightarrow T_{n,v_{Ge}}$ inheriting the extra structure in the obvious way.

Since the top composite square, top center square and top right square are all pullback squares, it remains only to show that the bottom left square is a pullback. This last claim is simply a variation of Proposition 4.29, and follows from the same proof, since both labels and inertness conditions are inherited when assembling substitution data into trees via Proposition 3.42. \square

5.3 Bar constructions on spans

We use the results in the previous sections to obtain a string description of the bar constructions

$$\coprod_J^a N^{\bullet+1} A_j \wr^a \coprod_{I=J}^a N A_j.$$

For simplicity, we discuss first the particular case $\coprod^a N^{\bullet+1} A$. Writing the span as $\Sigma_G \leftarrow A \xrightarrow{F} \mathcal{V}$ the identifications $\Omega_{G,0}^{(A)} \simeq \Omega_{G,n+1}^{(A)}$ iteratively identify the operator in the bar construction $N^{\bullet+1} A$ as follows.

The top boundaries d_n have natural transformation given by

$$\begin{array}{ccccccc}
 \Omega_{G,n}^{(A)} & \xrightarrow{V_G^{\circ n}} & F^{\wr n} \wr \Omega_{G,0}^{(A)} & \xrightarrow{F^{\wr n} \wr F_1} & F^{\wr n} \wr \mathcal{V}^{op} & \xrightarrow{\Pi^{\circ n}} & \mathcal{V}^{op} \\
 \downarrow & & \downarrow & \swarrow F^{\wr n} \wr m & \parallel & & \parallel \\
 \Omega_{G,n-1}^{(A)} & \xrightarrow{V_G^{\circ n}} & F^{\wr n} \wr A & \xrightarrow{F^{\wr n} \wr F} & F^{\wr n} \wr \mathcal{V}^{op} & \xrightarrow{\Pi^{\circ n}} & \mathcal{V}^{op}
 \end{array} \quad (5.21)$$

where m is the natural transformation component of the multiplication $NA \rightarrow A$, and the remaining differentials d_i for $0 \leq i < n$ are given by

$$\begin{array}{ccccccc}
 \Omega_{G,n}^{(A)} & \xrightarrow{V_G^{\circ n+1}} & F^{\wr n+1} \wr A & \xrightarrow{F} & F^{\wr n+1} \wr \mathcal{V}^{op} & \xrightarrow{\Pi^{\circ n+1}} & \mathcal{V}^{op} \\
 d_i^{(A)} \downarrow & \swarrow \pi_i^{(A)} & \downarrow \sigma^i & & \downarrow \sigma^i & \swarrow \alpha_i & \parallel \\
 \Omega_{G,n-1}^{(A)} & \xrightarrow{V_G^{\circ n}} & F^{\wr n} \wr A & \xrightarrow{F} & F^{\wr n} \wr \mathcal{V}^{op} & \xrightarrow{\Pi^{\circ n}} & \mathcal{V}^{op}
 \end{array} \quad (5.22)$$

where $\pi_i^{(A)}$ interchanges lexicographic orders on the i -th F coordinate of F^{in} and α_i is the natural associativity isomorphism.

Maybe add degeneracies

Similarly, Proposition 5.19 shows that $\Omega_{G,n}^{(A)} \simeq \Omega_{G,0}^{(\coprod \Omega_{G,n-1}^{(A_j)})}$ so that the top boundaries d_n in the bar construction $N \circ \sqcup \circ (N^{\times l})^{on} \underline{A}$ are given by

$$\begin{array}{ccccccc} \Omega_{G,n}^{(A)} & \xrightarrow{V_G} & F \wr \coprod \Omega_{G,n-1}^{(A_j)} & \xrightarrow{V_G^{on-1}} & F \wr \coprod F^{in-1} \wr \Omega_{G,0}^{(A_j)} & \xrightarrow{F_1} & F \wr \coprod F^{in-1} \wr \mathcal{V}^{op} \xrightarrow{\Pi^{on-1}} F \wr \mathcal{V}^{op} \xrightarrow{\Pi} \mathcal{V}^{op} \\ \downarrow & & \downarrow & & \downarrow & \swarrow \underline{m} & \parallel \\ \Omega_{G,n-1}^{(A)} & \xrightarrow{V_G} & F \wr \coprod \Omega_{G,n-2}^{(A_j)} & \xrightarrow{V_G^{on-1}} & F \wr \coprod F^{in-1} \wr A_j & \xrightarrow{F} & F \wr \coprod F^{in-1} \wr \mathcal{V}^{op} \xrightarrow{\Pi^{on-1}} F \wr \mathcal{V}^{op} \xrightarrow{\Pi} \mathcal{V}^{op} \end{array} \quad (5.23)$$

where \underline{m} stands for the functor induced by the tuple of multiplication maps $m_j: N A_j \rightarrow A_j$, and the other boundaries d_i for $0 \leq i < n$ are given by

$$\begin{array}{ccccccc} \Omega_{G,n}^{(A)} & \xrightarrow{V_G} & F \wr \coprod \Omega_{G,n-1}^{(A_j)} & \xrightarrow{V_G^{on}} & F \wr \coprod F^{in} \wr A & \xrightarrow{F} & F \wr \coprod F^{in} \wr \mathcal{V}^{op} \xrightarrow{\Pi^{on}} F \wr \mathcal{V}^{op} \xrightarrow{\Pi} \mathcal{V}^{op} \\ d_i^{(A)} \downarrow & & \swarrow \pi_i^{(A)} & & \downarrow \sigma^i & & \downarrow \sigma^i \\ \Omega_{G,n-1}^{(A)} & \xrightarrow{V_G} & F \wr \coprod \Omega_{G,n-2}^{(A_j)} & \xrightarrow{V_G^{on-1}} & F \wr \coprod F^{in-1} \wr A & \xrightarrow{F} & F \wr \coprod F^{in-1} \wr \mathcal{V}^{op} \xrightarrow{\Pi^{on-1}} F \wr \mathcal{V}^{op} \xrightarrow{\Pi} \mathcal{V}^{op} \end{array} \quad (5.24)$$

DISJBARDN EQ

where again $\pi_i^{(A)}$ interchanges lexicographic orders on the i -th F coordinate and α_i is again an associativity isomorphism. We note that (5.24) follows directly from (5.22) for $0 \leq i < n$ but that the case $i = 0$, which uses the $N^{\times l}$ right action on $N \circ \sqcup$ (cf. Remark 5.3), which after unpacked leads to the composite diagram below.

$$\begin{array}{ccccccc} \Omega_{G,n}^{(A)} & \rightarrow & F \wr \coprod \Omega_{G,n-1}^{(A_j)} & \longrightarrow & F \wr \coprod F^{in-1} A_j & \rightarrow & F \wr \coprod F^{in-1} \mathcal{V}^{op} \longrightarrow F \wr \mathcal{V}^{op} \rightarrow \mathcal{V}^{op} \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \Omega_{G,n-1}^{(A)} & \rightarrow & F \wr \Omega_{G,n-1}^{(A)} & \rightarrow & F^{\wr 2} \wr \coprod \Omega_{G,n-2}^{(A_j)} & \rightarrow & F^{\wr 2} \wr \coprod F^{in-2} A_j \rightarrow F^{\wr 2} \wr \coprod F^{in-2} \mathcal{V}^{op} \rightarrow F^{\wr 2} \wr \mathcal{V}^{op} \rightarrow F \wr \mathcal{V}^{op} \rightarrow \mathcal{V}^{op} \\ d_0^{(A)} \downarrow & & \swarrow \pi_0 & & \downarrow \sigma^0 & & \downarrow \sigma^0 \\ \Omega_{G,n-1}^{(A)} & \longrightarrow & F \wr \coprod \Omega_{G,n-2}^{(A_j)} & \longrightarrow & F \wr \coprod F^{in-2} A_j & \longrightarrow & F \wr \coprod F^{in-2} \mathcal{V}^{op} \longrightarrow F \wr \mathcal{V}^{op} \longrightarrow \mathcal{V}^{op} \end{array} \quad (5.25)$$

ASSOCSPANJ1 EQ

Finally, using the inclusions $\Omega_{G,n}^{(A),J} \hookrightarrow \Omega_{G,n}^{(A)}$, one obtains analogous descriptions of the bar constructions $N \circ \sqcup \circ (N^{\times J})^{on} \underline{A}$, depicted below.

$$\begin{array}{ccccccc} \Omega_{G,n}^{(A),J} & \longrightarrow & F \wr \left(\coprod_J F^{in-1} \wr \Omega_{G,0}^{(A_j)} \sqcup \coprod_{l-J} A_j \right) & \xrightarrow{F_1} & F \wr \coprod F^{in-1} \wr \mathcal{V}^{op} & \longrightarrow & \mathcal{V}^{op} \\ \downarrow & & \downarrow & & \downarrow & \swarrow \underline{m} & \parallel \\ \Omega_{G,n-1}^{(A),J} & \longrightarrow & F \wr \left(\coprod_J F^{in-1} \wr A_j \sqcup \coprod_{l-J} A_j \right) & \xrightarrow{F} & F \wr \coprod F^{in-1} \wr \mathcal{V}^{op} & \longrightarrow & \mathcal{V}^{op} \end{array} \quad (5.26)$$

$$\begin{array}{ccccccc} \Omega_{G,n}^{(A),J} & \longrightarrow & F \wr \left(\coprod_J F^{in} \wr A_j \sqcup \coprod_{l-J} A_j \right) & \xrightarrow{F} & F \wr \coprod F^{in} \wr \mathcal{V}^{op} & \longrightarrow & \mathcal{V}^{op} \\ d_i^{(A)} \downarrow & & \swarrow \pi_i^{(A)} & & \downarrow \sigma^i & & \downarrow \sigma^i \\ \Omega_{G,n-1}^{(A),J} & \longrightarrow & F \wr \left(\coprod_J F^{in-1} \wr A_j \sqcup \coprod_{l-J} A_j \right) & \xrightarrow{F} & F \wr \coprod F^{in-1} \wr \mathcal{V}^{op} & \longrightarrow & \mathcal{V}^{op} \end{array} \quad (5.27)$$

DISJBARDNJ EQ

5.4 Transferring simplicial colimits of left Kan extensions

Given genuine equivariant operads $X, Y \in \mathbf{Op}_G$ one has an isomorphism

$$X \sqcup^a Y \simeq \operatorname{colim}_{\Delta^{op}} (\mathbb{F}_G^{\bullet+1} X \sqcup^a \mathbb{F}_G^{\bullet+1} Y)$$

so that combining [REPACKAGERES REM 4.74](#) and [PRECOMPPOSTCOMP REM 5.4](#) with the results in the previous section one obtains isomorphisms

$$X \sqcup^a Y \simeq \operatorname{colim}_{\Delta^{op}} (\operatorname{Lan} (N^{\bullet+1} \iota X \sqcup^a N^{\bullet+1} \iota Y)) \quad (5.28)$$

$$\simeq \operatorname{colim}_{\Delta^{op}} (\operatorname{Lan} (N \circ \sqcup \circ (N^{\times 2})^\bullet (\iota X, \iota Y))) \quad (5.29)$$

$$\simeq \operatorname{colim}_{\Delta^{op}} (\operatorname{Lan}_{\Omega_{G,\bullet}^{2,op} \rightarrow \Sigma_G^{op}} N_\bullet^{(X,Y)}) \quad (5.30)$$

COLIMLAN EQ

where we write $N_\bullet^{(X,Y)}: \Omega_{G,\bullet}^{2,op} \rightarrow \mathcal{V}$ for the induced functor.

The purpose of this section will be show that one can repackage formulas such as [\(5.30\)](#) with a single left Kan extension over a category $\Omega_G^2 = |\Omega_{G,\bullet}^2|$ obtained from $\Omega_{G,\bullet}^2$ via realization in \mathbf{Cat} . [COLIMLAN EQ](#)

We note that $\Omega_{G,\bullet}^2$ together with the corresponding functors to Σ_G , \mathcal{V}^{op} can be viewed as a simplicial object $\Delta^{op} \rightarrow \mathbf{WSpan}^l(\Sigma, G^{op}, \mathcal{V})$, and our first task will be to repackage such functors in terms of Grothendieck constructions.

Lemma 5.31. *Functors $F: \mathcal{D} \rtimes \mathcal{I}_\bullet \rightarrow \mathcal{C}$ are in bijection with lifts*

$$\begin{array}{ccc} & & \mathbf{WSpan}^l(*, \mathcal{C}) \\ & \nearrow \mathcal{I}_\bullet^F & \downarrow \text{fgt} \\ \mathcal{D} & \xrightarrow{\mathcal{I}_\bullet} & \mathbf{Cat}. \end{array}$$

where fgt is the functor forgetting the maps to $*$ and \mathcal{C} .

Proof. This is a matter of unpacking notation. The restrictions $F|_{\mathcal{I}_d}$ to the fibers $\mathcal{I}_d \subset \mathcal{D} \rtimes \mathcal{I}_\bullet$ are precisely the functors $\mathcal{I}_d^F: \mathcal{I}_d \rightarrow \mathcal{C}$ describing $\mathcal{I}_\bullet^F(d)$.

Furthermore, the images $F((d, i) \rightarrow (d', f_*(i)))$ of the pushout arrows over a fixed arrow $f: d \rightarrow d'$ of \mathcal{D} assemble to a natural transformation

$$\begin{array}{ccc} \mathcal{I}_d & \xrightarrow{\mathcal{I}_d^F} & \mathcal{C} \\ f_* \downarrow & \Downarrow & \uparrow \\ \mathcal{I}_{d'} & \xrightarrow{\mathcal{I}_{d'}^F} & \mathcal{C} \end{array} \quad (5.32)$$

which describes $\mathcal{I}_\bullet^F(f)$. It is straightforward to check that the associativity and unitality conditions coincide. \square

In the cases of interest we will have $\mathcal{D} = \Delta^{op}$, so that \mathcal{I}_\bullet can be interpreted as an object $\mathcal{I}_\bullet \in \mathbf{Cat}^{\Delta^{op}}$. By recalling the standard cosimplicial object $[\bullet] \in \mathbf{Cat}^\Delta$ given by $[n] = (0 \rightarrow 1 \rightarrow \dots \rightarrow n)$ one obtains the following definition.

Definition 5.33. The left adjoint

$$|-|: \mathbf{Cat}^{\Delta^{op}} \rightleftarrows \mathbf{Cat}: (-)^{[\bullet]}$$

will be called the *realization* functor.

Remark 5.34. More explicitly, one has

$$|\mathcal{I}_\bullet| = \operatorname{coeq} \left(\coprod_{[n] \rightarrow [m]} [n] \times \mathcal{I}_m \rightrightarrows \coprod_{[n]} [n] \times \mathcal{I}_n \right). \quad (5.35)$$

REALDEF EQ

Example 5.36. Any $\mathcal{I} \in \mathbf{Cat}$ induces objects $\mathcal{I}, \mathcal{I}_\bullet, \mathcal{I}^{[\bullet]} \in \mathbf{Cat}^{\Delta^{op}}$ where \mathcal{I} is the constant simplicial object and \mathcal{I}_\bullet is the nerve $N\mathcal{I}$ with each level regarded as a discrete category. It is straightforward to check that $|\mathcal{I}| = |\mathcal{I}_\bullet| = |\mathcal{I}^{[\bullet]}| = \mathcal{I}$.

Lemma 5.37. *Given $\mathcal{I}_\bullet \in \mathbf{Cat}^{\Delta^{op}}$ one has an identification $ob(|\mathcal{I}_\bullet|) \simeq ob(\mathcal{I}_0)$. Furthermore, the arrows of $|\mathcal{I}_\bullet|$ are generated by the image of the arrows in $\mathcal{I}_0 \simeq \mathcal{I}_0 \times [0]$ and the image of the arrows in $[1] \times ob(\mathcal{I}_1)$.*

For each $i_1 \in \mathcal{I}_1$, we will denote the arrow of $|\mathcal{I}_\bullet|$ induced by the arrow in $[1] \times \{i_1\}$ by

$$d_1(i_1) \xrightarrow{i_1} d_0(i_1).$$

Proof. We write $d_{\hat{k}}, d_{\hat{k}, \hat{l}}$ for the simplicial operators induced by the maps $[0] \xrightarrow{0 \mapsto k} [n]$, $[1] \xrightarrow{0 \mapsto k, 1 \mapsto l} [n]$ which can informally be thought of as the “composite of all faces other than d_k, d_l ”. Using (5.35) one has equivalence relations of objects

$$[n] \times \mathcal{I}_n \ni (k, i_n) \sim (0, d_{\hat{k}}(i_n)) \in [0] \times \mathcal{I}_0$$

and since for any generating relation $(k, i_n) \sim (l, i'_n)$ it is $d_{\hat{k}}(i_n) = d_{\hat{l}}(i'_n)$ the identification $ob(|\mathcal{I}_\bullet|) \simeq ob(\mathcal{I}_0)$ follows.

To verify the claim about generating arrows, note that any arrow of $[n] \times \mathcal{I}_n$ factors as

$$(k, i_n) \rightarrow (l, i_n) \xrightarrow{I_n} (l, i'_n) \quad (5.38)$$

for $I_n: i_n \rightarrow i'_n$ an arrow of \mathcal{I}_n . The $d_{\hat{l}}$ relation identifies the right arrow in (5.38) with $(0, d_{\hat{l}}(i_n)) \xrightarrow{d_{\hat{l}}(I_n)} (0, d_{\hat{l}}(i'_n))$ in $[0] \times \mathcal{I}_0$ while (if $k < l$) the $d_{\hat{k}, \hat{l}}$ relation identifies the left arrow with $(0, d_{\hat{k}, \hat{l}}(i_n)) \rightarrow (1, d_{\hat{k}, \hat{l}}(i_n))$ in $[1] \times \mathcal{I}_1$. The result follows. \square

Remark 5.39. Given $\mathcal{I}_\bullet \in \mathbf{Cat}^{\Delta^{op}}$, $\mathcal{C} \in \mathbf{Cat}$, the isomorphisms

$$Hom_{\mathbf{Cat}}(|\mathcal{I}_\bullet|, \mathcal{C}) \simeq Hom_{\mathbf{Cat}^{\Delta^{op}}}(\mathcal{I}_\bullet, \mathcal{C}^{[\bullet]})$$

together with the fact that $\mathcal{C}^{[\bullet]}$ is always 2-coskeletal show that $|\mathcal{I}_\bullet|$ is determined by the categories $\mathcal{I}_0, \mathcal{I}_1, \mathcal{I}_2$ and maps between them, i.e. by the truncated version of formula (5.35) with $n, m \leq 2$.

Indeed, it can be shown that a sufficient set of generating relations in $|\mathcal{I}_\bullet|$ is given by (i) the relations in \mathcal{I}_0 (including relations stating that identities of \mathcal{I}_0 are identities of $|\mathcal{I}_\bullet|$); (ii) relations stating that for each $i_0 \in \mathcal{I}_0$ the arrow $i_0 = d_1(s_0(i_0)) \xrightarrow{s_0(i_0)} d_1(s_0(i_0)) = i_0$ is an identity; (iii) for each arrow $I_1: i_1 \rightarrow i'_1$ in \mathcal{I}_1 the relation that the square below commutes

$$\begin{array}{ccc} d_1(i_1) & \xrightarrow{i_1} & d_0(i_1) \\ d_1(I_1) \downarrow & & \downarrow d_0(I_1) \\ d_1(i'_1) & \xrightarrow{i'_1} & d_0(i'_1) \end{array}$$

and (iv) for each object $i_2 \in \mathcal{I}_2$ the relation that the following triangle commutes.

$$\begin{array}{ccc} d_{1,2}(i_2) & \xrightarrow{d_1(i_2)} & d_{0,1}(i_2) \\ & \searrow d_2(i_2) \quad \nearrow d_0(i_2) & \\ & d_{0,2}(i_2) & \end{array}$$

Example 5.40. For $\Omega_{G,\bullet}$ the simplicial object of planar strings one has $|\Omega_{G,\bullet}| = \Omega_{G,\bullet}^t$, the category of G -trees and tall maps. Indeed, arrows of $\Omega_{G,0}$ and objects of $\Omega_{G,1}$ are naturally identified with the quotient arrows and planar tall arrows of Ω_G^t , which are a generating set of arrows. And likewise, relations in $\Omega_{G,0}$, arrows in $\Omega_{G,1}$ and objects in $\Omega_{G,2}$ are identified with the relations of Ω_G^t .

Analogously, for $\Omega_{G,\bullet}^J$ the simplicial object of planar l -labeled strings that are $(\{l\} - J)$ -inert, one has $|\Omega_{G,\bullet}^J| = \Omega_{G,\bullet}^{J,t}$, the category of l -labeled G -trees and $(\{l\} - J)$ -inert tall maps.

The following is the key result in this section.

Proposition 5.41. *Let $\mathcal{I}_\bullet \in \text{Cat}^{\Delta^{op}}$. Then there is a natural functor*

$$\Delta^{op} \ltimes \mathcal{I}_\bullet \xrightarrow{s} |\mathcal{I}_\bullet|. \quad (5.42)$$

Further, s is final.

Remark 5.43. The s in the result above stands for *source*. This is because, for any $\mathcal{I} \in \text{Cat}$, the map $\Delta^{op} \ltimes \mathcal{I}^{[\bullet]} \rightarrow |\mathcal{I}^{[\bullet]}| \simeq \mathcal{I}$ is given by $s(i_0 \rightarrow \dots \rightarrow i_n) = i_0$.

Proof. Recall that $|\mathcal{I}_\bullet|$ is the coequalizer $(\text{REALDEF EQ } 5.35)$. Given $(k, g_m) \in [n] \times \mathcal{I}_m$, we will write $[k, g_m]$ for the corresponding object in $|\mathcal{I}_\bullet|$. To simplify notation, we will write objects of \mathcal{I}_n as i_n and implicitly assume that $[k, i_n]$ refers to the class of the object $(k, i_n) \in [n] \times \mathcal{I}_n$.

We define s on objects by $s([n], i_n) = [0, i_n]$ and on an arrow $(\phi, I_m): (n, i_n) \rightarrow (m, i'_m)$ as the composite (note that $\phi: [m] \rightarrow [n]$ and $I_m: \phi^*(i_n) \rightarrow i_m$)

$$[0, i_n] \rightarrow [\phi(0), i_n] = [0, \phi^*(i_n)] \xrightarrow{I_m} [0, i'_m]. \quad (5.44)$$

TARGETDEFINITION EQ

To check associativity, the cases of of a pair of either two fiber arrows (i.e. arrows where ϕ is the identity) or two pushforward arrows (i.e. arrows where I_m is the identity) are immediate from (5.44), hence we are left with the case $([n], i_n) \xrightarrow{I_n} ([n], i'_n) \rightarrow ([m], \phi^*(i'_n))$ of a fiber arrow followed by a pushforward arrow. Noting that in $\Delta^{op} \ltimes \mathcal{I}_\bullet$ this composite can be

rewritten as $([n], i_n) \rightarrow ([m], \phi^*(i_n)) \xrightarrow{\phi^*(I_n)} ([m], \phi^*(i'_n))$ this amounts to checking that

$$\begin{array}{ccccc} [0, i_n] & \longrightarrow & [\phi(0), i_n] & = & [0, \phi^*(i_n)] \\ I_n \downarrow & & I_n \downarrow & & \downarrow \phi^*(I_n) \\ [0, i'_n] & \longrightarrow & [\phi(0), i'_n] & = & [0, \phi^*(i_n)] \end{array} \quad (5.45)$$

commutes in $|\mathcal{I}_\bullet|$, which is the case since the left square is encoded by a square in $[n] \times \mathcal{I}_n$ and the right square is encoded by an arrow in $[m] \times \mathcal{I}_n$.

We now turn to showing that s is final.

Fix $j \in \mathcal{I}_0$. We will show that $[0, j] \downarrow \Delta^{op} \ltimes \mathcal{I}_\bullet$ is indeed connected. By Lemma $(\text{OBJGENREL LEMMA } 5.37)$ any object in this undercategory has a description (not necessarily unique) as a pair

$$\left(([n], i_n), [0, j] \xrightarrow{f_1} \dots \xrightarrow{f_r} s([n], i_n) \right)$$

where each f_i is a generating arrow of $|\mathcal{I}_\bullet|$ induced by either an arrow I_0 of \mathcal{I}_0 or object $i_1 \in \mathcal{I}_1$.

We will connect this object to the canonical object $(([0], h), [0, h] = [0, h])$, arguing by induction on r . If $n \neq 0$, the map $d_0: ([n], i_n) \rightarrow ([0], d_0^*(i_n))$ and the fact that $s(d_0^*) = id_{[0, d_0^*(i_n)]}$ provides an arrow to an object with $n = 0$ without changing r . If $n = 0$, one can apply the induction hypothesis by lifting f_r to $\Delta^{op} \ltimes \mathcal{I}_\bullet$ according to one of two cases: (i) if f_r is induced by an arrow I_0 of \mathcal{I}_0 , the lift of f_r is simply $([0], i'_0) \xrightarrow{I_0} ([0], i_0)$; (ii) if f_r is induced by $i_1 \in \mathcal{I}_1$ the lift is provided by the map $([1], i_1) \rightarrow ([0], d_0(i_1))$. \square

In practice, we will need to know that s satisfies the following stronger finality condition with respect to left Kan extensions.

Corollary 5.46. *Consider a map $\mathcal{I}_\bullet \rightarrow \mathcal{J}$ between $\mathcal{I}_\bullet \in \text{Cat}^{\Delta^{op}}$ and a constant object $\mathcal{J} = \mathcal{J}_\bullet \in \text{Cat}^{\Delta^{op}}$. Then the source map s*

$$\begin{array}{ccc} \Delta^{op} \ltimes \mathcal{I}_\bullet & \xrightarrow{s} & |\mathcal{I}_\bullet| \\ & \searrow & \swarrow \\ & \mathcal{J} & \end{array}$$

is Lan-final over \mathcal{J} , i.e. the functors $s \downarrow j: (\Delta^{op} \ltimes \mathcal{I}_\bullet) \downarrow j \rightarrow |\mathcal{I}_\bullet| \downarrow j$ are final for all $j \in \mathcal{J}$.

Proof. It is clear that $(\Delta^{op} \ltimes \mathcal{I}_\bullet) \downarrow j \simeq \Delta^{op} \ltimes (\mathcal{I}_\bullet \downarrow j)$ while Lemma 2.2 guarantees that, since $(-) \downarrow j$ is a left adjoint, $|\mathcal{I}_\bullet| \downarrow j \simeq |\mathcal{I}_\bullet \downarrow j|$. One thus reduces to Proposition 5.41. \square

We end this section with two basic lemmas that will allow us to apply Corollary 5.46 to the tree categories we will be interested in.

Lemma 5.47. *Let $\mathcal{I}_\bullet^F \in \text{Span}(*, \mathcal{C})^{\Delta^{op}}$ be such that the diagrams*

$$\begin{array}{ccc} \mathcal{I}_n & \xrightarrow{F_n} & \mathcal{C} \\ d_i \downarrow & \nearrow \delta_i & \uparrow F_{n-1} \\ \mathcal{I}_{n-1} & \xrightarrow{F_{n-1}} & \mathcal{C} \end{array} \quad \begin{array}{ccc} \mathcal{I}_n & \xrightarrow{F_n} & \mathcal{C} \\ s_j \downarrow & \nearrow \sigma_j & \uparrow F_{n+1} \\ \mathcal{I}_{n+1} & \xrightarrow{F_{n+1}} & \mathcal{C} \end{array} \quad (5.48) \quad \text{IDENTSIMPRELSISO EQ}$$

commute up to isomorphism for $0 < i \leq n$, $0 \leq j \leq n$.

Then the functors $\bar{F}_n: \mathcal{I}_n \rightarrow \mathcal{C}$ given by the composites

$$\mathcal{I}_n \xrightarrow{d_1, \dots, n} \mathcal{I}_0 \xrightarrow{F_0} \mathcal{C}$$

assemble to an object $\mathcal{I}_\bullet^{\bar{F}} \in \text{Span}(*, \mathcal{C})^{\Delta^{op}}$ which is isomorphic to \mathcal{I}_\bullet^F and such that the corresponding diagrams (5.48) for $0 < i \leq n$, $0 \leq j \leq n$ are strictly commutative.

Proof. This follows by a straightforward verification. \square

Lemma 5.49. *A (necessarily unique) factorization*

$$\begin{array}{ccc} \Delta^{op} \ltimes \mathcal{I}_\bullet & \xrightarrow{\quad} & \mathcal{C} \\ & \searrow s & \nearrow \text{---} \\ & & |\mathcal{I}_\bullet| \end{array} \quad (5.50) \quad \text{SOURCEFACT EQ}$$

exists iff for the associated object $\mathcal{I}_\bullet \in \text{Span}(*, \mathcal{C})^{\Delta^{op}}$ (cf. Lemma 5.31) all faces d_i for $0 < i \leq n$ and degeneracies s_j for $0 \leq j \leq n$ are strictly commutative, i.e. they are given by diagrams

$$\begin{array}{ccc} \mathcal{I}_n & \xrightarrow{F_n} & \mathcal{C} \\ d_0 \downarrow & \nearrow \varphi_n & \uparrow F_{n-1} \\ \mathcal{I}_{n-1} & \xrightarrow{F_{n-1}} & \mathcal{C} \end{array} \quad \begin{array}{ccc} \mathcal{I}_n & \xrightarrow{F_n} & \mathcal{C} \\ d_i \downarrow & \nearrow & \uparrow F_{n-1} \\ \mathcal{I}_{n-1} & \xrightarrow{F_{n-1}} & \mathcal{C} \end{array} \quad \begin{array}{ccc} \mathcal{I}_n & \xrightarrow{F_n} & \mathcal{C} \\ s_j \downarrow & \nearrow & \uparrow F_{n+1} \\ \mathcal{I}_{n+1} & \xrightarrow{F_{n+1}} & \mathcal{C} \end{array} \quad (5.51) \quad \text{IDENTSIMPRELS EQ}$$

Proof. For the “if” direction, it suffices to note that s sends all pushout arrows of $\Delta^{op} \ltimes \mathcal{I}_\bullet$ for faces d_i , $0 < i \leq n$ and degeneracies s_j , $0 \leq j \leq n$ to identities and this yields the commutative diagrams (5.51).

For the “only if” direction, this will follow by building a functor $\mathcal{I}_\bullet \xrightarrow{\bar{F}} \mathcal{C}^{[\bullet]}$ together with the naturality of the source map s (recall that $|\mathcal{C}^{[\bullet]}| \simeq \mathcal{C}$). We define $\bar{F}_{n|k \rightarrow k+1}$ as the map

$$F_{n-k} d_{0, \dots, k-1} \xrightarrow{\varphi_{n-k} d_{0, \dots, k-1}} F_{n-k-1} d_{0, \dots, k}. \quad (5.52) \quad \text{EQUIVALENCEDEF EQ}$$

The claim that $s \circ (\Delta^{op} \ltimes \bar{F})$ recovers the horizontal map in (5.50) is straightforward, hence the real task is to prove that (5.52) indeed defines a map of simplicial objects.

$$\varphi_{n-1} d_i = \varphi_n, \quad 1 < i \quad \varphi_{n-1} d_1 = (\varphi_{n-1} d_0) \circ \varphi_n, \quad \varphi_{n+1} s_i = \varphi_n, \quad 0 < i, \quad \varphi_{n+1} s_0 = id_{F_n} \quad (5.53)$$

Next, note that there is no ambiguity in writing simply $\varphi_{n-k} d_{0, \dots, k-1}$ to denote the map (5.52). We now check that $\bar{F}_{n-1} d_i = d_i \bar{F}_n$, $0 \leq i \leq n$, which must be verified after restricting to each $k \rightarrow k+1$, $0 \leq k \leq n-2$. There are three cases, depending on i and k :

$$(i < k+1) \quad \varphi_{n-k-1} d_{0, \dots, k-1} d_i = \varphi_{n-k-1} d_{0, \dots, k};$$

$$(i = k + 1) \quad \varphi_{n-k-1} d_{0,\dots,k-1} d_i = \varphi_{n-k-1} d_1 d_{0,\dots,k-1} = (\varphi_{n-k-1} d_0 \circ \varphi_{n-k}) d_{0,\dots,k-1} = (\varphi_{n-k-1} d_{0,\dots,k}) \circ (\varphi_{n-k} d_{0,\dots,k-1});$$

$$(i > k + 1) \quad \varphi_{n-k-1} d_{0,\dots,k-1} d_i = \varphi_{n-k-1} d_{i-k} d_{0,\dots,k-1} = \varphi_{n-k} d_{0,\dots,k-1}.$$

The case of degeneracies is similar. \square

Remark 5.54. One can twist all results by the opposite functor

$$\Delta \xrightarrow{(-)^{op}} \Delta$$

which sends $[n]$ to itself and d_i, s_i to d_{n-i}, s_{n-i} . In doing so, one obtains vertical isomorphisms

$$\begin{array}{ccc} \Delta^{op} \ltimes (\mathcal{J}_\bullet \circ (-)^{op}) & \xrightarrow{s} & |\mathcal{J}_\bullet \circ (-)^{op}| \\ \simeq \downarrow & & \downarrow \simeq \\ \Delta^{op} \ltimes \mathcal{J}_\bullet & \xrightarrow[t]{} & |\mathcal{J}_\bullet| \end{array}$$

which reinterpret the “source” functor as what one might call the “target” functor, with $t([n], i_n) = [n, i_n]$ rather than $s([n], i_n) = [0, i_n]$.

Corollary 5.46 now says that t is Lan-final and Lemmas 5.47, 5.49 generalize in the obvious way by replacing s with t and d_0 with d_n .

5.5 The category of extension trees

In this section we combine the previous sections to obtain a compact description of free extension pushouts

$$\begin{array}{ccc} \mathbb{F}_G A & \longrightarrow & X \\ \downarrow & & \downarrow \\ \mathbb{F}_G B & \longrightarrow & Y \end{array} \quad (5.55) \quad \text{FREEEXT EQ}$$

as a left Kan extension over a convenient category of trees.

For simplicity, we first explain how to obtain a similar description for the simpler case of a coproduct $X \amalg^a Y$. By (5.30), one has a description

$$\begin{aligned} X \amalg^a Y &\simeq \text{colim}_{\Delta^{op}} \left(\text{Lan}_{\Omega_G^{2,op} \rightarrow \Sigma_G^{op}} N_\bullet^{(X,Y)} \right) \\ &\simeq \text{Lan}_{\Delta^{op} \ltimes \Omega_G^{2,op} \rightarrow \Sigma_G^{op}} N_\bullet^{(X,Y)} \end{aligned}$$

where the second identification follows from formal properties of Grothendieck constructions.

Combining the fact that (5.27) consists of natural isomorphisms with (the Remark 5.54 dual of) Lemma 5.47, yields an isomorphic twisted functor $\tilde{N}_\bullet^{(X,Y)}$ with strictly commutative s_i and d_i for $i \neq n$. The dual of Lemma 5.49 now says that $\tilde{N}_\bullet^{(X,Y)}$ factors via the target map t through $\Omega_G^{2,op} \sim |\Omega_G^{2,op}|$ (writing $\tilde{N}^{(X,Y)}$ for the factorization) and thus the dual of Corollary 5.46 finally yields

$$X \amalg^a Y \simeq \text{Lan}_{\Omega_G^{2,op} \rightarrow \Sigma_G^{op}} \tilde{N}^{(X,Y)}. \quad (5.56)$$

We recall that by Example 5.40, $\Omega_G^{\underline{2}}$ is simply the category of $\underline{2}$ -labeled trees and tall label maps.

More generally, one has

$$\coprod_J^a X_j \amalg^a \coprod_{l-J}^a \mathbb{F}_G X_j \simeq \text{Lan}_{\Omega_G^{J,op} \rightarrow \Sigma_G^{op}} \tilde{N}^{(\underline{X})}. \quad (5.57) \quad \text{LANCOPRODDDESC}$$

where Ω_G^J is the category of l -labeled trees and tall $(l - J)$ -inert label maps.

Remark 5.58. We note that the twisting $\tilde{N}_\bullet^{(X,Y)}$ is fairly harmless. For explicitness, we focus on the simplest case of a “unary coproduct”, in which case (5.57) is simply recovering the genuine equivariant operad X from its bar resolution. In that case $N_2^X: \Omega_{G,2}^{op} \rightarrow \mathcal{V}$ is given by the top map in (4.53) or, equivalently, by the top map in (4.54) (we note that, in the notation therein, it is $A = \Sigma_G$). On the other hand, the twisted map $\tilde{N}_2^X: \Omega_{G,2}^{op} \rightarrow \mathcal{V}$ is given by the left bottom composite in either of (4.53), (4.54). Informally, the role of this twisting is therefore simply that of replacing the order on $V_G(T_n)$ induced lexicographically by planar strings $T_0 \rightarrow \dots \rightarrow T_n$ with the simpler order induced directly from T_n .

In what follows we will largely be able to ignore this technicality. Indeed, the role of lexicographic orders in building (5.57) is that of guaranteeing that \tilde{N}_\bullet satisfies the necessary simplicial identities, which are ensured by appealing to the bar construction for the monad N .

We now turn to the task of building (5.55) as a left Kan extension. One has a colimit description

$$\mathbb{F}B \coprod_{\mathbb{F}A} X \simeq \text{colim}_{\Delta^{op}} \left(\mathbb{F}B \sqcup \mathbb{F}A \sqcup X \xleftarrow{\quad} \mathbb{F}B \sqcup \mathbb{F}A \sqcup \mathbb{F}A \sqcup \mathbb{F}A \sqcup X \xleftarrow{\quad} \mathbb{F}B \sqcup \mathbb{F}A \sqcup \mathbb{F}A \sqcup \mathbb{F}A \sqcup \mathbb{F}A \sqcup \mathbb{F}A \sqcup X \quad \dots \right) \quad (5.59)$$

where all differentials are fold maps of $\mathbb{F}A$ except to the n -th differential d_n , which is induced by the two maps $\mathbb{F}A \rightarrow X$, $\mathbb{F}A \rightarrow \mathbb{F}B$.

By the previous discussion each individual object $X \sqcup (\mathbb{F}A)^{\sqcup 2n+1} \sqcup \mathbb{F}B$ in (5.59) can be described as a left Kan extension over the tree category $\Omega_G^{\{X\}}$ where $\{X\} \subset \{B, A, \dots, A, X\}$ is a singleton. The maps in (5.59) can themselves be encoded as span maps between the $\Omega_G^{\{X\}}$. To see this, we make (5.59) more precise. Firstly, we write $\langle n \rangle$ for the poset

$$-\infty \leq -n \leq -n+1 \leq \dots \leq -1 \leq 0 \leq 1 \leq \dots \leq n-1 \leq n \leq +\infty.$$

The posets $\langle n \rangle$ together with antisymmetric (i.e. such that $f(-x) = -f(x)$) poset maps preserving all three of $-\infty, 0, +\infty$ then form a simplicial object¹ $\langle - \rangle: \Delta^{op} \rightarrow \mathbf{F}$.

(5.55) thus induces a simplicial object $(B, A, X)_{\langle n \rangle} \in \mathbf{F} \wr \text{Fun}(\Sigma_G^{op}, \mathcal{V})$.

Each level of $(\iota B, \iota A, \iota X)_{\langle n \rangle}$ is then a $N^{\times \{+\infty\}}$ -algebra on $(\text{WSpan}^l(\Sigma_G^{op}, \mathcal{V}))^{\times \langle n \rangle}$, compatibly with the simplicial maps. One thus obtains a *bisimplicial* object

$$\Sigma_G^{op} \leftarrow \Omega_{G,\bullet}^{\{+\infty\}(\bullet), op} \xrightarrow{N_\bullet^{(B,A,X)}(\bullet)} \mathcal{V}$$

on $\text{WSpan}^l(\Sigma_G^{op}, \mathcal{V})$ whose realization along the string direction yields the spans

$$\Sigma_G^{op} \leftarrow \Omega_G^{\{+\infty\}(\bullet), op} \xrightarrow{N^{(B,A,X)}(\bullet)} \mathcal{V} \quad (5.60)$$

discussed above, except now assembled into a simplicial object in $\text{WSpan}^l(\Sigma_G^{op}, \mathcal{V})$.

All degeneracies s_i and differentials d_i of (5.60) other than the top differential d_n are induced by maps α^* described in §5.4 and thus given by strictly commutative diagrams, so that Lemma 5.49 and Corollary 5.46 can be applied (this time with no need to appeal to Lemma 5.47) so as to allow (5.59) to be repackaged as

$$\mathbb{F}B \coprod_{\mathbb{F}A} X \simeq \text{Lan}_{\Omega_G^{e, op} \rightarrow \Sigma_G^{op}} N^{(B,A,X)} \quad (5.61)$$

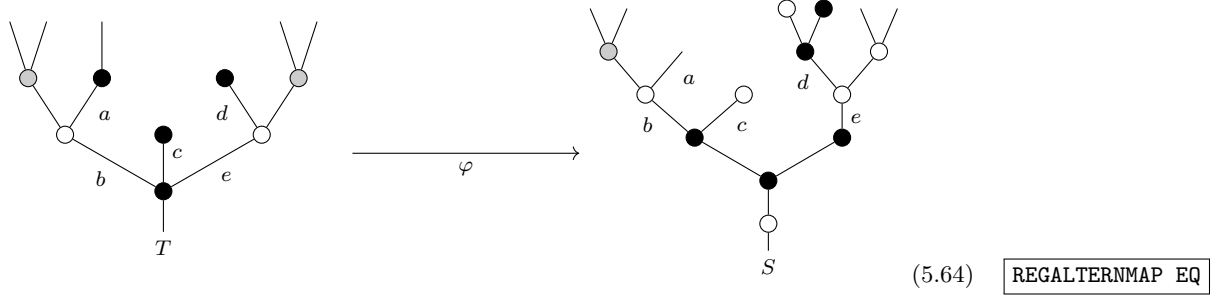
where we write Ω_G^e for $|\Omega_G^{\{+\infty\}(\bullet)}|$. We now turn to the task of describing Ω_G^e , starting with by defining it directly.

¹Indeed, we recall that the opposite simplex category Δ^{op} can equivalently be described as the category of *intervals*, i.e. finite ordered posets with distinct top and bottom, along with order maps preserving both top and bottom. $\langle n \rangle$ can then be regarded as obtained by gluing the interval $0 \leq 1 \leq \dots \leq n \leq +\infty$ with its opposite.

Definition 5.62. The *extension tree category* Ω_G^e is the category whose objects are $\{B, A, X\}$ -labeled trees and whose maps $\varphi: T \rightarrow S$ are tall maps of trees such that

- (i) if $T_{v_{Ge}}$ has an A -label, then $S_{v_{Ge}} = T_{v_{Ge}}$ and $S_{v_{Ge}}$ has an A -label;
- (ii) if $T_{v_{Ge}}$ has a B -label, then $S_{v_{Ge}} = T_{v_{Ge}}$ and $S_{v_{Ge}}$ has either an A -label or a B -label;
- (iii) if $T_{v_{Ge}}$ has a X -label, then $S_{v_{Ge}}$ has only A and X -labels.

Example 5.63. The following is an example of a planar map in Ω_G^e , where black nodes represent X -labeled nodes, grey nodes represent B -labeled nodes and white nodes represent A -labeled nodes.



Proposition 5.65. One has an identification

$$\Omega_G^e \simeq |\Omega_G^{\{+\infty\}(\bullet)}|.$$

Proof. We note first that Ω_G^e contains all label maps that are $\{A, B\}$ -inert. In fact, any map of Ω_G^e clearly has a unique factorization as such a label map followed by an underlying planar isomorphism of trees that replaces some of the X and B labels with A labels. We will refer to the former as label maps and to the latter as relabel maps.

We recall that $\Omega_G^{\{+\infty\}(n)}$ consists of trees with $2n + 3$ types of labels: X -labels, B -labels and $2n + 1$ distinct types of A -labels. One can equivalently encode such a tree as a string $T_0 \rightarrow \dots \rightarrow T_n$ of relabel maps. Indeed, the A -label nodes of T_n in such a string are partitioned into $2n + 1$ types according to that node's labels on the T_i (which are either all A 's, some X 's and then A 's or some B 's and then A 's). Moreover, a diagram

$$\begin{array}{ccccccc} T_0 & \longrightarrow & T_1 & \longrightarrow & \dots & \longrightarrow & T_n \\ f_0 \downarrow & & f_1 \downarrow & & & & f_n \downarrow \\ T'_0 & \longrightarrow & T'_1 & \longrightarrow & \dots & \longrightarrow & T'_n \end{array}$$

with f_i label maps of Ω_G^e is then equivalent to a label map $f_n: T_n \rightarrow T'_n$ respecting all $2n + 3$ labels in $\Omega_G^{\{+\infty\}(n)}$. Since the string description above is also compatible with the simplicial structure maps in the obvious way, the result is now clear. \square

Our next task will be that of identifying a convenient Lan-final subcategory $\bar{\Omega}_G^e \hookrightarrow \Omega_G^e$. We first introduce the auxiliary notion of alternating trees. We recall the notion of input path (Notation 3.4) $I(e) = \{f \in T: e \leq_d f\}$ for an edge $e \in T$, which naturally extends to T in any of $\Omega, \Phi, \Omega_G, \Phi_G$.

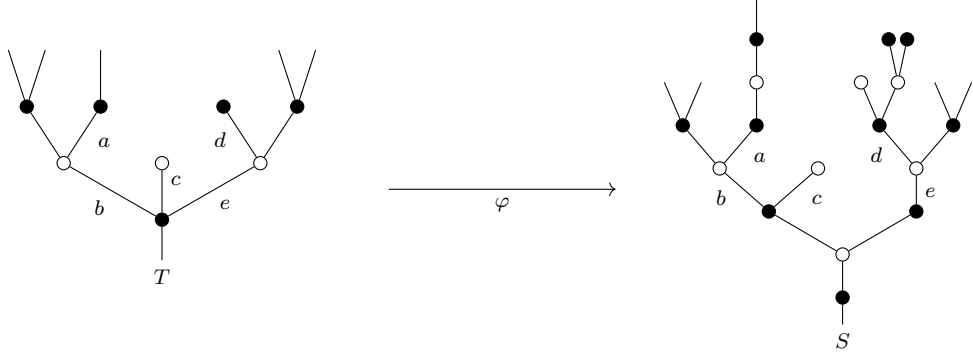
Definition 5.66. A G -tree $T \in \Omega_G$ is called *alternating* if, for all leafs $l \in T$ one has that the input path $I(l)$ has an even number of elements.

Further, a vertex $e^\dagger \leq e$ is called *active* if $|I(e)|$ is odd and *inert* otherwise.

Finally, a tall map $T \xrightarrow{\varphi} T'$ between alternating G -trees is called a *tall alternating map* if for any inert vertex $e^\dagger \leq e$ of T one has that $T'_{e^\dagger \leq e}$ is an inert vertex of T' .

We will denote the category of alternating G -trees and tall alternating maps by Ω_G^a .

Example 5.67. Two alternating trees (for $G = *$ the trivial group) and a planar tall alternating map between them follow, with active nodes in black (\bullet) and white nodes in white (\circ).



(5.68)

REGALTERNMAPLR EQ

The term “alternating” comes from the fact that no adjacent nodes have the same color. We note, however, that there is additional restriction: the “outer” vertices, i.e. those immediately below a leaf or the one immediately above the root, are necessarily black/active (not, however, that this does *not* apply to stumps).

Remark 5.69. One can extend Definition 3.39 to the alternating context by defining a substitution datum to be alternating if it is given by isomorphisms for inert nodes and by alternating maps for active nodes. It is then straightforward to check that Proposition 3.42 and its equivariant analogue Proposition 4.19 extend to give alternating analogues.

Definition 5.70. $\bar{\Omega}_G^e \hookrightarrow \Omega_G^e$ is the full subcategory of (B, A, X) -labeled trees whose underlying trees is alternating, active nodes are labeled by X , and passive nodes are labeled by A or B .

We note that conditions (i) and (ii) in Definition 5.62 imply that maps in $\bar{\Omega}_G^e$ are underlying alternating maps.

The following establishes the required finality of $\bar{\Omega}_G^e$ in Ω_G^e .

LXP PROP

Proposition 5.71. For each $U \in \Omega_G^e$ there exists a unique $\text{lr}_X(U) \in \bar{\Omega}_G^e$ together with a unique planar label map of Ω_G^e

$$\text{lr}_X(U) \rightarrow U.$$

Furthermore, lr_X extends to a right retraction $\text{lr}_X: \Omega_G^e \rightarrow \bar{\Omega}_G^e$.

Proof. Given U , we form a collection of outer faces $\{U_i^A\} \sqcup \{U_j^B\} \sqcup \{U_k^X\}$ where the U_i^A, U_j^B are simply the A, B -labeled nodes and the $\{U_k^X\}$ are the maximal outer subtrees whose nodes have only X -labels (we note that these may possibly be sticks). Lemma 3.51 then guarantees that the $V_G(U_k^X)$ are disjoint, so that one can apply (the equivariant version of Proposition 3.49) to build

$$T = \text{lr}(U) \rightarrow U \tag{5.72}$$

LRXDEF EQ

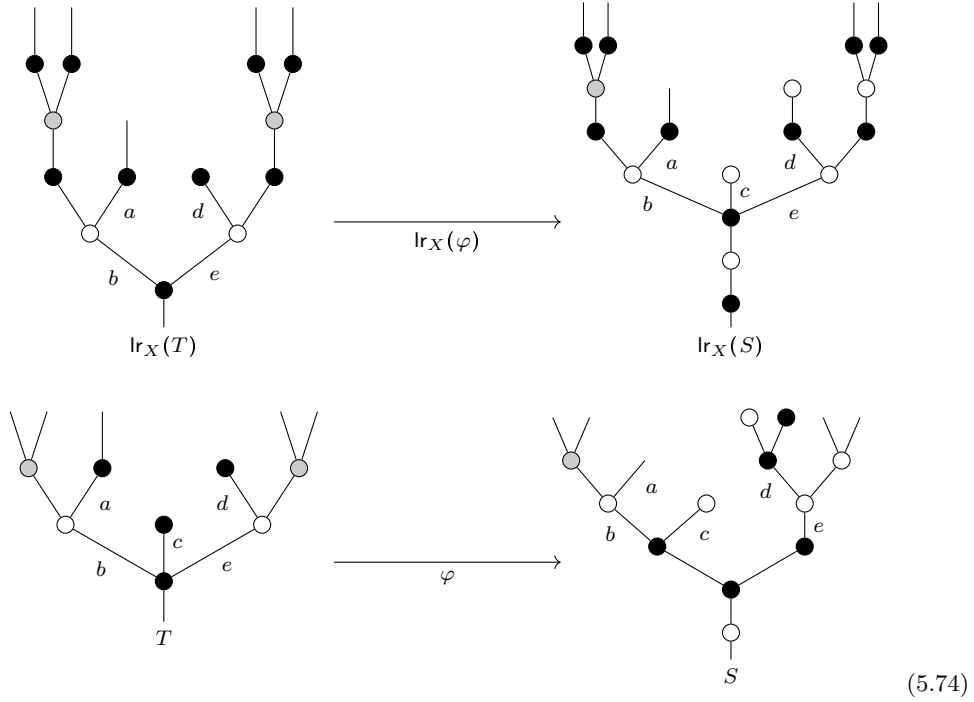
such that $\{U_{v_{Ge}}\} = \{U_i^A\} \sqcup \{U_j^B\} \sqcup \{U_k^X\}$. T has an obvious (B, A, X) -labeling making (5.72) into a label map, but we must still check $T \in \bar{\Omega}_G^e$, i.e. that T is alternating with the X -labeled vertices being precisely the X -labeled vertices. Let us now write any input path of T as $I(e) = (e = e_n \leq e_{n-1} \leq \dots \leq e_1 \leq e_0)$. By Lemma 3.51 and maximality of the U_k^X , no pair of consecutive vertices v_{Ge_i} and $v_{Ge_{i+1}}$ can be both X -labeled. On the other hand, again by Lemma 3.51 any edge of U belongs to some U_k^X and therefore: (i) at least one of in each pair of consecutive vertices v_{Ge_i} and $v_{Ge_{i+1}}$ is X -labeled; (ii) if $r \in T$ is a root, v_{Gr} is X -labeled; (iii) if $l \in T$ is a leaf $v_{Gl_{n-1}}$ is X -labeled. This suffices to conclude $T \in \bar{\Omega}_G^e$, and uniqueness of T is immediate from the uniqueness in Lemma 3.51.

It remains to check that lr_X in fact defines a functor. We consider the following diagram.

$$\begin{array}{ccc} \text{lr}_X(U) & \longrightarrow & U \\ \text{lr}_X(f) \downarrow & & \downarrow f \\ \text{lr}_X(V) & \longrightarrow & V \end{array}$$

When f is a root pullback map, we define $\text{lr}_X(f)$ to likewise be a root pullback map. When f is a rooted tall map, writing $T = \text{lr}_X(U)$ one has a map of rooted T -substitution data $\{\text{lr}_X(V_{v_{G_e}})\} \rightarrow \{V_{v_{G_e}}\}$, which after converted to a tree map yields the desired map $\text{lr}_X(f)$. To check that lr_X respects composition of maps, the only non immediate case is that of a root pullback followed by a rooted map, in which case this follows from Remark 4.22. PULLCOMP REM \square

Example 5.73. REGALTERNMAP EQ The following illustrates the lr_X construction when applied to the map φ in (5.64). (5.64)



6 Filtration of cellular extensions

Put together, the results in the previous section show that the free extension $\mathcal{P}[u]$ given by the pushout

$$\begin{array}{ccc} \mathbb{F}_G X & \longrightarrow & \mathcal{P} \\ u \downarrow & & \downarrow \\ \mathbb{F}_G Y & \longrightarrow & \mathcal{P}[u] \end{array} \quad (6.1) \quad \boxed{\text{CELLEXTPUSH EQ}}$$

is given by a left Kan extension along $(\bar{\Omega}_G^e)^{op} \xrightarrow{lr} \Sigma_G^{op}$. So as to study the homotopical properties of the map $\mathcal{P} \rightarrow \mathcal{P}[u]$ we will identify a suitable filtration of this map, which will in turn be induced by a suitable filtration of the extension tree category $\bar{\Omega}_G^e$.

6.1 Filtration pieces

We now turn to the task of describing our filtration of $\bar{\Omega}_G^e$.

Firstly, we write $V_X(T)$ (resp. $V_Y(T)$) to denote the set of (non-equivariant) vertices of T with a X -label (resp. Y -label). We now define the *degree* of $T \in \bar{\Omega}_G^e$, denoted $|T|$, to be the sum $|T|_X + |T|_Y$, where $|T|_X, |T|_Y$ are defined by

$$|T|_X = \frac{|V_X(T)|}{|Gr|} = \sum_{Gv \in V_{G,X}(T)} \frac{|Gv|}{|Gr|}, \quad |T|_Y = \frac{|V_Y(T)|}{|Gr|} = \sum_{Gv \in V_{G,Y}(T)} \frac{|Gv|}{|Gr|}$$

for Gr the root orbit of T .

Intuitively, $|T|_X$ counts the number of X -labeled vertices in each individual tree component of T .

Remark 6.2. One of the key properties of the degrees just defined is that they are invariant under root pullback.

Definition 6.3. We define subcategories of $\bar{\Omega}_G^e$:

- $\bar{\Omega}_G^e[\leq k]$ (resp. $\Omega_G^e[k]$) is the full subcategory of trees $T \in \bar{\Omega}_G^e$ with $|T| \leq k$ (resp. $|T| = k$);
- $\bar{\Omega}_G^e[\leq k, -]$ (resp. $\bar{\Omega}_G^e[k, -]$) is the full subcategory of $\bar{\Omega}_G^e[\leq k]$ (resp. $\bar{\Omega}_G^e[k]$) of trees T with $|T|_Y \neq k$;
- $\bar{\Omega}_G^e[k, 0]$ is the full subcategory of $\bar{\Omega}_G^e[k]$ of trees T with $|T|_X = 0$ (or, equivalently, $|T|_Y = k$).

The above definitions still hold if we replace $\bar{\Omega}_G^e$ with Ω_G^a ; in particular, we have vertical forgetful functors

$$\begin{array}{ccc} \bar{\Omega}_G^e[k, -] & \hookrightarrow & \bar{\Omega}_G^e[k] \\ & \searrow \text{fgt} & \swarrow \text{fgt} \\ & \Omega_G^a[k] & \end{array}$$

Remark 6.4. The categories $\bar{\Omega}_G^e[k]$ and $\bar{\Omega}_G^e[k, -]$ have only rather limited morphisms. In fact, all maps in these categories must be underlying quotients of trees. Indeed, it is clear from Definition 5.62 that maps never lower degree and, moreover, degree is preserved iff \mathcal{P} -vertices are substituted by \mathcal{P} -vertices (rather than larger trees in $\bar{\Omega}_G^e$, which would necessarily possess X -vertices).

Moreover, we have a clear isomorphism of categories $\bar{\Omega}_G^e[k, 0] \simeq \Omega_G^a[k]$.

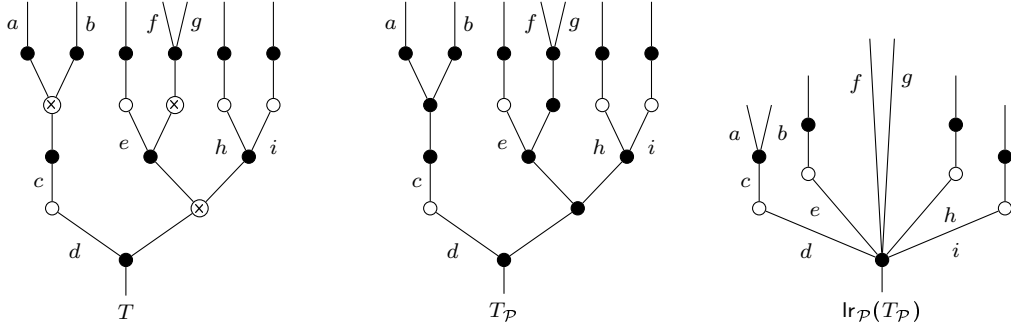
Lemma 6.5. $\bar{\Omega}_G^e[\leq k-1]$ is *Ran-initial* in $\bar{\Omega}_G^e[\leq k, -]$ over Σ_G .

In the proof we will make use of the following construction on $\Omega_{G,e}$: given $T \in \Omega_{G,e}$ we will let $T_{\mathcal{P}}$ denote the result of replacing all X -labeled nodes of T with \mathcal{P} -labeled nodes.

YINERT REM

Remark 6.6. Unlike the $\text{lr}_{\mathcal{P}}$ construction of Proposition 5.71, which defines a functor $\text{lr}_{\mathcal{P}}: \Omega_G^e \rightarrow \bar{\Omega}_G^e$, the construction $(-)_{\mathcal{P}}$ does not define a full functor $\Omega_G^e \rightarrow \bar{\Omega}_G^e$, instead being functorial, and the obvious maps $T_{\mathcal{P}} \rightarrow T$ natural, only with respect to the Y -inert maps of Ω_G^e .

Example 6.7. Combining the $(-)_{\mathcal{P}}$ and $\text{lr}_{\mathcal{P}}$ constructions one obtains a construction sending trees in $\bar{\Omega}_G^e$ to trees in $\bar{\Omega}_G^e$. We illustrate this for the tree $T \in \bar{\Omega}_G^e$ below, where black nodes are \mathcal{P} -labeled, white nodes filled with \times are X -labeled, and empty white nodes are Y -labeled.



Proof of Lemma 6.5. Just as in the proof of Lemma 4.67, for each $C \in \Sigma_G$, the undercategories $C \downarrow \bar{\Omega}_G^e[\leq k-1]$, $C \downarrow \bar{\Omega}_G^e[\leq k, -]$ have initial subcategories $C \downarrow_{r, \approx} \bar{\Omega}_G^e[\leq k-1]$, $C \downarrow_{r, \approx} \bar{\Omega}_G^e[\leq k, -]$ of those objects $(S, q: C \rightarrow \text{lr}(S))$ such that q is an ordered isomorphism on roots, and thus an isomorphism in Σ_G .

It now suffices to show (cf. (4, X.3.1)) that for each $(S, q: C \rightarrow \text{lr}(S))$ in $C \downarrow_{r, \approx} \bar{\Omega}_G^e[\leq k, -]$ the undercategory

$$(S, q) \downarrow (C \downarrow_{r, \approx} \bar{\Omega}_G^e[\leq k-1]) \quad (6.8)$$

UNDERCATPR EQ

is non-empty and connected. Moreover, we note that an object in (6.8) is uniquely encoded by a map $T \rightarrow S$ inducing a rooted isomorphism on lr .

The case $S \in \Omega_G^e[\leq k-1]$ is immediate. Otherwise, since $|S|_Y \neq k$ it is $\|k\|_{\mathcal{P}}(S_{\mathcal{P}}) < k$ and the map $\text{lr}_{\mathcal{P}}(S_{\mathcal{P}}) \rightarrow S$, which is a rooted isomorphism on lr , shows that (6.8) is indeed non-empty.

Otherwise, given any rooted tall map $T \rightarrow S$ with $T \in \bar{\Omega}_G^e[k-1]$ (which gives a rooted isomorphism on lr and thus encodes a unique object of (6.8)). One can then form a diagram

$$\begin{array}{ccccc} & & S & \longleftarrow & \text{lr}_{\mathcal{P}}(S_{\mathcal{P}}) \\ & \nearrow & \uparrow Y\text{-inert} & & \uparrow \\ T & \longrightarrow & T' & \longleftarrow & \text{lr}_{\mathcal{P}}(T'_{\mathcal{P}}) \end{array} \quad (6.9)$$

K-1LANFINAL EQ

where $T \rightarrow T' \rightarrow S$ is the natural factorization such that the second map is Y -inert, i.e., T' is obtained from T by simply relabeling to X those Y -labeled vertices of T that become X -vertices in S . Note that the existence of the right square in (6.9) follows from the map $T' \rightarrow S$ being Y -inert together with Remark 6.6. Since (6.9) becomes a diagram of rooted isomorphism on lr , if produces the necessary zigzag connecting the objects $T \rightarrow S$ and $\text{lr}_{\mathcal{P}}(S_{\mathcal{P}}) \rightarrow S$ in (6.8), finishing the proof. \square

Similarly to the $(-)_{\mathcal{P}}$ construction, there is also a construction T_Y which replaces all X -labels of $T \in \bar{\Omega}_G^e$ with Y -labels. Moreover, in this case the construction restricts directly to a construction on $\bar{\Omega}_G^e$, which is easily seen to be functorial (and the $T_Y \rightarrow T$ maps natural) with regards to \mathcal{P} -inert maps. Remark 6.4 thus implies that $(-)_Y: \bar{\Omega}_G^e[k] \rightarrow \bar{\Omega}_G^e[k, 0]$ is a left retraction, resulting in the following.

Lemma 6.10. $\bar{\Omega}_G^e[k, 0]$ is Ran -initial in $\bar{\Omega}_G^e[k]$ over Σ_G .

N_FINALITY_LEMMA

In what follows we write $N^e: \Omega_G^{e,op} \rightarrow \mathcal{V}$ for the functor in (5.61), and abuse notation by likewise writing N^e for any of its restrictions to the subcategories in Definition 6.3. We are now in a position to produce the desired filtration of the map $\mathcal{P} \rightarrow \mathcal{P}[u]$ in (6.1).

PK_DEFN

Definition 6.11. Let \mathcal{P}_k denote the left Kan extension

$$\begin{array}{ccc} \bar{\Omega}_G^e[\leq k]^{op} & \xrightarrow{N^e} & \mathcal{V} \\ \downarrow \text{lr} & \nearrow \mathcal{P}_k & \\ \Sigma_G^{op} & & \end{array}$$

Noting that $\bar{\Omega}_G^e[\leq 0] \simeq \Sigma_G$ (since $|T| = 0$ only if T is a G -corolla with \mathcal{P} -labeled vertex) and that $\bar{\Omega}_G^e$ is the union of (the nerves of) the $\bar{\Omega}_G^e[\leq k]$, one has a filtration

$$\mathcal{P} = \mathcal{P}_0 \rightarrow \mathcal{P}_1 \rightarrow \mathcal{P}_2 \rightarrow \cdots \rightarrow \text{colim}_k \mathcal{P}_k = \mathcal{P}[u]. \quad (6.12)$$

FILT EQ

To analyze (6.12) homotopically we will further make use of a pushout description of each individual map $\mathcal{P}_{k-1} \rightarrow \mathcal{P}_k$. To do so, we note that the diagram of inclusions

$$\begin{array}{ccc} \bar{\Omega}_G^e[k, -] & \longrightarrow & \bar{\Omega}_G^e[\leq k, -] \\ \downarrow & & \downarrow \\ \bar{\Omega}_G^e[k] & \longrightarrow & \bar{\Omega}_G^e[\leq k] \end{array} \quad (6.13)$$

INCDIAG EQ

is a pushout of at the level of nerves. Indeed, this follows since

$$\bar{\Omega}_G^e[k] \cap \bar{\Omega}_G^e[\leq k, -] = \bar{\Omega}_G^e[k, -], \quad \bar{\Omega}_G^e[k] \cup \bar{\Omega}_G^e[\leq k, -] = \bar{\Omega}_G^e[\leq k],$$

and since a map $T \rightarrow S$ in $\bar{\Omega}_G^e[\leq k]$ will be in one of subcategories in (6.13) iff T is.

Since Lemma 6.5 provides an identification $\text{Lan}_{\bar{\Omega}_G^e, e[\leq k, -]^{op}} N^e \simeq \text{Lan}_{\bar{\Omega}_G^e, e[\leq k-1]^{op}} N^e = \mathcal{P}_{k-1}$, applying left Kan extensions to (6.13) yields the pushout diagram below.

$$\begin{array}{ccc} \text{Lan}_{\bar{\Omega}_G^e, e[k, -]^{op}} N^e & \longrightarrow & \mathcal{P}_{k-1} \\ \downarrow & & \downarrow \\ \text{Lan}_{\bar{\Omega}_G^e, e[k]^{op}} N^e & \longrightarrow & \mathcal{P}_k \end{array} \quad (6.14)$$

FILTRATION_LAN_SQUARE

HERE

6.2 Notation

Luis: should this be stated earlier when defining the categorical wreath products?

In order to state our filtration result, we will need to identify another categorical construction. This filtration will be built out of “pushout products over trees of maps of sequences”. This subsection is dedicated to making that statement precise.

Definition 6.15. Given a map $Y_0 \rightarrow Y_1$ of G -symmetric sequences $\mathcal{V}^{\Sigma_G^{op}}$, and $(A, D) \in \mathbf{F} \wr \Sigma_G$, we borrow notation from [1] and define the functor

$$[u]^D: (0 \rightarrow 1)^A \rightarrow \mathcal{V}$$

as the composite

$$(0 \rightarrow 1)^A \rightarrow \mathbf{F} \wr \mathcal{V} \xrightarrow{\times} \mathcal{V}$$

where the first map is defined on $\xi: A \rightarrow \{0, 1\}$ by

$$(a \mapsto \xi(a)) \mapsto (A, (a \mapsto Y_{\xi(a)}(D(a))))$$

Q_DEFINITION

Definition 6.16. Given $u : Y_0 \rightarrow Y_1$ and $(A, D) \in \mathbf{F} \wr \Sigma_G$ as before, let $\mathbf{pc}(A)$ denote the “punctured cube” subcategory

$$\mathbf{pc}(A) := (0 \rightarrow 1)^A \setminus \{(1)_a\} \subseteq (0 \rightarrow 1)^A,$$

and define

$$Q[u]^D := \operatorname{colim}_{\mathbf{pc}(A)} [u]^D,$$

and

$$[u]^{\square D} : Q[u]^D \rightarrow \bigotimes_{a \in A} Y_1(D(a))$$

as the natural map.

6.3 Filtration Result

We can now state our filtration of the cellular extension $\mathcal{P} \rightarrow \mathcal{P}[u]$.

Theorem 6.17. *Let \mathcal{P} be a genuine G -operad, and suppose we are given a map of G -symmetric sequences $u : Y_0 \rightarrow Y_1$. Then we have a filtration in G -sequences of the cellular extension*

$$\mathcal{P} = \mathcal{P}_0 \rightarrow \mathcal{P}_1 \rightarrow \dots \rightarrow \operatorname{colim}(\mathcal{P}_i) = \mathcal{P}[u],$$

where $\mathcal{P}_{k-1} \rightarrow \mathcal{P}_k$ is given by the pushout

$$\begin{array}{ccc} \operatorname{Lan}_{\bar{\Omega}_G^e[k, -]^{op}} N^e & \longrightarrow & \mathcal{P}_{k-1} \\ \downarrow & & \downarrow \\ \operatorname{Lan}_{\bar{\Omega}_G^e[k]^{op}} N^e & \longrightarrow & \mathcal{P}_k \end{array}$$

where each Lan is over the leaf-root functor associated to the given category.

Levelwise, for each $C \in \Sigma_G$, we have a filtration of $\mathcal{P}(C) \rightarrow \mathcal{P}[u](C)$ in $\mathcal{V}^{\operatorname{Aut}(C)}$, where $\mathcal{P}_{k-1}(C) \rightarrow \mathcal{P}_k(C)$ is given by the pushout

$$\begin{array}{ccc} \coprod_{[T] \in \Omega_G^a[k](C)/\simeq} \left(\bigotimes_{v \in V_{G, \mathcal{P}}(T)} \mathcal{P}(T_v) \otimes Q[u]^{\vee_{G, in}(T)} \right) \otimes_{\operatorname{Aut}(T)} \operatorname{Aut}(C) & \longrightarrow & \mathcal{P}_{k-1}(C) \\ \downarrow & & \downarrow \\ \coprod_{[T] \in \Omega_G^a[k](C)/\simeq} \left(\bigotimes_{v \in V_{G, \mathcal{P}}(T)} \mathcal{P}(T_v) \otimes \bigotimes_{v \in V_{G, in}(T)} Y_1(T_v) \right) \otimes_{\operatorname{Aut}(T)} \operatorname{Aut}(C) & \longrightarrow & \mathcal{P}_k(C) \end{array}$$

where the left vertical map is the iterated box product

$$\coprod_{V_{G, \mathcal{P}}(T)} \square_{\mathcal{P}(T_v)} \iota_{\mathcal{P}(T_v)} \square[u]^{\square_{G, in}(T)},$$

$\iota_{\mathcal{P}(T_v)}$ is the canonical map $\mathcal{Q} \rightarrow \mathcal{P}(T_v)$ out of the initial object, and $\Omega_G^a[k](C)$ is as in Definition 6.3.

Proof. The first result is just a restatement of Diagram (6.14). Levelwise analysis follows from understanding the left-hand vertical map of Diagram (6.14), which we will denote

$$l[k] : L_1[k] \rightarrow L_2[k].$$

By stacking left Kan extensions, we have

$$L_i[k] \simeq \operatorname{Lan}_{\Omega_G^a[k]} (\operatorname{Lan}_{\bar{\Omega}_G^e[\epsilon_i] \rightarrow \Omega_G^a[k]} N^e),$$

where $[\epsilon_1] = [k, -]$ and $[\epsilon_2] = [k]$. Evaluating at $C \in \Sigma_G$ using pointwise left Kan extensions yields

$$L_i[k](C) \simeq \operatorname{colim}_{\substack{\Omega_G^{a,op} \downarrow_r C \\ T \leftarrow C}} \left(\operatorname{colim}_{\substack{\Omega_G^e[\epsilon_i]^{op} \downarrow_r T \\ T^e \leftarrow T}} N^e(T^e) \right).$$

Further, we observe that $\bar{\Omega}_G^e[k]^{op} \downarrow_r T$ is equivalent to the cube category $(0 \rightarrow 1)^{V_{G,in}(T)}$ (with only $\operatorname{Aut}(T)$ -induced isomorphisms), while $\bar{\Omega}_G^e[k, -]^{op} \downarrow_r T$ is similarly equivalent to the punctured cube category $\mathbf{pc}(V_{G,in}(T))$. Unpacked, these statements, in particular that cube categories have terminal objects, Lemma 6.10, and the fact that $\Omega_G^{a,op} \downarrow_r C$ is a groupoid, combine to imply that $l[k]$ is equivalent to the map

$$\coprod_{[T] \in \Omega_G^{a,op}[k](C)/\simeq} \left(\bigotimes_{V_{G,p}(T)} \mathcal{P}(T_{Gv}) \otimes Q[u]^{V_{G,in}(T)} \rightarrow N^e(T_Y) \right) \otimes_{\operatorname{Aut}(T)} \operatorname{Aut}(C),$$

as desired. □

COFIB SEC

7 Cofibrancy

Add to this

8 Model Structures on Genuine Operads

come back: this is all disorganized, internally, externally, everything

replaced \mathbb{F} with \mathcal{F} (as opposed to \mathbb{F})

In order to encode the homotopical information inspired by N_∞ -operads discussed in the introduction, we will introduce (semi) model structures on the categories $\mathcal{V}\mathbf{Op}_G$ and $\mathcal{V}\mathbf{Op}^G$ for a wide range of \mathcal{V} , which are true model categories in the cases we are most interested in (i.e. for $\mathcal{V} = \mathbf{sSet}$). These model structures will be determined by a choice of weak indexing system, a generalization of the notion defined in [2].

8.1 Weak Indexing Systems

We recall certain constructions found in [6] relating graph subgroups, finite H -sets, and systems of categories.

Definition 8.1. A G -graph subgroup of $G \times \Sigma_n$ is a subgroup $\Lambda \leq G \times \Sigma_n$ such that $\Lambda \cap \Sigma_n = e$. Equivalently, $\Gamma = \Gamma(\phi)$ is the graph of some homomorphism $G \geq H \xrightarrow{\phi} \Sigma_n$.

Definition 8.2. A G -vertex family is a collection

$$\mathcal{F} = \coprod_{n \geq 0} \mathcal{F}_n$$

where each \mathcal{F}_n is a family of G -graph subgroups of $G \times \Sigma_n$, closed under subgroups and conjugation. For a fixed \mathcal{F} , we call an H -set $A \in \mathbf{F}^H$ \mathcal{F} -admissible if for some (equivalently, any) choice of bijection $A \leftrightarrow \{1, \dots, |A|\}$, the graph subgroup of $G \times \Sigma_n$ encoding the induced H -action on $\{1, \dots, |A|\}$ is in \mathcal{F}_n .

Definition 8.3. For any G -vertex family \mathcal{F} , a G -tree $T \in \Omega_G$ is called \mathcal{F} -admissible if, for each vertex $e_1 \dots e_n \leq e$ in $V(T)$, the set $\{e_1, \dots, e_n\}$ is an \mathcal{F} -admissible $\mathrm{Stab}_G(e)$ -set. We let $\Omega_{\mathcal{F}} \subseteq \Omega_G$ and $\Sigma_{\mathcal{F}} \subseteq \Sigma_G$ denote the full subcategories spanned by the \mathcal{F} -admissible trees.

Definition 8.4. A G -vertex family is called a *weak indexing system* if $\Omega_{\mathcal{F}}$ is a sieve of Ω_G ; that is, for any map $f : S \rightarrow T$ with $T \in \Omega_{\mathcal{F}}$, we have that S (and the map f) are in $\Omega_{\mathcal{F}}$.

We note that this always holds for any \mathcal{F} if f is an outer face or a quotient (for the latter, this follows from each \mathcal{F}_n being closed under subgroups). However, closure under degeneracies implies that all trivial orbits H/H are \mathcal{F} -admissible, while closure under inner faces implies that the \mathcal{F} -admissible sets are closed under “broad self-induction”: if $A \sqcup H/K$ and B are \mathcal{F} -admissible H - and K -sets, respectively, then $A \sqcup H \times_K B$ is also an \mathcal{F} -admissible H -set. It also implies, in particular, the following:

Lemma 8.5. The valence map lr restricts to a map $\mathrm{lr} : \Omega_{\mathcal{F}} \rightarrow \Sigma_{\mathcal{F}}$; that is, if T is \mathcal{F} -admissible, so is $\mathrm{lr}(T)$. \square

Lemma 8.6. A weak indexing system \mathcal{F} is an indexing system (in the sense of [2]) if and only if all trivial H -sets are \mathcal{F} -admissible, for all $H \leq G$. \square

Proof. come back

We will define \mathcal{F} -model structures on $\mathcal{V}\mathbf{Op}_G$ for any weak indexing system \mathcal{F} ; the \mathcal{F} -model structure on $\mathcal{V}\mathbf{Sym}_G$ will exist for any G -vertex family \mathcal{F} , but transferring requires the additional closure properties.

8.2 Semi Model Structures on Genuine Operads

Fix a G -vertex family $\mathcal{F} = \{\mathcal{F}_n\}$. For the following section, we fix the following about our base category \mathcal{V} :

Definition 8.7. We say \mathcal{V} satisfies ASSUMPTION 1 (for \mathcal{F}) if the following hold:

1. \mathcal{V} is a cofibrantly-generated Cartesian symmetric monoidal model category, and
2. \mathcal{V} has cellular fixed point functors for all finite groups (c.f. [Stephan16](#) [\[7\]](#)).

Definition 8.8. The \mathcal{F} -projective model structure on $\mathcal{V}\text{Sym} = \mathcal{V}^{\Sigma_G^{op}}$ is the unique model structure induced by the adjunction

$$\mathcal{V}^{\Sigma_G^{op}} \rightleftarrows \mathcal{V}^{\Sigma_{\mathcal{F}}^{op}}.$$

Explicitly, a map f is a fibration (resp. weak equivalence) if $f(C)$ is one in \mathcal{V} for all $C \in \Sigma_{\mathcal{F}}$.

Definition 8.9. A map $f : \mathcal{O} \rightarrow \mathcal{P}$ in $\mathcal{V}\text{Op}_G$ is called a

1. \mathcal{F} -fibration (resp. \mathcal{F} -weak equivalence) if $f(C) : \mathcal{O}(C) \rightarrow \mathcal{P}(C)$ is one in \mathcal{V} for all \mathcal{F} -admissible G -corollas $C \in \Sigma_{\mathcal{F}}$.
2. \mathcal{F} -cofibration if it has the left lifting property against all maps which are both \mathcal{F} -fibrations and \mathcal{F} -weak equivalences.
3. $\Sigma_{\mathcal{F}}$ -cofibration if f is an \mathcal{F} -cofibration in $\mathcal{V}\text{Sym}_G$.

In particular, $\mathcal{P} \in \mathcal{V}\text{Op}_G$ will be called \mathcal{F} -cofibrant if $\emptyset \rightarrow \mathcal{P}$ is an \mathcal{F} -cofibration.

Definition 8.10. The \mathcal{F} -model structure on $\mathcal{V}\text{Op}_G$, if it exists, is the unique model structure with the above specified weak equivalences and fibrations. Equivalently, it is the transferred model structure along the adjoints

$$\mathcal{V}\text{Op}_G \xrightleftharpoons[\text{fgt}]{\mathbb{F}_G} \mathcal{V}^{\Sigma_G^{op}} \xrightleftharpoons{\quad} \prod_{\text{Ob}(\Sigma_G)} \mathcal{V} \xrightleftharpoons{\quad} \prod_{\text{Ob}(\Sigma_{\mathcal{F}})} \mathcal{V}$$

Using general arguments of [Hi03](#) [\[3\]](#), this structure would be cofibrantly generated, with generating arrows

$$\begin{aligned} I_{\mathcal{F}} &= \{\mathbb{F}_G(\Sigma_G(-, C) \cdot i) \mid C \in \Sigma_{\mathcal{F}}, i \in I\} \\ J_{\mathcal{F}} &= \{\mathbb{F}_G(\Sigma_G(-, C) \cdot j) \mid C \in \Sigma_{\mathcal{F}}, j \in J\}, \end{aligned}$$

for I (resp. J) the generating (trivial) cofibrations of \mathcal{V} .

Definition 8.11. If \mathcal{F} is the complete G -vertex family - so \mathcal{F}_n is the family of all graph subgroups of $G \times \Sigma_n$ - we refer to the \mathcal{F} -model structure as the *genuine* model structure.

Theorem 8.12. The genuine semi-model structure on $\mathcal{V}\text{Op}_G$ exists for all \mathcal{V} satisfying ASSUMPTION 1.

Proof. By general arguments of Kan [\[3, 11.6.1\]](#), it suffices to show that any transfinite composite of cellular extensions $\mathcal{P} \rightarrow \mathcal{P}[u]$, each built by pushouts

$$\begin{array}{ccc} \mathbb{F}_G X & \longrightarrow & \mathcal{P} \\ u \downarrow & & \downarrow \\ \mathbb{F}_G Y & \longrightarrow & \mathcal{P}[u] \end{array}$$

where $u : X \rightarrow Y$ is a generating trivial cofibration and \mathcal{P} is cofibrant in $\mathcal{V}_{gen}^{\Sigma_G^{op}}$, is itself a weak equivalence in $\mathcal{V}_{gen}^{\Sigma_G^{op}}$.

In particular, it suffices to show that, for u a genuine level trivial cofibration and \mathcal{P} genuine level cofibrant, any map $\mathcal{P} \rightarrow \mathcal{P}[u]$ is itself a genuine level trivial cofibration; since these are weaker conditions on u and \mathcal{P} , and transfinite composition is levelwise, this implies the above result. This case follows from the levelwise filtration from Theorem 6.17, by applying Propositions 8.14 and 8.15. \square

Remark 8.13. In proving the above, we will often use the fact that, given families $\mathcal{F} \subseteq \bar{\mathcal{F}}$ of subgroups of a group Π , the identity map

$$\mathcal{V}_{\mathcal{F}}^G \rightarrow \mathcal{V}_{\bar{\mathcal{F}}}^G$$

is left Quillen (and in particular preserves cofibrations). In particular, any \mathcal{F} -cofibration is a genuine cofibration.

Proposition 8.14. Fix $T \in \Omega_G$, and suppose we are given cofibrations $f(Gv) \in \mathcal{V}_{gen}^{\text{Aut}(T_{Gv})}$ for all $Gv \in V_G(T)$, such that $f(Gv) = f(\alpha(Gv))$ for all $\alpha \in \text{Aut}(T)$. Then the iterated box product

$$f^{\square V_G(T)} = \square_{Gv \in V_G(T)} f(Gv)$$

is a cofibration in $\mathcal{V}_{gen}^{\text{Aut}(T)}$.

Proof. Using grafting composition $T \simeq C \circ (T_1^1, \dots, T_1^{k_1}, T_2^1, \dots, T_r^{k_r})$, we go by induction on $|V_G(T)|$. The base cases of $|V_G(T)| = 0$ or 1 are trivial. Now, we note that we have a decomposition

$$f^{\square V_G(T)} = f(Gv_r) \square \square_{i=1}^r \left(\left(f^{\square V_G(T_i)} \right)^{\square k_i} \right)$$

where Gv_r is the root orbit. We will build this map in stages, preserving cofibrancy in each step.

- By induction, for each i , $f^{\square V_G(T_i)}$ is a cofibration in $\mathcal{V}_{gen}^{\text{Aut}(T_i)}$.
- By Proposition [POWERF PROP](#), each $\left(f^{\square V_G(T_i)} \right)^{\square k_i}$ is a cofibration in $\mathcal{V}_{gen}^{\Sigma_{k_i} \wr \text{Aut}(T_i)}$.
- By Remark [EXTERTADJ EQ](#), $\square_{i=1}^r \left(\left(f^{\square V_G(T_i)} \right)^{\square k_i} \right)$ is a cofibration in $\mathcal{V}_{gen}^{\Pi \Sigma_{k_i} \wr \text{Aut}(T_i)}$.
- By Proposition [FGTLEFT PROP](#), $f(Gv_r)$ is a cofibration in $\mathcal{V}_{gen}^{\text{Aut}(T)}$.
- Finally, by the decomposition on $\text{Aut}(T)$ and Proposition [BIQUILLENG PROP](#), we have the full $f^{\square V_G(T)}$ is a cofibration in $\mathcal{V}_{gen}^{\text{Aut}(T)}$, as desired.

If any $f(Gv)$ were trivial, then, during the appropriate step above, the resulting box product would again be trivial, by the same referenced results. \square

Corollary 8.15. For any G -vertex system \mathcal{F} , the \mathcal{F} -semi-model structure on $\mathcal{V}\text{Op}_G$ exists.

Proof. This follows from the proof of Theorem [GENUINE_SEMI_VOP_G_THM](#) 8.12. In particular, it suffices to show that if $u : X \rightarrow Y$ is a level trivial \mathcal{F} -cofibration and \mathcal{P} is level \mathcal{F} -cofibrant in $\mathcal{V}_{gen}^{\Sigma_G^{\text{op}}}$, then the cellular extension $\mathcal{P} \rightarrow \mathcal{P}[u]$ is a level trivial \mathcal{F} -cofibration. However, such u are level genuine cofibrations, and such \mathcal{P} are level genuine cofibrant, and hence $\mathcal{P} \rightarrow \mathcal{P}[u]$ is a level trivial genuine cofibration, and hence a level trivial \mathcal{F} -cofibration. \square

8.3 True Model Structures

come back

8.4 Preservation of Cofibrant Objects

come back

8.5 Cofibrant Symmetric Collections

come back: can do all of this for $\mathcal{V}^{\Omega_G^{op}}$ and $\mathcal{V}^{\Sigma_G^{op}}$, don't need these crazy categories.

We first classify cofibrant objects in $\mathcal{V}^{\Omega_G^e[k]^{op}}$, by breaking apart our category $\Omega_G^e[k]$.

Definition 8.16. Given a tree $T_0 \in \Omega$, let $\Omega_G[T_0]$ denote the full subcategory of Ω_G^q spanned by those trees which receive a map from $G \cdot T_0$; that is, all trees of the form $G \cdot T_0/N$.

Lemma 8.17. $\Omega_G[T_0] \simeq_{O_{\Gamma_{T_0}}} \text{as categories, where } \Gamma_{T_0} \text{ is the family of graph subgroups of } G \times \Sigma_{T_0}.$ \square

Definition 8.18. Refining the above, given an odd tree $T_0 \in \Omega^{\text{odd}}$, let $T_0(Y) \in \Omega^e$ denote the labeled tree with underlying tree T_0 and all even nodes labeled with Y . Further, let $\Omega^e[T_0]$ denote the full subcategory of Ω^e spanned by those trees (S_0, λ_{S_0}) which receive a map from $T_0(Y)$ in Ω^e . Similarly, let $\Omega_G^e[T_0]$ denote the full subcategory of Ω_G^e spanned by those trees (S, λ_S) which receive a map from $G \cdot T_0(Y)$.

We have an inclusion $\tau : G \times \Omega^e[T_0] \hookrightarrow \Omega_G^e[T_0]$, refining the inclusion $G \times \Omega \hookrightarrow \Omega_G$. This induces an adjunction

$$\mathcal{V}^{G \times \Omega^e[T_0]^{op}} \xrightleftharpoons[\tau_*]{\tau^*} \mathcal{V}^{\Omega_G^e[T_0]^{op}}$$

and we observe that

$$\tau_* X(G \cdot T_0/N, \lambda) \simeq X(G \cdot T_0, q^* \lambda)^N,$$

where we are using the fact that even element in $\Omega_G^e[T_0]$ has underlying tree of the form $G \cdot T_0/N$, and $q^* \lambda$ is the vertex labeling

$$q^* \lambda : V_G(G \cdot T_0) \rightarrow V_G(G \cdot T_0/N) \xrightarrow{\lambda} \{Y, X\}.$$

We further repackage $\Omega_G^e[T_0]$. In particular, we observe that if there is a map $(T', \lambda') \rightarrow (T'', \lambda'')$ in $\Omega_G^e[T_0]$, it is uniquely determined by the underlying quotient map $T' \rightarrow T''$. Indeed, $\Omega_G^e[T_0](T', T'')$ is the subset of $\Omega_{\Gamma_{T_0}}(G \times \Sigma_{T_0}/N', G \times \Sigma_{T_0}/N'')$, where $T' \simeq G \cdot T_0/N'$ and $T'' \simeq G \cdot T_0/N''$, of those maps q such that $v'' \in V_Y(T'')$ implies $q^{-1}(v'') \in V_Y(T')$. Stephan 16

We can now prove a proposition, modeled on the proof of [7, Theorem 2.10].

Proposition 8.19. *If $X \in \mathcal{V}^{\Omega_G^e[T_0]^{op}}$ is cofibrant, then $\eta_X : X \rightarrow \tau_* \tau^* X$ is an isomorphism.*

Proof. come back, type up these sheets

First: η is an iso on representables.

Second: carries through across the necessary cellular extensions. \square

8.5.1 G -Operads

Definition 8.20. A map $f : \mathcal{O} \rightarrow \mathcal{P}$ in $\mathcal{V}\text{Op}^G$ is called a

1. \mathcal{F} -fibration (resp. \mathcal{F} -weak equivalence) if ...

come back

Definition 8.21. The \mathcal{F} -model structure on $\mathcal{V}\text{Op}^G$, ...

come back

Lemma 8.22. *The \mathcal{F} -semi-model structure, if it exists, is the transferred model structure along the adjunction*

$$\mathcal{V}\text{Op}_{\mathcal{F}}^G \rightleftarrows \mathcal{V}\text{Op}_G^{\mathcal{F}}$$

Corollary 8.23. *The \mathcal{F} -(-semi)-model structure exists on $\mathcal{V}\text{Op}^G$ whenever it exists on $\mathcal{V}\text{Op}_G$.*

Theorem 8.24. *$\mathcal{V}\text{Op}_{\mathcal{F}}^G$ and $\mathcal{V}\text{Op}_G^{\mathcal{F}}$ are Quillen equivalent.*

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