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## 0.1 December 2022

### 0.1.1 (11/28) Ok, let's give this a try

I want to read *Higher Topos Theory* (HTT). That book is > 700 pages, and fairly dense ones, so it's a bit of a project. On top of that, HTT isn't really a self-contained read (and that's sort of the nature of the subject). So I'll be drawing on lots of additional material. The subject seems well worth learning, even unavoidable at times (e.g., in the areas I am interested in), so this should be a productive little activity.

...

I need to cover some ground before actually opening HTT. First I need to think about *simplicial sets*. Their role in higher category theory is ubiquitous. They give us a combinatorial model for the homotopy theory of spaces, and also a model for  $\infty$ -categories. (On the list of things to do is make precise sense of those statements.) Some references are [Rie], [Mat], [Fri08], and [kerodon.net](http://kerodon.net).

**Definition 0.1.1.** Denote by  $\Delta$  the *simplex category*, defined to have...

- As objects, the ordered set  $[n] := \{0 < 1 < \dots < n\}$  for each  $n \geq 0$ ; and
- As maps, the weakly order-preserving set maps.

**Definition 0.1.2.** A *simplicial set* is a contravariant functor  $\Delta \rightarrow \mathbf{Set}$ . The *category of simplicial sets*, denoted  $\mathbf{sSet}$ , is the functor category  $\mathbf{Fun}(\Delta^{op}, \mathbf{Set})$ .

**Notation 0.1.1.** Let  $X : \Delta^{op} \rightarrow \mathbf{Set}$  be a simplicial set. We may write it  $X_\bullet$ , and denote by  $X_n$  the set  $X([n])$ . We call the elements of  $X_n$  the  *$n$ -simplices* of  $X$ .

**Notation 0.1.2.** We may write  $\langle f_0, \dots, f_n \rangle$  to denote the function  $[n] \rightarrow [m]$  given by  $n \mapsto f_n$ .

Simplicial sets are not just simplices. They carry additional structure, that arising from morphisms in  $\Delta$ . We can give a simple description of  $\Delta$ . This in turn gives some intuition for what a simplicial set "is."

**Proposition 0.1.3** (The structure of  $\Delta$ ). *For each  $n \geq 0$  and  $0 \leq i \leq n$ , define the*

$$\begin{aligned} & i\text{-th face map } d^i : [n-1] \rightarrow [n] \text{ as } \langle 0, \dots, \hat{i}, \dots, n \rangle, \text{ and the} \\ & i\text{-th degeneracy map } s^i : [n+1] \rightarrow [n] \text{ as } \langle 0, \dots, i, i, \dots, n \rangle. \end{aligned}$$

*Every morphism in  $\Delta$  may be written as a composition of face and degeneracy maps. (Also, the face/degeneracy maps satisfy various relations, the simplicial identities; in fact  $\Delta$  is the category generated by those maps, subject to these identities.)*

Thus a simplicial set  $X_\bullet$  can be described as a collection of sets  $X_n$  ( $n$ -cells) together with face and degeneracy maps which satisfy the "simplicial identities." I should write more about how this notion arises from topology, in particular the singular complex. That in turn would be a good time to relate all this back to topology (nerves, geometric realization, ...) which is important.

### 0.1.2 (12/1) Why simplicial sets, simplicial complexes

I had stuff written here. But it was incomplete, and the "story" here is an aside I want to write about a bit more carefully at some point. I'm leaving this day blank for the time being.

### 0.1.3 (12/4) Basic structure in sSet

We need to make some terminology regarding / record examples of simplicial sets.

**Definition 0.1.4.** The *standard  $n$ -simplex*  $\Delta^n$  is the simplicial set represented by  $[n]$ , i.e.  $\Delta^n := \mathbf{Hom}_\Delta(-, [n])$ .

**Definition 0.1.5.** Let  $X_\bullet, Y_\bullet$  be simplicial sets. We say  $Y_\bullet$  is a *simplicial subset* of  $X_\bullet$  if  $Y_n \subseteq X_n$  and  $Xf|_{Y_n} = Yf$  for every  $n \geq 0$  and simplicial operator  $f$ . In other words, the action of operators on  $Y$  is the restriction of their action on  $X$ . In other words,  $Y_\bullet$  is a subfunctor of  $X_\bullet$ .

**Proposition 0.1.6.** Let  $X_\bullet$  be a simplicial set. The Yoneda lemma asserts a bijection  $\text{Hom}_{\mathbf{sSet}}(\Delta^n, X_\bullet) \cong X_n$ . Under this bijection, each  $n$ -cell  $a \in X_n$  corresponds to a map  $f_a : \Delta^n \rightarrow X_\bullet$  satisfying  $f_a(\text{id}_{[n]}) = a$ .

**Definition 0.1.7.** Let  $X_\bullet$  be a simplicial set. By the above, we may identify its  $n$ -cells with maps  $\Delta^n \rightarrow X_\bullet$ . Call a cell  $a \in X_n$  *degenerate* if it factors as  $\Delta^n \rightarrow \Delta^m \rightarrow X_\bullet$  for some  $m < n$ . (See [Lur22, Tag 0011] for equivalent conditions.)

**Proposition 0.1.8.** The standard simplex  $\Delta^n$  has a unique non-degenerate  $n$ -simplex, that arising from  $\text{id}_{[n]}$ . We may call this the *generator* of  $\Delta^n$ .

**Definition 0.1.9** (Boundary of  $\Delta^n$ ). Define a simplicial subset  $\partial\Delta^n$ , the *boundary of  $\Delta^n$* , by

$$(\partial\Delta^n)_k := \{\text{non-surjective maps } [k] \rightarrow [n]\} \subseteq \text{Hom}_{\Delta^{op}}([k], [n]).$$

**Proposition 0.1.10.** The boundary of  $\Delta^n$  is the maximal proper simplicial subset of  $\Delta^n$ .

**Definition 0.1.11** (Horns in  $\Delta^n$ ). For  $0 \leq i \leq n$ , define a simplicial subset  $\Lambda_i^n$ , the  *$i$ -th horn in  $\Delta^n$* , by

$$(\Lambda_i^n)_k := \{f \in \text{Hom}_{\Delta^{op}}([k], [n]) : f([k] \cup \{i\}) \neq [n]\}.$$

In other words, its cells are those maps “missing something besides  $i$ .” A horn  $\Lambda_i^n$  is called *outer* if  $i \neq 0, n$  and *inner* otherwise.

Any simplicial operator  $f : [m] \rightarrow [n]$  factors through its image, i.e. we can uniquely write  $f = f^{inj} f^{surj}$ , a surjection followed by an injection. Furthermore, this is unique. We get the following.

**Proposition 0.1.12.** Let  $\sigma : \Delta^n \rightarrow X_\bullet$  be an  $n$ -cell of  $X_\bullet$ . Then  $\sigma$  factors uniquely as

$$\Delta^n \xrightarrow{\alpha} \Delta^m \xrightarrow{\tau} X_\bullet,$$

Where  $\alpha$  represents a surjection  $[n] \rightarrow [m]$  and  $\tau$  is not degenerate. Call  $m$  the *dimension* of the cell  $\sigma$ . (My notation, maybe poor, not that important.)

So, degenerate  $n$ -simplices are just non-degenerate simplices in a lower dimension (their “dimension”), trying to bite off more than they can chew.

**Definition 0.1.13** (Skeleta). Let  $X_\bullet$  be a simplicial set. For  $k \geq -1$ , define a simplicial subset  $\text{sk}_k(X_\bullet)$ , the  *$k$ -skeleton* of  $X_\bullet$ , by

$$(\text{sk}_k(X_\bullet))_n := \{n\text{-simplices of } X_\bullet \text{ with dimension at most } k\}.$$

**Remark 0.1.14.** The face maps  $d^i : [n-1] \rightarrow [n]$  induce maps  $d^i : \Delta^{n-1} \rightarrow \Delta^n$  via post-composition. Now, consider an  $n$ -cell  $a \in X_n$  and its representation  $a : \Delta^n \rightarrow X_\bullet$ . We have that  $d_i(a) \in X_{n-1}$  is represented by  $ad^i$ .

## 0.1.4 (12/6) Colimits in/functors out of sSet

Today I want to understand part of Akhil’s notes, about functors out of  $\mathbf{sSet}$ . This is closely related to understanding colimits in  $\mathbf{sSet}$ , by general theory for presheaf categories. So we also want to understand colimits in  $\mathbf{sSet}$ . (And we should want to understand these regardless.) Let’s go over this.

Here’s a standard structure result for presheaf categories.

**Proposition 0.1.15.** If a category  $\mathcal{C}$  is small, then every presheaf on  $\mathcal{C}$  is canonically the colimit of representable presheaves. In particular, every simplicial set is canonically the colimit of standard simplices.

*Proof.* This is written out in Akhil’s notes. I’ll give the idea. Also see [Lur22, Remark 00X5].

Consider a presheaf  $F : \mathcal{C}^{op} \rightarrow \mathbf{Set}$ . We associate to  $F$  the category  $\mathbf{D}_F$  with

- Objects: morphisms from represented presheaves to  $F$ , i.e. arrows  $[-, X] \rightarrow F$ ; and
- Morphisms: morphisms between represented presheaves such that the obvious triangle commutes.

There is a functor  $\phi_F : D_F \rightarrow \text{PShv}(\mathcal{C})$  which sends objects  $[-, X] \rightarrow F$  to  $[-, X]$ . By construction, for each object  $c \in D_F$ , there is a morphism  $\phi_F(c) \rightarrow F$ , and the diagram described by  $\phi_F$  together with these morphisms commutes. We therefore have a distinguished morphism

$$\lim_{D_F} \phi_F \rightarrow F.$$

This map turns out to be an isomorphism.  $\square$

Hereafter, denote by  $\bar{\mathcal{C}}$  the category of presheaves on  $\mathcal{C}$ .

Suppose  $\mathcal{D}$  is cocomplete. We want to understand functors  $\bar{F} : \bar{\mathcal{C}} \rightarrow \mathcal{D}$ . The previous proposition says that objects in  $\bar{\mathcal{C}}$  are colimits of representables. So, if  $\bar{F}$  preserves colimits, then  $\bar{F}$  is determined by  $\bar{F}|_{\mathcal{C}}$ , i.e. what it does to  $\mathcal{C}$  (embedded via Yoneda). We've described an injection of sets

$$\text{Fun}'(\bar{\mathcal{C}}, \mathcal{D}) \hookrightarrow \text{Fun}(\mathcal{C}, \mathcal{D}). \quad (16)$$

Here,  $\text{Fun}'$  denotes the set of colimit-preserving functors.

Conversely, suppose given a functor  $F : \mathcal{C} \rightarrow \mathcal{D}$ . Does it extend along the Yoneda embedding to a functor  $\bar{F} : \bar{\mathcal{C}} \rightarrow \mathcal{D}$ ? We can do something here, let me write it out:

- (1) As above, for each presheaf  $G : \mathcal{C}^{op} \rightarrow \text{Set}$ , consider it as a colimit of  $\phi_G : D_G \rightarrow \mathcal{C}$ . (We can do this because it lands in represented functors.)
- (2) This is 'functorial' in the following sense: a morphism  $G \rightarrow H$  induces a functor  $D_G \rightarrow D_H$  such that the obvious triangle commutes.
- (3) Define a functor  $\bar{F} : \bar{\mathcal{C}} \rightarrow \mathcal{D}$  by

$$\bar{F}(G) := \text{colim}_{D_G} F \circ \phi_G.$$

This is a functor because of (2).

This functor  $\bar{F}$  really extends  $F$ , i.e. the obvious diagram commutes. For suppose  $G = [-, c]$ ; then  $D_G$  has a final object  $[-, c] \rightarrow [-, c]$ , therefore  $\bar{F}(G) = \text{colim}_{D_G} F \circ \phi_G = F(G)$ .

**Proposition 0.1.17.** *Suppose given a functor  $F : \mathcal{C} \rightarrow \mathcal{D}$  to a cocomplete category. Then the associated functor  $\bar{F} : \bar{\mathcal{C}} \rightarrow \mathcal{D}$  constructed above preserves all colimits. In fact,  $\bar{F}$  is a left adjoint. The right adjoint to  $\bar{F}$  is the functor defined by*

$$\mathcal{D} \ni d \mapsto (c \mapsto \text{Hom}_{\mathcal{D}}(Fc, d)) \in \bar{\mathcal{C}}.$$

**Proposition 0.1.18.** *Suppose given a functor  $F : \mathcal{C} \rightarrow \mathcal{D}$  to a cocomplete category. Then the mapping  $F \mapsto \bar{F}$  describes a bijection of sets*

$$\text{Fun}(\mathcal{C}, \mathcal{D}) \xrightarrow{\sim} \text{LeftAdjoints}(\bar{\mathcal{C}}, \mathcal{D}).$$

The proofs are short and formal.

**Corollary 0.1.19.** *If a functor  $\bar{F} : \bar{\mathcal{C}}^{op} \rightarrow \text{Set}$  takes colimits to limits, then it is representable.*

*Proof.* Suppose as given  $\bar{F}$ . By the above, it is left adjoint to some  $\bar{G} : \text{Set}^{op} \rightarrow \mathcal{C}$ . Define  $f := \bar{G}(\{pt\})$ , the image of the terminal object in  $\text{Set}^{op}$ . I claim that  $f$  represents  $F$ . (Insert short, formal proof; it's in Akhil's notes.)  $\square$

### 0.1.5 (12/23) The singular complex and geometric realization

Finals are over and I've had some time to wind down at home. Last time I worked through part of Akhil's notes about functors out of  $\mathbf{sSet}$ . (Emily Riehl talks about something similar in her notes, but I have not gotten through those, so let me say nothing about that right now.)

Next I want to relate  $\mathbf{Top}$ ,  $\mathbf{Cat}$ , and  $\mathbf{sSet}$ . This is the backdrop for the idea that higher categories "bridge" topology/homotopy theory and ordinary categories. Today I'll go over the relation of  $\mathbf{sSet}$  to  $\mathbf{Top}$ , by which I mean the adjunction

the geometric realization functor  $|-|$  the total singular complex functor.

There are a few ways to introduce this adjunction. Lurie, Charles, and Akhil each do it differently. As a matter of taste, I prefer Akhil's approach. (Possibly related: [Lur22, Tag 002D].) Lurie's approach has some important ideas behind it too, I think, but that is overruled because I am feeling sleepy today.

**Definition 0.1.20.** Define a functor  $|-| : \mathbf{\Delta} \rightarrow \mathbf{Top}$  as follows.

- Each object  $[n]$  is sent to the *topological  $n$ -simplex*  $\Delta_{top}^n \subseteq \mathbb{R}^{n+1}$ , defined as those  $(t_0, \dots, t_n)$  satisfying  $t_i \geq 0$  and  $\sum t_i = 1$  and given the subspace topology.
- Each morphism  $f : [m] \rightarrow [n]$  is sent to the map

$$(t_0, \dots, t_m) \mapsto (u_j), \quad u_j = \sum_{i:f(i)=j} t_i.$$

**Definition 0.1.21** (Geometric realization). Since  $\mathbf{Top}$  is cocomplete, according to Proposition 0.1.17 and 0.1.18 the functor of Definition 0.1.20 extends uniquely to a left adjoint  $|-| : \mathbf{sSet} \rightarrow \mathbf{Top}$ . We call this *geometric realization*.

In fact, as in Proposition 0.1.18, we know the right adjoint to geometric realization. It sends a space  $X$  to the simplicial set  $[n] \mapsto \mathrm{Hom}_{\mathbf{Top}}(|[n]| = \Delta_{top}^n, X)$ . This is an important construction I maybe should have defined earlier.

**Definition 0.1.22** (Singular complex). Let  $X$  be a space. Denote by  $\mathbf{Sing}(X)_\bullet$  the simplicial set given as follows.

- The  $n$ -cells are the continuous maps  $\Delta_{top}^n \rightarrow X$ , and
- Each simplicial operator  $f : [m] \rightarrow [n]$  acts by precomposing with the continuous map

$$\Delta_{top}^m \rightarrow \Delta_{top}^n, \quad (t_j) \mapsto (u_j = \sum_{f(i)=j} t_i).$$

We call  $\mathbf{Sing}(X)_\bullet$  the *singular complex* of  $X$ . We define a functor  $\mathbf{Sing}(-)_\bullet : \mathbf{Top} \rightarrow \mathbf{sSet}$  in the obvious way.

**Proposition 0.1.23.** *Prior discussion tells us that geometric realization  $|-| : \mathbf{sSet} \rightarrow \mathbf{Top}$  is left adjoint to the singular complex functor.*

**Proposition 0.1.24.** *Since geometric realization is a left adjoint, it commutes with colimits. Furthermore, geometric realization commutes with finite limits of compactly generated spaces.*

We will see later that this adjunction is homtopically well-behaved.

I next want to describe geometric realization. We already have the general construction laid out for us by Proposition 0.1.17 and the preceding discussion. Given  $X_\bullet$ , we will form the *category of simplices*, also called its *category of elements*, whose elements are the morphisms  $\Delta^n \rightarrow X_\bullet$  (i.e., the cells of  $X_\bullet$ ), and we take the colimit of  $|-|$  restricted to this subcategory. (This is not circular since we are really applying the "baby" geometric realization to the simplex category, Yoneda embedded.)

**Definition 0.1.25.** Given  $X_\bullet \in \mathbf{sSet}$ , its *category of simplices* or *category of elements* has as objects all morphisms  $\Delta^n \rightarrow X_\bullet$  for every  $n$ , and morphisms the maps  $\Delta^m \rightarrow \Delta^n$  making the obvious diagram commute. We write this category  $\mathbf{el}(X)$ .

This category of elements/simplices  $\text{el}(X)$  is precisely the category  $D_X$  described on (12/6) with  $C = \mathbf{\Delta}$ . (Lurie writes this  $\mathbf{\Delta}_X$ .) Also as noted there, there is a natural functor  $\phi_X : \text{el}(X) \rightarrow \mathbf{sSet}$ . Geometric realization is by definition the colimit

$$|X| \cong \text{co lim}_{\text{el}(X)} | - | \circ \phi_X.$$

Here, we are thinking of the "baby" geometric realization defined only on  $\mathbf{\Delta}$ .

**Remark 0.1.26.** General machinery gave us geometric realization. I think there are a few things worth saying about this, but I don't totally know what. I'll leave this remark here as a "to-do." Some possibly related keywords and references: "Grothendieck construction," "Kan extension," [nLab](#), [\[Rie, §4\]](#), and [Subsection 01Q7](#).

## 0.2 January 2023

### 0.2.1 (1/23) Plans have changed, nerves of categories

I've gone radio silent for a month. One big reason why is that I am busy this semester. Another is that some mutuals want to organize a reading group/seminar similar, but not identical to, what I've been trying to do here, and I may join them. Maybe the biggest difference is that they want to focus on Charles' quasicategory notes (under Charles' supervision).

This will probably mean repeating myself a bit while I change tracks to Charles' notes.

In any case, I want to talk about the nerve of a category. This is part of the basic "Spaces, categories, and simplicial sets" picture. In particular, the nerve of a category is a simplicial set encoding that category.

**Definition 0.2.1.** Let  $\mathbf{C}$  be a category. Define a simplicial set  $NC$ , the *nerve* of  $\mathbf{C}$  to have as cells  $(NC)_n := \text{Hom}_{\text{Cat}}([n], \mathbf{C})$  and so that operators  $f : [m] \rightarrow [n]$  act by precomposition. This defines the *nerve functor*  $N : \text{Cat} \rightarrow \text{sSet}$ .

Here's a feel for the structure of a nerve. The  $n$ -cells of  $NC$  may be canonically identified with the set of length  $n$  tuples of composable arrows in  $\mathbf{C}$ . The 0-cells in particular may be identified with objects of  $\mathbf{C}$ . An operator  $f : [m] \rightarrow [n]$ , or in Charles' notation  $\langle f_1, \dots, f_m \rangle$ , acts by taking  $n$ -strings of composable arrows and "collapsing edges" by composing the arrows, those collapsed edges being determined by the  $f_i$ . (At least that's how I try to think about it. I think that's correct. UPDATE: Yes this is correct, see Charles' notes, Proposition 4.4.) For instance,  $\langle 0, 2 \rangle^*$  takes a pair of composable arrows  $(f, g) \in (NC)_2$  and sends them to their composite  $gf \in (NC)_1$ . See also Charles notes, p. 13.

Now we ask a nascent question: can we characterize nerves of categories?

**Proposition 0.2.2.** *Let  $X$  be a simplicial set. For  $n \geq 2$ , consider the function*

$$\phi_n : X_n \rightarrow \{(g_i) \in (X_1)^n : g_j \langle 1 \rangle = g_{j+1} \langle 0 \rangle \text{ for all } i\}$$

*(The latter set being the collection of "n-paths" of 1-cells in  $X$ ) Which acts by  $a \mapsto (a \langle 0, 1 \rangle, \dots, a \langle n-1, n \rangle)$ . These  $\phi_n$  are bijections for all  $n \geq 2$  if and only if  $X$  is the nerve of a category.*

Maybe a lazy way to digest this is that "a simplicial set is the nerve of a category iff, thinking of  $n$ -cells as length  $n$  strings of arrows, their 1-dimensional structure exactly reflects the structure that should arise from the existence and uniqueness of composites."

**Proposition 0.2.3.** *The nerve functor  $N : \text{Cat} \rightarrow \text{sSet}$  is fully-faithful. That is, morphisms of nerves  $NC \rightarrow ND$  correspond exactly to functors  $\mathbf{C} \rightarrow \mathbf{D}$ .*

### 0.2.2 (1/26) Spines

We characterized nerves as those simplicial sets whose  $n$ -cells were exactly determined by the collection of length  $n$  strings of "composable" 1-cells, in the obvious way. This captures the existence and uniqueness of composites for morphisms in a category. We can go about this characterization a bit more systematically.

**Definition 0.2.4.** Let  $n \geq 0$ . The *spine* of the standard  $n$ -simplex  $\Delta^n$  is the simplicial subset defined by

$$(\text{Spine}^n)_k := \{(f_0, \dots, f_k) : [k] \rightarrow [n] : f_k \leq f_0 + 1\} \subseteq \Delta_k^n.$$

Informally, the spine is the set of vertices of  $\Delta^n$  together with the arrows between adjacent vertices (considered with their total ordering).

**Proposition 0.2.5.** *Let  $X$  be a simplicial set. For every  $n \geq 0$ , the map*

$$\text{Hom}(\text{Spine}^n, X) \rightarrow \{(a_i) \in (X_1)^n : a_i \langle 1 \rangle = a_{i+1} \langle 0 \rangle\} \tag{6}$$

*Given by  $f \mapsto (f \langle 0, 1 \rangle, \dots, f \langle n-1, n \rangle)$  is a bijection.*

Pictorially, I think this is obvious. Here's a clean proof.



*Proof.* One point we need: we previously talked about colimits in  $\mathbf{sSet}$ . Or at least I intended to. Here's the main fact: *a colimit of simplicial sets  $X_\alpha$  exists and has as its  $n$ -cells the colimit of the  $n$ -cells of the  $X_\alpha$ .* This is true for presheaves in general; we say their (co)limits are "computed objectwise."

Another point we need: here's a definition. Suppose  $S$  is a totally ordered set. We denote by  $\Delta^S$  the simplicial set having  $(\Delta^S)_n := \{\text{order-preserving maps } [n] \rightarrow S\}$ . If  $S$  is finite and nonempty, there is a unique isomorphism  $\Delta^{|S|-1} \cong \Delta^S$ . In the case that  $S \subseteq [n]$ , this is a good way to notate subcomplexes of  $\Delta^n$ .

Here's a fact I won't prove: *given a subcomplex  $K \subseteq \Delta^n$ , writing  $A$  for the poset of  $S \subseteq [n]$  such that  $\Delta^S \subseteq K$ , the canonical map  $\text{colim}_{S \in A} \Delta^S \rightarrow K$  is an isomorphism.*

Finally, our proposition: in the case that  $K = \text{Spine}^n$ , the poset  $A$  consists of sets of the form  $\{j\}$  and  $\{j+1\}$ , and we have that  $\text{colim}_{S \in A} \Delta^S \cong \text{Spine}^n$ . Now:

$$\text{Hom}(\text{Spine}^n, X) \cong \text{Hom}(\text{colim}_{S \in A} \Delta^S, X) \cong \lim_A \text{Hom}(\Delta^S, X).$$

See that the latter set is precisely the RHS of (6). □

Maybe the key observation is that  $\Delta^n$  is "generated" precisely by the arrows of  $\text{Spine}^n$ . (Make this formal? Say this better? Well, this is how I think about it.)

**Proposition 0.2.7.** *A simplicial set  $X$  is the nerve of some category if and only if for each  $n \geq 2$ , every morphism  $f : \text{Spine}^n \rightarrow X$  extends uniquely along the inclusion  $\text{Spine}^n \hookrightarrow \Delta^n$ .*

*Proof.* The unique extension condition is equivalent to bijectivity of the restriction  $\text{Hom}(\Delta^n, X) \rightarrow \text{Hom}(\text{Spine}^n, X)$ . By Proposition 0.2.5, the latter set is isomorphic to

$$\{(a_i) \in (X_1)^n : a_i \langle 1 \rangle = a_{i+1} \langle 0 \rangle\}.$$

Then the desired result is immediate considering Proposition 0.3.34. □

### 0.2.3 (1/30) Inner Horns

Recall that for each  $n$  and  $0 \leq i \leq n$  we defined the  $i$ -th horn  $\Lambda_k^n \subseteq \Delta^n$  to have as  $k$ -cells those cells  $f : [k] \rightarrow [n]$  of  $\Delta^n$  which "miss something other than  $i$ ," i.e. those satisfying  $f([n]) \cup \{i\} \neq [n]$ . If  $j \neq 0, n$  then we called  $\Lambda_j^n$  an *inner horn*.

Drawing some pictures of horns and thinking of 1-cells as arrows, we think of inner horns as those collections of arrows that "should be composable." Similar to how we handled spines, we may think to characterize nerves as those simplicial sets whose inner horns have unique extensions. By our analogy comparing inner horns to composable arrows, this unique extension condition is analogous the existence and uniqueness of composites.

**Theorem 0.2.8.** *A simplicial set  $X$  is the nerve of some category if and only if for every  $n \geq 2$  and inner horn  $\Lambda_j^n$ , every morphism  $\Lambda_j^n \rightarrow X$  extends uniquely along  $\Lambda_j^n \hookrightarrow \Delta^n$ .*

*Proof.* Charles gives a full proof on p. 21 of his notes. The "only if" direction is not complicated. For the "if" direction:

- We can construct a category  $C$  whose nerve realizes  $X$  explicitly. The objects and morphisms are specified by  $X_0$  and  $X_1$ .
- Existence *and* uniqueness of fillers are necessary for the existence and uniqueness of composites.
- Existence of a filler for  $\Lambda_1^3$  or  $\Lambda_2^3$  is necessary for the associative law to hold.
- Then one exhibits an isomorphism  $X \rightarrow NC$ .

□

## 0.3 February 2023

### 0.3.1 (2/4) Quasicategories

A *quasicategory* or  $\infty$ -*category* is a simplicial set  $X$  such that every inner horn  $\Lambda_j^n \rightarrow X$  has a filler (i.e. an extension along  $\Lambda_j^n \hookrightarrow \Delta^n$ .) We have shown that ordinary categories are precisely those quasicategories with *unique* horn extensions.

**Definition 0.3.1.** Some terminology. Let  $X, Y$  be quasicategories.

- *Objects* of  $X := X_0$ .
- *Morphisms* of  $X := X_1$ .
- *Identity morphism* of  $x \in X_0 := x\langle 0, 0 \rangle$ .
- *Products of quasicategories* are just their products as simplicial sets.
- *Coroducts of quasicategories* are just their products as simplicial sets.
- A *morphism of quasicategories*  $X \rightarrow Y$  is a map of simplicial sets.
- A *Natural transformation*  $f_0 \implies f_1$  of functors  $f_0, f_1 : X \rightarrow Y$  is a map of simplicial sets  $\phi : X \times \Delta^1 \rightarrow Y$  such that  $\phi|_{X \times \{i\}} = f_i$ .

It's a fact to be proven that the (co)product of quasicategories is again a quasicategory. Here's more terminology.

**Definition 0.3.2.** Let  $X$  be a simplicial set. Let  $\sim$  denote the equivalence relation on the set  $\coprod X_n$  of cells of  $X$  generated by the relation which identifies a cell  $a$  with any other cell of the form  $af$  for some simplicial operator  $f$ . A *connected component* of  $X$  is an equivalence class of  $\sim$ . We write  $\pi_0 X$  for the set of equivalence classes. A simplicial set is called *connected* if  $\pi_0 X$  is a singleton.

**Proposition 0.3.3.** *Let  $X$  be a simplicial set and suppose  $x, y$  are cells in the same connected component of  $X$ , i.e.  $x = yf$  for some  $f : [m] \rightarrow [n]$ . If  $F : X \rightarrow Y$  is a map of simplicial sets, then  $F(yf) = F(y)Y(Xf)$ . The latter is  $F(x)$  by hypothesis, thus  $F(x) \sim F(y)$ . So morphisms  $F : X \rightarrow Y$  induce maps  $\pi_0 X \rightarrow \pi_0 Y$  on connected components.*

**Proposition 0.3.4.** *The induced map  $\pi_0(X \times Y) \rightarrow \pi_0(X) \times \pi_0(Y)$  is a bijection.*

### 0.3.2 (2/6) Sub, opposite quasicategories

**Definition 0.3.5.** Let  $C$  be a quasicategory. A subcomplex  $C' \subseteq C$  is called a *subcategory* of  $C$  if for all  $n \geq 2$  and  $0 < k < n$ , every  $f : \Lambda_k^n \rightarrow C$  such that  $f(\Lambda_k^n) \subseteq C'$  extends "into  $C'$ ," i.e. extends to a map  $f : \Delta^n \rightarrow C'$ .

It is clear that subcategories of quasicategories are quasicategories.

**Definition 0.3.6.** Let  $C$  be a simplicial set. A simplicial subset  $C' \subseteq C$  is called *full* if

- For every cell  $\sigma : \Delta^n \rightarrow C$  such that for every  $0 \leq i \leq n$  the vertex  $\sigma(i) \in C$  belongs in  $C'$ , the cell  $\sigma$  belongs in  $C'$ .

If  $C$  is a quasicategory and  $C'$  is a full subcomplex, then it is a quasicategory. In this case we say  $C'$  is a *full subcategory*.

Next we can define the opposite of a quasicategory. In ordinary categories, we do this by reversing composition. We can do something similar once we identify an involution on the simplex category  $\mathbf{\Delta}$ .

**Definition 0.3.7.** Define an involution functor  $\text{op} : \mathbf{\Delta} \rightarrow \mathbf{\Delta}$  as follows.

- It acts as the identity on objects.
- It sends the morphism  $\langle f_0, \dots, f_m \rangle : [m] \rightarrow [n]$  to its "reverse"  $\langle n - f_m, \dots, n - f_0 \rangle : [m] \rightarrow [n]$ .

**Definition 0.3.8.** Let  $X : \Delta^{op} \rightarrow \text{Set}$  be a simplicial set. We define the *opposite simplicial set* as  $X^{op} := X \circ \text{op}$ .

One sees that  $(\Delta_j^n)^{op} \cong \Delta_{n-j}^n$  and that  $(NC)^{op} = N(C^{op})$ . The former fact ensures that opposites of quasicategories are quasicategories. The latter ensures that this notion of opposites restricts to the usual 1-categorical notion.

### 0.3.3 (2/7) Examples of $\infty$ -categories

**Example 0.3.1.** The nerve  $NC$  of a category  $C$  is a quasicategory. This is immediate by our characterization of nerves (Theorem 0.2.8).

**Example 0.3.2.** The singular complex  $\text{Sing}(X)$  of a space  $X$  is a quasicategory. In fact, we can say a little bit more. Denote by  $(\Lambda_j^n)_{top}$  the *topological horn*, defined as you might expect:

$$(\Lambda_j^n)_{top} := \{t \in \Delta^n : t_i = 0 \text{ for some } i \in [n] \setminus \{j\}\}.$$

It is clear that for any  $j$ , the simplex  $\Delta_{top}^n$  retracts onto  $(\Lambda_j^n)_{top}$ . Thus by precomposing with the retract we get, for every  $j$ , an inverse to the restriction

$$\text{Hom}(\Delta^n, \text{Sing}X) \rightarrow \text{Hom}(\Lambda_j^n, \text{Sing}X).$$

In other words, we can fill every  $\Lambda_j^n \rightarrow \text{Sing}X$  via the retract. This shows that  $\text{Sing}(X)$  is a quasicategory. In fact, we've shown all horns fill, not just inner horns. We call such simplicial sets *Kan complexes*.

**Example 0.3.3.** Let  $A$  be an abelian group and  $d \geq 0$  an integer. In spaces, the *Eilenberg-MacLane spaces*  $K(A, d)$  represent  $H^d(-; A)$ . We will define an analogous simplicial set  $K = K(A, d)$ , the *Eilenberg-MacLane objects* in  $\mathbf{sSet}$ , like so.

- An element of  $K_n$  is a collection  $(a_\delta \in A)_\delta$ , where the index  $\delta$  occurs over all operators  $\delta : [d] \rightarrow [n]$ , so that
  - If  $\delta$  is not injective,  $a_\delta = 0$ ; and
  - For each operator  $\gamma : [d+1] \rightarrow [n]$  we have  $\sum_{j=0}^{d+1} (-1)^j a_{\delta d^j} = 0$ .
- For each operator  $f : [m] \rightarrow [n]$  and  $a \in K_n$ , we define  $(af)_\delta := a_{f\delta}$ .

These  $K(A, d)$ 's are  $\infty$ -categories. In fact, they are simplicial abelian groups, which are always Kan complexes. In  $\mathbf{sSet}$ , they represent *normalized  $d$ -cocycles with values in  $A$* . (See Charles' notes, p. 29.)

**Example 0.3.4.** There is a simplicial set of ordinary categories, denoted  $\mathbf{Cat}_1$ . We define it like so.

- Each  $n$ -cell  $(\mathbf{Cat}_1)_n$  is the data of  $(C_i, F_{ij}, \zeta_{ijk})$  where
  - For each  $i \in [n]$ ,  $C_i$  is a category,
  - For each  $i \leq j$  in  $[n]$ ,  $F_{ij} : C_i \rightarrow C_j$  is a functor, and
  - For each  $i \leq j \leq k$  in  $[n]$ ,  $\zeta_{ijk} : F_{ik} \rightarrow F_{jk}F_{ij}$  is a natural isomorphism,
  - And furthermore, these data are subject to certain basic properties (e.g.  $F_{ii} = \text{id}_{C_i}$ ).
- Each operator  $f : [m] \rightarrow [n]$  acts on an  $n$ -cell  $(C_i, F_{ij}, \zeta_{ijk})$  by composing with the indices.

The simplicial set  $\mathbf{Cat}_1$  is an  $\infty$ -category. Let's discuss fillers.

- A 2-horn  $\Lambda_1^2 \rightarrow \mathbf{Cat}_1$  is the data of functors  $C_0 \xrightarrow{F_{01}} C_1 \xrightarrow{F_{12}} C_2$ . An extension is the data of a functor  $F_{02} : C_0 \rightarrow C_2$  and a natural isomorphism  $\zeta_{012} : F_{12}F_{01} \xRightarrow{\cong} F_{02}$ . An obvious *but not necessarily unique* candidate is  $F_{02} := F_{12}F_{01}$ .

- The data of a 3-horn  $\Lambda_1^3 \rightarrow \text{Cat}_1$  is a bit of a picture. A filler amounts to finding a natural isomorphism to fill the following diagram.

$$\begin{array}{ccc}
 F_{03} & \xrightarrow{\zeta_{013}} & F_{13}F_{01} \\
 \downarrow & & \downarrow \zeta_{123}F_{01} \\
 F_{23}F_{02} & \xrightarrow{F_{23}\zeta_{012}} & F_{23}F_{12}F_{01}
 \end{array}$$

We can always find this and it is unique, since we required the  $\zeta$ 's to be natural *isomorphisms*.

### 0.3.4 (2/8) The fundamental category of a simplicial set

The fundamental groupoid  $\pi_{\leq 1}X$  of a space  $X$  can be recovered from its singular complex  $\text{Sing}(X)$ . We will recast this construction  $\pi_{\leq 1}X$  for any  $\infty$ -category. The result will no longer be a groupoid in general (it will only be so for Kan complexes, I think). Let's see how far we get.

First we will look at a certain construction for all simplicial sets. By its definition, it's essentially a left adjoint to the nerve functor.

**Definition 0.3.9.** Let  $X$  be a simplicial set. A *fundamental category of  $X$*  is a category  $hX$  and a map  $\alpha : X \rightarrow N(hX)$  such that for every nerve  $NC$ , the restriction

$$\alpha^* : \text{Hom}(N(hX), NC) \rightarrow \text{Hom}(X, NC)$$

is a bijection. This characterizes  $hX$  up to unique isomorphism, if it exists. (It always does.)

**Proposition 0.3.10.** *Every simplicial set has a fundamental category.*

*Proof.* Charles sketches this on p. 30. The objects of our category are  $X_0$ . The morphisms are (those generated by) the edges  $X_1$ , where we identify composites according to the 2-cells of  $X$ . So we turn  $X$  into a category in the most obvious way, flattening the higher-categorical structure in the process. The map  $\alpha : X \rightarrow N(hX)$  is the one you'd expect.  $\square$

**Proposition 0.3.11.** *The fundamental category describes a functor  $h : \text{sSet} \rightarrow \text{Cat}$ , and this functor is left adjoint to the nerve functor  $N$ .*

### 0.3.5 (2/9) Homotopy for $\infty$ -categories

Now we start down a long, dark path. Neither of these adjectives matter up-to-homotopy, however.

**Definition 0.3.12.** Let  $C$  denote an  $\infty$ -category and let  $f, g : x \rightarrow y$  be two morphisms between objects  $x, y$  in  $C$ . A *homotopy from  $f$  to  $g$*  is a 2-cell  $a \in C_2$  such that  $a_{01} = f$ ,  $a_{12} = \text{id}_y$ , and  $a_{02} = g$ .

**Proposition 0.3.13.** *The homotopy relation is an equivalence relation on  $\text{Hom}_C(x, y)$ , i.e. the set of edges  $i$  with  $i_0 = x$  and  $i_1 = y$ . Thus we may unambiguously say maps are (or are not) *homotopic* and speak of *homotopy classes*.*

**Remark 0.3.14.** The existence of inner horn extensions is necessary for this relation to be symmetric and transitive. So quasicategories stand out amongst simplicial sets as those having a good notion of homotopy.

**Proposition 0.3.15.** *Maps  $f, g$  are homotopic in  $C$  if and only if they are homotopic in  $C^{\text{op}}$ .*

It's maybe a little weird that " $f$  homotopic to  $g$ " is a slightly asymmetric definition, in that even if  $f$  is homotopic to  $g$ , the data of a homotopy does not suffice to get a homotopy from  $f$  to  $g$  in  $C^{\text{op}}$ . I don't think this matters much, in light of the previous proposition. Lurie also gives an alternate, symmetric notion of homotopy to address this point [Lur22, Tag 00V0].

Suppose as given  $f \in \text{Hom}_C(x, y)$  and  $g \in \text{Hom}_C(y, z)$ . We say an edge  $h \in \text{Hom}_C(x, z)$  is a *composite* of  $(g, f)$  if there exists a 2-cell  $a$  such that (what you expect).

**Proposition 0.3.16.** *Composition respects the homotopy relation on morphisms. Thus, composites are unique up to homotopy.*

**Definition 0.3.17.** Let  $C$  be an  $\infty$ -category. Its *homotopy category*  $hC$  is the category having as objects  $C_0$  and as morphisms the homotopy classes of morphisms of  $C$ .

Now we have defined the *fundamental category of a simplicial set* and the *homotopy category of an  $\infty$ -category*. The fundamental category is supposed to be the homotopy category to some extent, so we should compare these two notions where they are both defined ( $\infty$ -categories).

**Definition 0.3.18.** Let  $C$  be an  $\infty$ -category. There is a natural map  $\pi : C \rightarrow N(hC)$  that “passes to homotopy.” It acts like so.

- An object is sent to itself (note  $C_0 = (hC)_0 = N(hC)_0$ ).
- A morphism  $f$  is sent to its homotopy class.
- An  $n$ -cell  $a \in C_n$  is sent to the unique  $\pi(a) \in N(hC)_n$  that satisfies  $\pi(a)_{i-1,i} = \pi(a_{i-1,i})$  for all  $i$ . (See also [Lur22, Construction 004G].)

This map  $\pi : C \rightarrow N(hC)$  is compatible with simplicial operators, in the sense that given a cell  $a \in C_n$ , one has  $[a_{01}] \circ \cdots \circ [a_{n-1,n}] = [a_{0n}]$ .

**Proposition 0.3.19.** *If  $C$  is an ordinary category, then  $f \simeq g$  iff  $f = g$ . Thus if an  $\infty$ -category  $C$  is isomorphic to a nerve of a 1-category, then  $\pi : C \rightarrow N(hC)$  is an isomorphism, so it must be isomorphic to the nerve of its homotopy category.*

**Proposition 0.3.20** (Universal property of homotopy category). *Let  $C$  be an  $\infty$ -category and  $D$  a small category. If  $f : C \rightarrow ND$  is a map of simplicial sets, then there exists a unique map  $g : N(hC) \rightarrow ND$  such that  $f = g \circ \pi$ .*

*Proof.* We will construct  $g$ . We will do so by constructing a functor  $g : hC \rightarrow D$ . On objects  $c \in \text{ob}(hC) = C_0$ , we define  $g(c) := f(c) \in (ND)_0 = \text{ob}(D)$ . On morphisms, we define  $g([h]) := f(h)$ . This is well-defined, for if  $h \simeq h'$  exhibited by some  $a \in C_2$ , then  $\phi(a) \in (ND)_2$  exhibits the identity  $f(h') = \text{id} \circ h$ .  $\square$

**Corollary 0.3.21.** *The homotopy category construction is left adjoint to the nerve functor:*

$$h : \mathbf{qCat} \rightleftarrows \mathbf{Cat} : N$$

(Easy to-do: homotopy category of products.)

### 0.3.6 (2/12) About composition in $\infty$ -categories

Let  $C$  be an  $\infty$ -category. Let  $x, y, z \in C_0$  be objects and let  $f \in \text{Hom}_C(x, y)$  and  $g \in \text{Hom}_C(y, z)$  be morphisms (i.e. 1-cells starting/ending at their domains/targets.) Last time we defined a *composite of morphisms  $f, g$  in  $C$*  to be any  $h \in \text{Hom}_C(x, z)$  such that there exists a 2-cell  $a \in C_2$  such that  $a_{01} = f$ ,  $a_{12} = g$ , and  $a_{02} = h$ . Composites exist and are unique up-to-homotopy (thus we can compose homotopy classes), but are not uniquely determined in general. We may ask whether every representative of a homotopy class of a composite can be realized on-the-nose as the extension of its (compositees?) The answer is yes.

**Proposition 0.3.22.** *If  $f : x \rightarrow y, g : y \rightarrow z$ , and  $h : x \rightarrow z$  are morphisms in an  $\infty$ -category  $C$ , then  $h \in [g] \circ [f]$  if and only if  $h$  is a composite of  $f$  with  $g$ , i.e. there exists  $u \in C_2$  satisfying*

$$u|_{\Delta^{0,1}} = f, \quad u|_{\Delta^{1,2}} = g, \quad u|_{\Delta^{0,2}} = h.$$

The proof is nice. I’d reproduce it here but I don’t feel like making that diagram right now.

### 0.3.7 (2/13) Isomorphisms and inverses in $\infty$ -categories

Denote by  $C$  an  $\infty$ -category and  $f : x \rightarrow y$  a morphism in  $C$ . We say  $f$  is an *isomorphism* or an *equivalence* if  $[f]$  is an isomorphism in  $hC$ . Unwinding a bit, this is equivalent to the existence of a  $g : y \rightarrow x$  such that  $[f] \circ [g] = [1_y]$  and  $[g] \circ [f] = [1_x]$ . The property of being an isomorphism is related to inverses; the following is elementary.

**Proposition 0.3.23.** *Let  $f : x \rightarrow y$  be a morphism in an  $\infty$ -category  $C$ . A morphism  $g : y \rightarrow x$  is called a preinverse to  $f$  if  $[f] \circ [g] = [id_y]$ , and a postinverse if  $[g] \circ [f] = [id_x]$ . If  $g$  is both, we call it an inverse. TFAE.*

1.  $f$  is an isomorphism.
2.  $f$  has an inverse.
3.  $f$  has a preinverse and a postinverse.
4.  $f$  has a preinverse with a preinverse.
5.  $f$  has a postinverse with a postinverse.

As for composites, inverses are not generally unique, but are so up-to-homotopy.

**Proposition 0.3.24.** *If  $F : C \rightarrow D$  is a map of quasicategories, then  $F$  sends isomorphisms to isomorphisms.*

*Proof.* Suppose that  $f : x \rightarrow y$  is an isomorphism in  $C$ . By Proposition 0.3.23,  $f$  admits an inverse  $g : y \rightarrow x$ . By definition, it satisfies  $[f] \circ [g] = [id_y]$ , so by Proposition 0.3.22 there exists  $u \in C_2$  witnessing  $id_y = f \circ g$ . By this, I mean the obvious identities with simplicial operators hold. Morphisms of simplicial sets commute with operators, hence  $F(u)$  witnesses  $id_{F(y)} = F(f) \circ F(g)$ . This shows that  $F(g)$  is a preinverse to  $F(f)$ . By an identical argument, one sees that  $F(g)$  is a postinverse. So  $F(g)$  is an inverse and we are done.  $\square$

### 0.3.8 (2/13) $\infty$ -groupoids, cores, and Kan complexes

Here are some definitions.

- An  $\infty$ -category  $C$  is called a *quasigroupoid* or  *$\infty$ -groupoid* if  $hC$  is a groupoid, i.e. if every morphism is an isomorphism.
- For an ordinary category  $C$ , its *core*  $C^{core}$  is the subcategory with the same objects and only the isomorphisms of  $C$ .
- For an  $\infty$ -category  $C$ , its *core*  $C^{core}$  is the simplicial subset consisting of all cells of  $C$  whose edges are all isomorphisms.
- Recall that a simplicial set is called a *Kan complex* if all horns (not necessarily inner) have extensions.

Note that  $N(C^{core}) = (NC)^{core}$ , so our terminology is justified. Now here are some facts.

**Proposition 0.3.25.** *If  $C$  is an  $\infty$ -category, then  $\pi_0 C^{core} = \{\text{objects of } C\} / \cong$ .*

**Proposition 0.3.26.** *If  $C$  is an  $\infty$ -category, then  $C^{core}$  is a subcategory and an  $\infty$ -groupoid. Furthermore, every sub- $\infty$ -groupoid is contained in  $C^{core}$ . In other words,  $C^{core}$  is the maximal subcategory which is also an  $\infty$ -groupoid.*

**Proposition 0.3.27.** *Every Kan complex is an  $\infty$ -groupoid.*

*Proof.* Suppose that  $K$  is a Kan complex and  $f : x \rightarrow y$  is a morphism in  $K$ . Consider the horn  $u : \Lambda_0^2 \rightarrow K$  with  $u_{01} = f$  and  $u_{02} = id_x$ . Extending this horn gives us  $g := u_{12}$  with  $[g] \circ [f] = [id_x]$ . Thus, every morphism admits a preinverse, and this turns out to be sufficient for an  $\infty$ -category to be an  $\infty$ -groupoid.  $\square$

**Proposition 0.3.28** (Joyal's theorem; harder). *Every  $\infty$ -groupoid is a Kan complex.*

**Definition 0.3.29.** Since  $\text{Sing } X$  is a Kan complex, the proposition allows us to define the *fundamental  $\infty$ -groupoid* of a space  $X$  as  $\text{Sing } X$ .

### 0.3.9 (2/15) The functor quasicategory

The nerve functor  $N : \text{Cat} \rightarrow \text{sSet}$  is fully faithful, so functors of categories correspond to morphisms of their nerves. Maybe this suggests that if we want a “mapping space,” or really a “mapping  $\infty$ -category,” its 0- and 1-categorical structure should consist of morphisms  $X \rightarrow Y$  of simplicial sets and natural transformations between them. Morphisms are the same thing as maps  $X \times \Delta^0 \rightarrow Y$ . A natural transformation is a suitable map  $X \times \Delta^1 \rightarrow Y$ . This suggests the following.

**Definition 0.3.30.** Let  $X, Y$  be simplicial sets. Their *function complex* is the simplicial set  $\text{Fun}(X, Y)$  with

$$(\text{Fun}(X, Y))_n := \text{Hom}_{\text{sSet}}(\Delta^n \times X, Y).$$

**Proposition 0.3.31.** *There is a natural bijection*

$$\text{Hom}(X \times Y, Z) \xrightarrow{\sim} \text{Hom}(X, \text{Fun}(Y, Z)).$$

**Proposition 0.3.32.** *For ordinary  $C$  and  $D$ , one has  $N(\text{Fun}(C, D)) \cong \text{Fun}(NC, ND)$ .*

Eventually we will see that *function complexes to an  $\infty$ -category are  $\infty$ -categories*. This is what we want. We can't prove this yet.

### 0.3.10 (2/16) Lifting properties time — weakly saturated classes

My assessment to become a personal fitness trainer is approaching, so I'm shifting focus to that for a little while. I'll probably be leaving more to-do's than I should be.

Quasicategories are defined in terms of lifting properties. Now we will take some time to generally study lifting properties, which will be useful for studying quasicategories.

**Definition 0.3.33.** Let  $C$  be a category admitting small colimits. A class of morphisms  $A$  is called a *weakly saturated class* if it

1. Contains all isomorphisms,
2. Is closed under cobase change (also called pushouts), composition, transfinite composition, coproducts, and retracts. (See Charles p. 38 for the definitions.)

Given any class of morphisms  $S$ , its *weak saturation*  $\bar{S}$  is the smallest weakly saturated class containing  $S$ .

**Example 0.3.5.** Take  $C = \text{Set}$ . The weak saturation of  $\{\{0, 1\} \rightarrow \{1\}\}$  is the class of surjective maps. The weak saturation of  $\{\emptyset \rightarrow \{1\}\}$  is the class of injective maps.

**Example 0.3.6.** Take  $C = \text{Set}$ . The surjections/injections also arise as weak saturations. Of what?

**Proposition 0.3.34.** *Let  $S$  be a category with small colimits and let  $\mathcal{C}$  be a class of objects. Let  $\mathcal{A}$  be the class of maps with the following lifting property: if  $i : A \rightarrow B$  is in  $\mathcal{A}$ , then for every  $f : A \rightarrow C$  to an object of  $\mathcal{C}$ , we can fill the following diagram:*

$$\begin{array}{ccc} A & \xrightarrow{f} & C \\ \downarrow i & & \nearrow \\ B & & \end{array}$$

*Then  $\mathcal{A}$  is a weakly saturated class. (Example:  $S = \text{sSet}$ ,  $\mathcal{C} = \{\infty\text{-categories}\}$ ).*

*Proof.* To-do. (Worked out in meeting.) □

### 0.3.11 (2/16) Classes of horns, anodyne morphisms

As indicated, we are interested in  $\infty$ -categories, so we ought to study lifting properties of horns in particular. We make some definitions for this.

**Definition 0.3.35.** We define the following sets of horns.

$$\begin{aligned} \text{InnHorn} &:= \{\Lambda_k^n \hookrightarrow \Delta^n : 0 < k < n, n \geq 2\}, \\ \text{Horn} &:= \{\Lambda_k^n \hookrightarrow \Delta^n : 0 \leq k \leq n, n \geq 1\}, \\ \text{RHorn} &:= \{\Lambda_k^n \hookrightarrow \Delta^n : 0 < k \leq n, n \geq 1\}, \\ \text{LHorn} &:= \{\Lambda_k^n \hookrightarrow \Delta^n : 0 \leq k < n, n \geq 1\}. \end{aligned}$$

We call their weak saturations in  $\mathbf{sSet}$  the *(inner, right, left) anodyne morphisms*.

**Proposition 0.3.36.** *Monomorphisms of simplicial sets form a weakly saturated class. Therefore, since Horn consists of monomorphisms, its weak saturation must too. So (inner, right, left) anodyne maps are always monomorphisms.*

**Proposition 0.3.37.** *Let  $C$  be an  $\infty$ -category. If  $A \hookrightarrow B$  is an inner anodyne inclusion, then every  $f : A \rightarrow C$  extends to  $B$ .*

*Proof.* Let  $\mathcal{A}$  denote the set of maps of simplicial sets  $X \rightarrow Y$  which extend along every map  $X \rightarrow C$ . ( $C$  is fixed here.) Since  $C$  is a quasicategory, we have  $\text{InnHorn} \subseteq \mathcal{A}$ . By Proposition 0.3.34, the class  $\mathcal{A}$  is weakly saturated, so  $\overline{\text{InnHorn}} \subseteq \mathcal{A}$ . That is what we wanted to show.  $\square$

**Proposition 0.3.38.** *(To-do: Prop 16.10.)*

**Example 0.3.7.** Here are some examples of inner anodyne morphisms. (Important to-do: finish.)

- The inclusions of spines  $I^n \hookrightarrow \Delta^n$  are inner anodyne for every  $n$ . In particular, if  $C$  is an  $\infty$ -category, every map  $I^n \rightarrow C$  extends to a  $\Delta^n \rightarrow C$ .
- $\vdots$

### 0.3.12 (2/16) Lifting calculus

Here's a definition I expected a bit earlier in Charles' notes.

**Definition 0.3.39.** Say an object  $X$  *satisfies the extension property* for  $f : A \rightarrow B$  if for every  $u : A \rightarrow X$  we can find an extension  $B \rightarrow X$ .

**Definition 0.3.40.** Suppose as given maps  $f : A \rightarrow B$  and  $g : X \rightarrow Y$ . A *lifting problem* for  $(f, g)$  is a pair of maps  $u : A \rightarrow X$  and  $v : B \rightarrow Y$  making a commutative square. A *lift* for the lifting problem is a fill  $s$  to the obvious diagram:

$$\begin{array}{ccc} A & \xrightarrow{u} & X \\ f \downarrow & \nearrow s & \downarrow g \\ B & \xrightarrow{v} & Y \end{array}$$

**Definition 0.3.41.** Let  $f, g$  be morphisms in a category. We write  $f \boxdot g$  if every lifting problem for  $(f, g)$  admits a lift. We call this the *lifting relation* on morphisms. If  $f \boxdot g$ , we say:

- $f$  has the left lifting property rel. to  $g$ , or
- $g$  has the right lifting property rel. to  $f$ , or
- $f$  lifts against  $g$ .

**Definition 0.3.42.** Let  $A$  be a class of morphisms. We define the *right complement*  $A^\boxdot := \{g : a \boxdot g, \forall a \in A\}$ . We define the *left complement*  ${}^\boxdot A$  similarly.



**Proposition 0.3.43.** *Let  $\mathcal{A}$  be any class of morphisms in a category with small colimits. The left complement  ${}^{\square}\mathcal{A}$  is weakly saturated, and the right complement  $\mathcal{A}^{\square}$  is weakly cosaturated.*

*Proof.* (To-do: prove. Also, Charles' related exercises.) □

**Example 0.3.8.** Let  $C$  be an abelian category, let  $\mathcal{P} = \{0 \rightarrow P : P \text{ projective}\}$ , and let  $\mathcal{B}$  be the class of epimorphisms in  $C$ . By the definition of projective objects, we have  $\mathcal{P} \square \mathcal{B}$ . Thus  $\mathcal{B} \subseteq \mathcal{P}^{\square}$ .

(To-do: show converse?)

### 0.3.13 (2/17) Inner fibrations

A map  $p$  of simplicial sets is called an *inner fibration* if  $\text{InnHorn} \square p$ . Thus,  $\text{InnFib} = \text{InnHorn}^{\square}$ .

**Proposition 0.3.44.** *A simplicial set  $C$  is an  $\infty$ -category iff  $C \rightarrow *$  is an inner fibration.*

**Proposition 0.3.45.**  *$\text{InnFib}$  is defined as a right complement, thus  $\text{InnFib}$  is weakly cosaturated. This implies, for instance, that if  $C$  is an  $\infty$ -category and  $D \rightarrow C$  is an inner fibration, then  $D$  is an  $\infty$ -category.*

**Proposition 0.3.46** (*. kerodon*) *If  $X$  is a simplicial set, then a morphism  $X \rightarrow ND$  is an inner fibration iff  $X$  is an  $\infty$ -category.*

*Proof.* (To-do.) □

### 0.3.14 (2/20) Factorizations

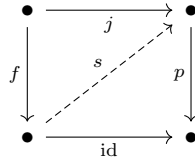
Recall that we defined *inner fibrations*  $\text{InnFib}$  as the right complement of  $\text{InnHorn}$ . This tells us something—maybe this is why we call it a “complement.”

**Proposition 0.3.47** (Small object argument). *Let  $S$  be a set of morphisms in  $\mathbf{sSet}$ . Then every map  $f$  of simplicial sets admits a factorization  $f = p \circ j$  with  $p \in S^{\square}$  and  $j \in \overline{S}$ .*

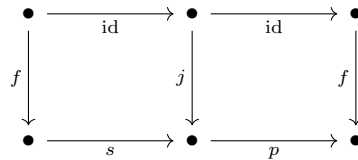
**Corollary 0.3.48.** *If  $S$  is any set of morphisms in  $\mathbf{sSet}$ , then  $\overline{S} = {}^{\square}(S^{\square})$ .*

*Proof.* Since  ${}^{\square}(S^{\square})$  is a left complement, it is weakly saturated (Proposition 0.3.43), thus  $\overline{S} \subseteq {}^{\square}(S^{\square})$ .

Now suppose that  $f \in S^{\square}$ . By the previous proposition, we may write  $f = pj$  for  $p \in S^{\square}$  and  $j \in \overline{S}$ , and by assumption  $f$  admits a lift in the following diagram.



Thus, we get the following commutative diagram.



This exhibits  $f$  as a retract of  $j$ . Since  $j \in \overline{S}$  and weak saturations are closed under retracts, we have  $f \in \overline{S}$ . □

**Corollary 0.3.49.** *Every map  $f$  of simplicial sets can be factored  $f = pj$  with  $p$  an inner fibration and  $j$  inner anodyne.*

### 0.3.15 (2/21) Factorization systems and unique lifts

Last time, we proved that for a class  $S$  of maps in  $\mathbf{sSet}$ , we have  $\overline{S} = \square (S^\square)$  and we can factor every map as a composite of one map from  $\overline{S}$  and  $S^\square$ . Starting with  $S = \text{InnHorn}$ , we got a factorization of an arbitrary map as an inner anodyne followed by an inner fibration. We study such systems in general.

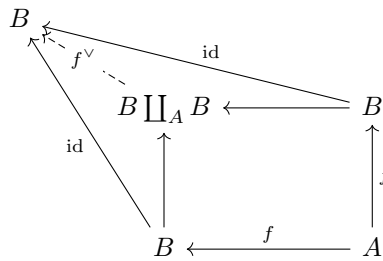
**Definition 0.3.50.** A *weak factorization system* in a category is a pair of classes of maps  $(\mathcal{L}, \mathcal{R})$  with the following properties.

1. Every morphism factors as  $rl$  for  $l \in \mathcal{L}$  and  $r \in \mathcal{R}$ ; and
2.  $\mathcal{L} = \square \mathcal{R}$  and  $\mathcal{R} = \mathcal{L}^\square$ .

**Example 0.3.9.** The pair  $(\overline{\text{InnHorn}}, \text{InnHorn}^\square)$  is a weak factorization system.

We would like to understand lifting problems with unique solutions.

**Definition 0.3.51.** In a category with coproducts, let  $f : A \rightarrow B$  be a morphism. We define the *fold* of  $f$ , denoted  $f^\wedge : B \coprod_A B \rightarrow B$ , as the unique map making the following diagram commute.



**Proposition 0.3.52.** Let  $f, g$  be morphisms. The following are equivalent.

1. We have  $f \square g$  and  $f^\vee \square g$ .
2. The solution to any lifting problem for  $(f, g)$  exists and is unique.

*Proof.* (2)  $\implies$  (1) is obvious. For (1)  $\implies$  (2), existence is assumed, so we need only show uniqueness. Wait, what does uniqueness mean in an arbitrary category?  $\square$

**Definition 0.3.53.** A weak factorization system  $(\mathcal{L}, \mathcal{R})$  is called an *orthogonal factorization system* if  $\mathcal{L} = \square \mathcal{R}$  and  $\mathcal{R} = \mathcal{L}^\square$  are realized by *unique* lifts.

**Proposition 0.3.54.** The factorization  $f = rl$  is unique up to unique isomorphism in an orthogonal factorization system.

**Proposition 0.3.55.**  $(\{\text{surjections}\}, \{\text{injections}\})$  form an orthogonal factorization system in  $\mathbf{Set}$ . (Proof is obvious.)

**Proposition 0.3.56.** For any class of simplicial maps  $S$ , the pair  $(\overline{S \cup S^\vee}, (S \cup S^\vee)^\square)$  is an orthogonal system.

### 0.3.16 (2/23) Degenerate cells

We want to concretely understand monomorphisms of simplicial sets. For this, recall that we defined the *boundary* of  $\Delta^n$  as the subcomplex of  $\Delta^n$  whose  $k$ -cells are the non-surjective maps  $[k] \rightarrow [n]$ . Write  $\underline{\text{Cell}}$  for the class of inclusions  $\partial\Delta^n \hookrightarrow \Delta^n$  and  $\text{InnFib} := \text{Cell}^\square$ . Since  $\text{Cell}$  consists of monos, we know  $\overline{\text{Cell}}$  contains all monomorphisms. Our main theorem is the converse.

**Proposition 0.3.57.** The class  $\overline{\text{Cell}}$  is exactly the class of monomorphisms of simplicial sets.

We'll prove this (Proof 0.3.17) once we've set some stuff up.

Toward proving this, recall the notion of degenerate cells: a cell  $\sigma : \Delta^n \rightarrow X$  is called *degenerate* if there exists a non-injective operator  $f : [m] \rightarrow [n]$  such that  $\sigma = \tau f$ . Since every simplicial operator factors uniquely as  $f = f^{inj} f^{surj}$ , we see that  $\sigma$  is degenerate if and only if there is some non-identity *surjective*  $f$  such that  $a = b f$ . A cell which is not degenerate is called *non-degenerate*. We write  $X_n = X_n^{deg} \amalg X_n^{nd}$  for the decomposition of  $X_n$  into (non)-degenerate cells. Neither assemble to a subcomplex.

**Proposition 0.3.58.** *Here are some straightforward facts about degenerate cells.*

1. If  $f : X \rightarrow Y$  is a map of simplicial sets, then  $f(X_n^{deg}) \subseteq Y_n^{deg}$ .
2. If  $f : X \rightarrow Y$  is a map of simplicial sets, then  $f^{-1}(Y_n^{nd}) \subseteq X_n^{nd}$ .
3. If  $A \hookrightarrow X$  is a subcomplex, then

$$A_n^{nd} = X_n^{nd} \cap A_n, \text{ and}$$

$$A_n^{deg} = X_n^{deg} \cap A_n.$$

4. The elements of  $(\Delta^n)_k^{nd}$  are in bijection with the subsets of  $[n]$  of size  $k$ .
5. The *simplicial  $n$ -sphere*  $\Delta^n / \partial \Delta^n$ , defined as the pushout of  $\Delta^n \leftarrow \partial \Delta^n \rightarrow \Delta^0$ , has exactly two nondegenerate cells: its unique vertex and the generator  $\langle 0, 1, \dots, n \rangle$ . In other words, the image of  $\Delta^0 \rightarrow \Delta^n / \partial \Delta^n$  and of the generator in  $\Delta^n \rightarrow \Delta^n / \partial \Delta^n$  in the pushout square:

$$\begin{array}{ccc} \partial \Delta^n & \xrightarrow{\quad} & \Delta^n \\ \downarrow & & \downarrow \\ \Delta^0 & \longrightarrow & \Delta^n / \partial \Delta^n \end{array}$$

The *Eilenberg-Zilber lemma* says that every cell  $a$  of  $X$  occurs *uniquely* as  $a = b \sigma$  for a nondegenerate  $b$  and surjective operator  $\sigma$ . (This is not too complicated; the nontrivial part is uniqueness.) Let's state this in a slightly different, stronger form.

**Proposition 0.3.59.** *If  $X$  is a simplicial set, then for every  $n$  the map*

$$\prod_{j \geq 0} X_j^{nd} \times \text{Hom}_{\Delta^{surj}}([n], [j]) \rightarrow X_n$$

*Given by  $(j, a, \sigma) \mapsto a \sigma$  is a bijection. Furthermore, this map is natural with respect to surjective operators  $[n'] \rightarrow [n]$  and with respect to monomorphisms of simplicial sets  $X \rightarrow X'$ .*

There are various things to be said now. I think I will move on, and refer back to these things when they are needed.

### 0.3.17 (2/23) The skeletal filtration

If  $\sigma : \Delta^n \rightarrow X$  is an  $n$ -cell, it uniquely factors as  $\Delta^n \rightarrow \Delta^m \rightarrow X$  where the first map is surjective and the second is nondegenerate. So  $\sigma$  is "really" an  $m$ -cell, for some  $m \leq n$ . Now, we want a notion of the  $k$ -skeleton of  $X$ . Its  $n$ -cells should be the  $n$ -cells of  $X$  which are "really"  $j$ -cells for some  $j \leq k$ .

**Definition 0.3.60.** Let  $X$  be a simplicial set. The  *$k$ -skeleton* of  $X$ , written  $Sk_k X$ , is the smallest subcomplex containing all cells of dimension  $\leq k$ . Thus, we have

$$(Sk_k X)_n = \bigcup_{0 \leq j \leq k} \{y f : y \in X_j \text{ and } f : [n] \rightarrow [j]\}.$$

A nondegenerate cell  $\Delta^k \rightarrow X$  determines a cell  $\Delta^k \rightarrow Sk_k X$ . This map carries  $\partial \Delta^{k-1}$  to  $Sk_{k-1} X$ .

**Proposition 0.3.61.** *The evident square*

$$\begin{array}{ccc} \coprod_{i \in X_k^{nd}} \partial \Delta^k & \longrightarrow & Sk_{k-1}X \\ \downarrow & & \downarrow \\ \coprod_{i \in X_k^{nd}} \Delta^k & \longrightarrow & Sk_k X \end{array}$$

Is a pushout square. More generally, if  $A \subseteq X$  is a subcomplex, the following is a pushout square.

$$\begin{array}{ccc} \coprod_{i \in X_k^{nd}/A_k^{nd}} \partial \Delta^k & \longrightarrow & A \cup Sk_{k-1}X \\ \downarrow & & \downarrow \\ \coprod_{i \in X_k^{nd}/A_k^{nd}} \Delta^k & \longrightarrow & A \cup Sk_k X \end{array}$$

It is in this sense that simplicial sets are built out of standard simplices: a simplicial set  $X$  is filtered by  $X_0 = Sk_0 X \subseteq Sk_1 X \subseteq Sk_2 X \subseteq \dots$ , and each  $Sk_n$  is obtained from  $Sk_{n-1}$  by attaching copies of  $\Delta^n$  as in Proposition 0.3.61.

Now we are ready to prove our characterization of monomorphisms (Proposition 0.3.57).

*Proof.* A monomorphism of simplicial sets is isomorphic to an inclusion  $A \hookrightarrow X$ . It is clear that  $X \cong \text{colim}_k A \cup Sk_k X$ . But see that, by the above proposition, the maps  $A \cup Sk_{k-1} X \rightarrow A \cup Sk_k X$  arise via cobase change from coproducts of maps in Cell. Then the inclusion is exhibited as a countable composition(?) of maps in Cell, thus is in Cell.  $\square$

And so we have some handle on monomorphisms in sSet now.

**Corollary 0.3.62** (Geometric realizations are CW). *Recall that we constructed the geometric realization functor  $|-| : \text{sSet} \rightarrow \text{Top}$  as a left adjoint. Left adjoints preserve colimits, hence we have a pushout diagram*

$$\begin{array}{ccc} \coprod_{a \in X_k^{nd}} \partial \Delta_{top}^k & \longrightarrow & |Sk_{k-1}X| \\ \downarrow & & \downarrow \\ \coprod_{a \in X_k^{nd}} \Delta_{top}^k & \longrightarrow & |Sk_k X| \end{array}$$

Additionally, we have  $|X| = \lim_{\rightarrow} |Sk_k X|$ . This describes a canonical CW structure on the geometric realization  $|X|$  of a simplicial set. Evidently, cells of  $|X|$  correspond to nondegenerate simplices of  $X$ .

### 0.3.18 (2/25) Pushout-products, pullback-homs

Let  $f : A \rightarrow B$  and  $g : K \rightarrow L$  be morphisms in sSet. We define the *pushout-product* of  $f$  and  $g$ , denoted  $f \square g$ , as the unique dotted map making the following pushout square diagram commute.

$$\begin{array}{ccc} A \times K & \xrightarrow{\text{id} \times g} & A \times L \\ \downarrow f \times \text{id} & & \downarrow f \times \text{id} \\ B \times K & \xrightarrow{\quad \quad} & (B \times K) \coprod_{A \times K} (A \times L) \\ & \searrow \text{id} \times g & \swarrow f \square g \\ & & B \times L \end{array}$$

Dually, we define the *pullback-hom* of  $f$  and  $g$ , denoted  $f \square g$ , to be the unique dotted map making the following pullback square diagram commute.

$$\begin{array}{ccc}
 \text{Fun}(L, A) & & \\
 \begin{array}{c} \dashrightarrow \\ \text{---} \end{array} & \begin{array}{c} \text{Fun}(g, \text{id}) \\ \text{---} \end{array} & \\
 \text{Fun}(K, A) \times_{\text{Fun}(K, B)} \text{Fun}(L, B) & \xrightarrow{\quad} & \text{Fun}(K, A) \\
 \begin{array}{c} \downarrow \\ \text{---} \end{array} & & \begin{array}{c} \downarrow \\ \text{---} \end{array} \\
 \text{Fun}(L, B) & \xrightarrow{\quad \text{Fun}(g, \text{id}) \quad} & \text{Fun}(K, B)
 \end{array}$$

$f \square g$  (dotted arrow from  $\text{Fun}(L, A)$  to  $\text{Fun}(K, A) \times_{\text{Fun}(K, B)} \text{Fun}(L, B)$ )  
 $\text{Fun}(g, \text{id})$  (top arrow from  $\text{Fun}(L, A)$  to  $\text{Fun}(K, A)$ )  
 $\text{Fun}(g, \text{id})$  (bottom arrow from  $\text{Fun}(L, B)$  to  $\text{Fun}(K, B)$ )  
 $\text{Fun}(\text{id}, f)$  (left arrow from  $\text{Fun}(L, A)$  to  $\text{Fun}(K, A) \times_{\text{Fun}(K, B)} \text{Fun}(L, B)$ )  
 $\text{Fun}(\text{id}, f)$  (right arrow from  $\text{Fun}(K, A)$  to  $\text{Fun}(K, B)$ )

## 0.4 March 2023

### 0.4.1 (3/5) Pullback-hom as an enriched lifting problem

Suppose given  $g : K \rightarrow L$  and  $h : X \rightarrow Y$ . We have the pullback-hom

$$h^{\square g} : \text{Fun}(L, X) \rightarrow \text{Fun}(K, X) \times_{\text{Fun}(K, Y)} \text{Fun}(L, Y).$$

The vertices of  $\text{Fun}(L, X)$  are morphisms  $L \rightarrow X$  in  $\mathbf{sSet}$ . The vertices of  $\text{Fun}(K, X) \times_{\text{Fun}(K, Y)} \text{Fun}(L, Y)$  are those pairs of morphisms  $(s : K \rightarrow X, t : L \rightarrow Y)$  such that  $hs = tg$ , i.e. lifting problems for  $(g, h)$ . The pullback-hom  $h^{\square g}$  takes a morphism  $w : L \rightarrow X$  and composes it to  $(wg, gh)$ . This gives us a lifting problem for  $(g, h)$  that is solvable. Then the following is clear.

**Proposition 0.4.1.** *The pullback-hom  $h^{\square g}$  is surjective on vertices iff  $g \sqsupseteq h$ .*

In this sense,  $h^{\square g}$  encodes an "enriched" lifting problem for  $(g, h)$ . The target  $\text{Fun}(K, X) \times_{\text{Fun}(K, Y)} \text{Fun}(L, Y)$  parametrizes lifting problems for  $(g, h)$  while the source  $\text{Fun}(L, X)$  parametrizes families of lifting problems together with a chosen lift.

Also, let's talk about so-called *adjunctions of lifting problems*. The product and function complex constructions are adjoint. Ultimately, this leads to the following.

**Proposition 0.4.2.** *One has  $(f \square g) \sqsupseteq h$  if and only if  $f \sqsupseteq h^{\square g}$ .*

Here's a special case. Take  $K = \emptyset$  and  $Y = *$ . Then the proposition gives us that

$$(f \times \text{id}_L) \sqsupseteq (X \rightarrow *) \iff f \sqsupseteq (\text{Fun}(L, X) \rightarrow *).$$

0.5 April 2023

## 0.6 May 2023

### 0.6.1 (5/3) Operads for (Peter) May

For May, I will learn about operads and monads. Here are my motives.

- (1) Peter May coined the term *operad*.
- (2) They're interesting and fit into the  $\infty$ -categorical framework, eventually.
- (3) I read some of Moerdijk-Weiss's *Dendroidal sets* for Charles' Kan Seminar and thought it was exciting.
- (4) Peter May tipped me off that monads and operads would make a big appearance in his talks for the 2023 UChicago REU. (Probably related to his recent work with Ruoqi Zhang and Foling Zou.)

Here are some potential references.

- (1) May, *The Geometry of Iterated Loop Spaces* (1971)
  - (2) Markl-Shnider-Stasheff, *Operads in Algebra, Topology, and Physics* (2000)
  - (3) Heuts, *Simplicial and Dendroidal Homotopy Theory* (2022)
  - (4) Markl, *Operads and PROPs* (2006)
  - (5) Lawson,  *$E_n$ -ring spectra and Dyer-Lashof operations*
- 

Let me say what I *think* operads are supposed to do/be before I dive into it:

An operad abstracts away the structure of "the collection of operations on an algebraic structure." Here's a vague indication as to why this is useful: say an algebraic thing  $X$  has operations which "play nice" with its algebraic structure. If this occurs, it can have *great* consequences. It's natural that we then (1) find and study objects for which this occurs, and (2) study them in concert. But this has problems: (A) it may require *lots* of data to verify or realize that  $X$ 's operations "play nice" with its structure (*coherence data*), especially for complicated  $X$ , and/or especially if we're thinking up-to-homotopy, and (B) if we want to study such objects relative to each other, we'll have to compare several of these huge packages of data. Operads do the work for us: the idea is to say, "let  $\mathcal{C}$  be the operad codifying the possession of coherent operations." Then, given an object  $X$ , a choice (if one exists) of such structure on  $X$  amounts to a morphism  $\mathcal{C} \rightarrow \text{End}_X$ , the latter being a canonical "endomorphism operad" associated to  $X$ . That morphism essentially says, "we can interpret the structure within  $\mathcal{C}$  as some class of operations on  $X$ ." In other words, for an algebraic structure  $X$ , an operad classifies "coherent" operations on  $X$ , the details (e.g., how coherent?) dependent on which operad you're considering.

Maybe another way of putting it is that operads represent the formal algebraic theory, while we're interested in "instantiations" of these theories, i.e. their representations—I think we call these "algebras over the operads."

OK, let me actually learn what these are now.

**Definition 0.6.1.** An *operad*, *symmetric operad*, or *classical operad*  $\mathcal{C}$  is a collection of sets  $(\mathcal{C}(i))_{i \geq 0}$  with a distinguished operation  $1_{\mathcal{C}} \in \mathcal{C}(1)$  and functions  $\gamma : \mathcal{C}(n) \times \mathcal{C}(k_1) \times \cdots \times \mathcal{C}(k_n) \rightarrow \mathcal{C}(\sum k_s)$ , which we regard as *operations*, the *unit operation*, and as *composition*, respectively, and in this regard we require that these structures are suitably associative, unital, and equivariant up to reordering of inputs.

Concretely,  $\mathcal{C}$  is the data of

- (Operations) For each  $i \geq 0$ , a set  $\mathcal{C}(i)$  called  *$i$ -ary operations*; and
- (Composites) For each  $n \geq 0$  and  $k_1, \dots, k_n \geq 0$ , a *composition* map  $\gamma : \mathcal{C}(n) \times \mathcal{C}(k_1) \times \cdots \times \mathcal{C}(k_n) \rightarrow \mathcal{C}(\sum k_s)$ ; and
- (Unit) A distinguished *identity* operation  $1_{\mathcal{C}} \in \mathcal{C}(1)$ ; and



- (Symmetries) For each  $i \geq 0$ , an action  $\Sigma_i \rightarrow \text{Aut}\mathcal{C}(i)$

satisfying the following conditions.

- (Unitality) For every operation  $d \in \mathcal{C}(j)$ , we have  $\gamma(1; d) = d$  and  $\gamma(d; 1^{\times j}) = d$ .
- (Associativity) Blah blah blah
- ( $\Sigma_n$ -Equivariance) For each  $\Sigma_1^k j_s = j, c \in \mathcal{C}(k), d_s \in \mathcal{C}(j_s), \sigma \in \Sigma_k$ , and  $\tau_s \in \Sigma_{j_s}$ , we have

$$\begin{aligned} \gamma(c\sigma; (d_i)) &= \gamma(c; (d_{\sigma^{-1}i})) \cdot \sigma(j_1, \dots, j_s), \quad \text{and} \\ \gamma(c; (d_i\tau_i)) &= \gamma(c; (d_i))(\tau_1 \oplus \dots \oplus \tau_k). \end{aligned}$$

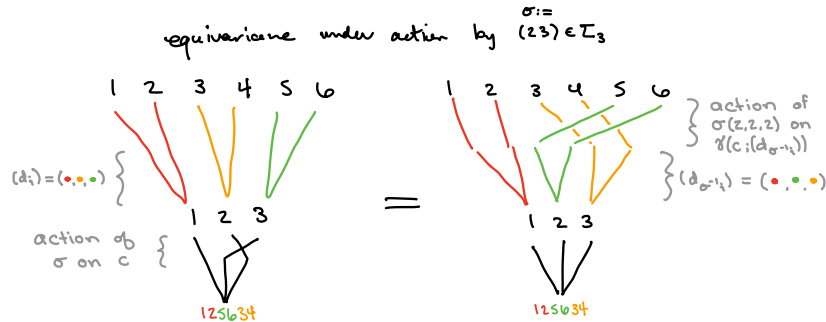
Here,  $\sigma(j_1, \dots, j_s) :=$  the permutation of  $j$  letters given by permuting the  $k$  blocks of letters determined by the partition  $j = \Sigma j_s$  according to  $\sigma$ .

**Definition 0.6.2.** An operad with no  $\Sigma_i$ -actions or equivariance is called *plain* or *non- $\Sigma$*  or *non-symmetric*.

**Definition 0.6.3.** Above, we defined an operad in  $\text{Set}$ . We can make an analogous definition in any bicomplete symmetric monoidal category  $(\mathbf{C}, \otimes, \mathbf{1})$ . In this case, the unit/identity is a distinguished morphism  $\mathbf{1} \rightarrow \mathcal{C}(1)$ . The symmetries become maps  $\Sigma_i \rightarrow \text{Iso}(\mathcal{C}(i), \mathcal{C}(i))$ . Such a thing is called an *operad in  $\mathbf{C}$* . This is like “enriching” an operad over a category.

**Definition 0.6.4.** A *morphism of operads*  $\mathcal{C} \rightarrow \mathcal{C}'$  is a collection of maps  $f_i : \mathcal{C}(i) \rightarrow \mathcal{C}'(i)$  such that  $f_1(1) = 1$  and (equivariance, compatibility with composition).

**Remark 0.6.5.** As indicated, we think of  $\mathcal{C}(i)$  as a set of  $i$ -ary operations, and the functions  $\gamma : \mathcal{C}(k) \times \mathcal{C}(n_1) \times \dots \times \mathcal{C}(n_k) \rightarrow \mathcal{C}(\sum n_s)$  as taking a  $k$ -ary operation  $c$  and plugging in  $k$  other operations  $(d_i)$ . The  $\Sigma_n$ -equivariance demands that if we tamper with the inputs for  $c$  then plug in the  $(d_i)$ , that is the same as plugging in the  $(d_i)$  in a different order then tampering with the order of their inputs. See the little picture.



**An operad’s purpose in life is to help define algebras over an operad.** Such a thing establishes an “algebraic structure representing the operad” upon an object. Here is the definition.

**Definition 0.6.6.** Let  $\mathcal{C}$  be an operad in a symmetrical monoidal  $\mathbf{C}$ . A  *$\mathcal{C}$ -algebra*  $A$  is an object  $A$  and maps  $\mathcal{C}(i) \otimes A^{\otimes i} \rightarrow A$  that are suitably associative, unital, and equivariant. ( We take  $A^{\otimes 0} = \mathbf{1}_{\mathbf{C}}$ .)

I’ll go over many examples soon. Some of these will let us reinterpret some of the above structures. But for the rest of today, I’ll just make a little remark.

**Remark 0.6.7** (Classical operads generalize monoids). Let  $\mathcal{C}$  be a classical operad. (A non- $\Sigma$  operad works too.) There is an associated category  $j_!\mathcal{C}$  with one object and morphisms given by  $\mathcal{C}(1)$ , the unary operations. Given  $f, g \in \mathcal{C}(1)$ , their composite  $g \circ f :=$  their image in  $\mathcal{C}(1) \times \mathcal{C}(1) \rightarrow \mathcal{C}(1)$ , and the unit is the identity operation  $1_{\mathcal{C}} \in \mathcal{C}(1)$ . This checks out thanks to the unitality and associativity axioms.

Conversely, given a one-object category  $\mathbf{M}$ , i.e. a monoid, we may form an operad  $j^*\mathbf{M}$  with solely unitary operations, given by  $(j^*\mathbf{M})(1) := \text{Hom}_{\mathbf{M}}(*, *)$ . The unit and composition functions are obvious, and the  $\Sigma_i$ -actions are trivial.

Altogether we get an *adjunction*

$$\text{Monoids} \begin{array}{c} \xrightarrow{j_!} \\ \xleftarrow{j^*} \end{array} \text{Operads}$$

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