

∞ -Categories for the Working Mathematician

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Preface

In this text we develop the theory of ∞ -categories from first principles in a model-independent fashion using a common axiomatic framework that is satisfied by a variety of models. In contrast with prior “analytic” treatments of the theory of ∞ -categories — in which the central categorical notions are defined in reference to the combinatorics of a particular model — our approach is “synthetic,” proceeding from definitions that can be interpreted simultaneously in many models to which our proofs then apply. While synthetic, our work is not schematic or hand-wavy, with the details of how to make things fully precise left to “the experts” and turtles all the way down.¹ Rather, we prove our theorems starting from a short list of clearly-enumerated axioms, and our conclusions are valid in any model of ∞ -categories satisfying these axioms.

The synthetic theory is developed in any ∞ -cosmos, which axiomatizes the universe in which ∞ -categories live as objects. So that our theorem statements suggest their natural interpretation, we recast ∞ -category as a technical term, to mean an object in some (typically fixed) ∞ -cosmos. Several models of $(\infty, 1)$ -categories² are ∞ -categories in this sense, but our ∞ -categories also include certain models of (∞, n) -categories³ as well as fibered versions of all of the above. This usage is meant to interpolate between the classical one, which refers to any variety of weak infinite-dimensional category, and the common one, which is often taken to mean quasi-categories or complete Segal spaces.

Much of the development of the theory of ∞ -categories takes place not in the full ∞ -cosmos but in a quotient that we call the *homotopy 2-category*, the name chosen because an ∞ -cosmos is something like a category of fibrant objects in an enriched model category and the homotopy 2-category is then a categorification of its homotopy category. The homotopy 2-category is a strict 2-category — like the 2-category of categories, functors, and natural transformations — and in this way the foundational proofs in the theory of ∞ -categories closely resemble the classical foundations of ordinary category theory except that the universal properties that characterize, e.g. when a functor between ∞ -categories defines a cartesian fibration, are slightly weaker than in the familiar case. In Part I, we define and develop the notions of equivalence and adjunction between ∞ -categories, limits and colimits in ∞ -categories, cartesian and cocartesian fibrations and their discrete variants, and prove an external version of the Yoneda lemma all from the comfort of the homotopy 2-category. In Part II, we turn our attention to homotopy coherent structures present in the full ∞ -cosmos to define

¹A less rigorous “model-independent” presentation of ∞ -category theory might confront a problem of infinite regress, since infinite-dimensional categories are themselves the objects of an ambient infinite-dimensional category, and in developing the theory of the former one is tempted to use the theory of the latter. We avoid this problem by using a very concrete model for the ambient $(\infty, 2)$ -category of ∞ -categories that arises frequently in practice and is designed to facilitate relatively simple proofs. While the theory of $(\infty, 2)$ -categories remains in its infancy, we are content to cut the Gordian knot in this way.

² (naturally marked quasi-categories) all define the ∞ -categories in an ∞ -cosmos.

³ Θ_n -spaces, iterated complete Segal spaces, and n -complicial sets also define the ∞ -categories in an ∞ -cosmos, as do (nee. weak) complicial sets, a model for (∞, ∞) -categories. We hope to add other models of (∞, n) -categories to this list.

and study homotopy coherent adjunctions and monads borne by ∞ -categories as a mechanism for universal algebra.

What’s missing from this basic account of the category theory of ∞ -categories is a satisfactory treatment of the “hom” bifunctor associated to an ∞ -category, which is the prototypical example of what we call a *module*. In Part III, we develop the calculus of modules between ∞ -categories and apply this to define and study pointwise Kan extensions. This will give us an opportunity to repackage universal properties proven in Part I as parts of the “formal category theory” of ∞ -categories.

This work is all “model-agnostic” in the sense of being blind to details about the specifications of any particular ∞ -cosmos. In Part IV we prove that the category theory of ∞ -categories is also “model-independent” in a precise sense: all categorical notions are preserved, reflected, and created by any “change-of-model” functor that defines what we call a *biequivalence*. This model-independence theorem is stronger than our axiomatic framework might initially suggest in that it also allows us to transfer theorems proven using “analytic” techniques to all biequivalent ∞ -cosmoi. For instance, the four ∞ -cosmoi whose objects model $(\infty, 1)$ -categories are all biequivalent. It follows that the analytically-proven theorems about quasi-categories⁴ from [36] transfer to complete Segal spaces, and vice versa.

⁴Importantly, the synthetic theory developed in the ∞ -cosmos of quasi-categories is fully compatible with the analytic theory developed by Joyal, Lurie, and many others. This is the subject of Appendix F.

Part I

Basic ∞ -category theory

Before introducing an axiomatic framework that will allow us to develop ∞ -category theory in general, we first consider one model in particular: namely, *quasi-categories*, which were first analyzed by Joyal in [24] and [25] and in several unpublished draft book manuscripts.

elementary face operators $[n-1] \xrightarrow{\delta^i} [n] \quad 0 \leq i \leq n \quad \text{and the}$

whose images respectively omit and double up on the element $i \in [n]$. Every morphism in Δ factors uniquely as an epimorphism followed by a monomorphism; these epimorphisms, the **degeneracy operators**, decompose as composites of elementary degeneracy operators, while the monomorphisms, the **face operators**, decompose as composites of elementary face operators.

Given a simplicial set X , it is conventional to write X_n for the set of n -**simplices**, defined by evaluating at $[n] \in \Delta$. By the Yoneda lemma, each n -simplex $x \in X_n$ corresponds to a map of simplicial sets $x: \Delta[n] \rightarrow X$. Accordingly, we write $x \cdot \delta^i$ for the i th face of the n -simplex, an $(n-1)$ -simplex classified by the composite map

Geometrically, $x \cdot \delta^i$ is the “face opposite the vertex i ” in the n -simplex x .

Since the morphisms of Δ are generated by the elementary face and degeneracy operators, the data of a simplicial set¹ X is often presented by a diagram

identifying the set of n -simplices for each $[n] \in \Delta$ as well as the (contravariant) actions of the elementary operators, conventionally denoted using subscripts.

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1.1.2. DEFINITION (quasi-category). A **quasi-category** is a simplicial set A in which any **inner horn** can be extended to a simplex, solving the displayed lifting problem:

$$\begin{array}{ccc} \Lambda^k[n] & \longrightarrow & A \\ \downarrow & \nearrow & \\ \Delta[n] & & \end{array} \quad n \geq 2, 0 < k < n. \quad (1.1.3)$$

Quasi-categories were first introduced by Boardman and Vogt [8] under the name “weak Kan complexes,” a **Kan complex** being a simplicial set admitting extensions as in (1.1.3) along all horn inclusions $n \geq 1, 0 \leq k \leq n$. Since any topological space can be encoded as a Kan complex,² in this way spaces provide examples of quasi-categories.

Categories also provide examples of quasi-categories via the nerve construction.

1.1.4. DEFINITION (nerve). The category \mathbf{Cat} of 1-categories embeds fully faithfully into the category of simplicial sets via the **nerve** functor. An n -simplex in the nerve of a 1-category C is a sequence of n composable arrows in C , or equally a functor $[n] \rightarrow C$ from the ordinal category $\mathfrak{n} + 1 := [n]$ with objects $0, \dots, n$ and a unique arrow $i \rightarrow j$ just when $i \leq j$.

1.1.5. REMARK. The nerve of a category C is 2-coskeletal as a simplicial set, meaning that every sphere $\partial\Delta[n] \rightarrow C$ with $n \geq 3$ is filled uniquely by an n -simplex in C (see Definition D.1.1). This is because the simplices in dimension 3 and above witness the associativity of the composition of the path of composable arrows found along their **spine**, the 1-skeletal simplicial subset formed by the edges connecting adjacent vertices. In fact, as suggested by the proof of the following proposition, any simplicial set in which inner horns admit *unique* fillers is isomorphic to the nerve of a 1-category; see Exercise 1.1.iii.

We decline to introduce explicit notation for the nerve functor, preferring instead to identify 1-categories with their nerves. As we shall discover the theory of 1-categories extends to ∞ -categories modeled as quasi-categories in such a way that the restriction of each ∞ -categorical concept along the nerve embedding recovers the corresponding 1-categorical concept. For instance, the standard simplex $\Delta[n]$ is the nerve of the ordinal category $\mathfrak{n} + 1$, and we frequently adopt the latter notation — writing $\mathbf{1} := \Delta[0]$, $\mathbf{2} := \Delta[1]$, $\mathbf{3} := \Delta[2]$, and so on — to suggest the correct categorical intuition.

To begin down this path, we must first verify the assertion that has implicitly just been made:

1.1.6. PROPOSITION (nerves are quasi-categories). *Nerves of categories are quasi-categories.*

PROOF. Via the isomorphism $C \cong \mathrm{cosk}_2 C$ and the adjunction $\mathrm{sk}_2 \dashv \mathrm{cosk}_2$ of D.1.1, the required lifting problem displayed below-left transposes to the one displayed below-right

$$\begin{array}{ccc} \Lambda^k[n] & \longrightarrow & C \cong \mathrm{cosk}_2 C \\ \downarrow & \nearrow & \\ \Delta[n] & & \end{array} \quad \Longleftrightarrow \quad \begin{array}{ccc} \mathrm{sk}_2 \Lambda^k[n] & \longrightarrow & C \\ \downarrow & \nearrow & \\ \mathrm{sk}_2 \Delta[n] & & \end{array}$$

²The total singular complex construction defines a functor from topological spaces to simplicial sets that is an equivalence on their respective homotopy categories — weak homotopy types of spaces correspond to homotopy equivalence classes of Kan complexes.

For $n \geq 4$, the inclusion $\text{sk}_2 \Lambda^k[n] \hookrightarrow \text{sk}_2 \Delta[n]$ is an isomorphism, in which case the lifting problems on the right admit (unique) solutions. So it remains only to solve the lifting problems on the left in the cases $n = 2$ and $n = 3$.

To that end consider

$$\begin{array}{ccc} \Lambda^1[2] & \longrightarrow & C \\ \downarrow & \nearrow & \\ \Delta[2] & & \end{array} \quad \begin{array}{ccc} \Lambda^1[3] & \longrightarrow & C \\ \downarrow & \nearrow & \\ \Delta[3] & & \end{array} \quad \begin{array}{ccc} \Lambda^2[3] & \longrightarrow & C \\ \downarrow & \nearrow & \\ \Delta[3] & & \end{array}$$

An inner horn $\Lambda^1[2] \rightarrow C$ defines a composable pair of arrows in C ; an extension to a 2-simplex exists precisely because any composable pair of arrows admits a (unique) composite.

An inner horn $\Lambda^1[3] \rightarrow C$ specifies the data of three composable arrows in C , as displayed in the diagram below, together with the composites gf , hg , and $(hg)f$.

$$\begin{array}{ccccc} & & c_1 & & \\ & f \nearrow & \downarrow & \searrow hg & \\ c_0 & \xrightarrow{\quad} & & \xrightarrow{(hg)f} & c_3 \\ & g \searrow & \downarrow & \nearrow h & \\ & & c_2 & & \end{array}$$

Because composition is associative, the arrow $(hg)f$ is also the composite of gf followed by h , which proves that the 2-simplex opposite the vertex c_1 is present in C ; by 2-coskeletality, the 3-simplex filling this boundary sphere is also present in C . The filler for a horn $\Lambda^2[3] \rightarrow C$ is constructed similarly. \square

1.1.7. DEFINITION (homotopy relation on 1-simplices). A parallel pair of 1-simplices f, g in a simplicial set X are **homotopic** if there exists a 2-simplex of either of the following forms

$$\begin{array}{ccc} & x_1 & \\ f \nearrow & & \searrow \\ x_0 & \xrightarrow{g} & x_1 \end{array} \quad \begin{array}{ccc} & x_0 & \\ & \searrow f & \\ x_0 & \xrightarrow{g} & x_1 \end{array} \quad (1.1.8)$$

or if f and g are in the same equivalence class generated by this relation.

In a quasi-category, the relation witnessed by any of the types of 2-simplex on display in (1.1.8) is an equivalence relation and these equivalence relations coincide:

1.1.9. LEMMA (homotopic 1-simplices in a quasi-category). *Parallel 1-simplices f and g in a quasi-category are homotopic if and only if there exists a 2-simplex of any or equivalently all of the forms displayed in (1.1.8).*

PROOF. Exercise 1.1.i. \square

1.1.10. DEFINITION (the homotopy category). By 1-truncating, any simplicial set X has an underlying reflexive directed graph

$$X_1 \begin{array}{c} \xrightarrow{\delta_1} \\ \xleftarrow{\sigma_0} \\ \xrightarrow{\delta_0} \end{array} X_0,$$

the 0-simplices of X defining the “objects” and the 1-simplices defining the “arrows,” by convention pointing from their 0th vertex (the face opposite 1) to their 1st vertex (the face opposite 0). The **free**

category on this reflexive directed graph has X_0 as its object set, degenerate 1-simplices serving as identity morphisms, and non-identity morphisms defined to be finite directed paths of non-degenerate 1-simplices. The **homotopy category** $\mathbf{h}X$ of X is the quotient of the free category on its underlying reflexive directed graph by the congruence³ generated by imposing a composition relation $h = g \circ f$ witnessed by 2-simplices

$$\begin{array}{ccc} & x_1 & \\ f \nearrow & & \searrow g \\ x_0 & \xrightarrow{h} & x_2 \end{array}$$

This implies in particular that homotopic 1-simplices represent the same arrow in the homotopy category.

1.1.11. PROPOSITION. *The nerve embedding admits a left adjoint, namely the functor which sends a simplicial set to its homotopy category:*

$$\begin{array}{ccc} & \xleftarrow{h} & \\ \text{Cat} & \perp & \mathbf{SSet} \\ & \xrightarrow{\quad} & \end{array}$$

PROOF. Using the description of $\mathbf{h}X$ as a quotient of the free category on the underlying reflexive directed graph of X , we argue that the data of a functor $\mathbf{h}X \rightarrow C$ can be extended uniquely to a simplicial map $X \rightarrow C$. Presented as a quotient in this way, the functor $\mathbf{h}X \rightarrow C$ defines a map from the 1-skeleton of X into C , and since every 2-simplex in X witnesses a composite in $\mathbf{h}X$, this map extends to the 2-skeleton. Now C is 2-coskeletal, so via the adjunction $\text{sk}_2 \dashv \text{cosk}_2$ of Definition D.1.1, this map from the 2-truncation of X into C extends uniquely to a simplicial map $X \rightarrow C$. \square

The homotopy category of a quasi-category admits a simplified description.

1.1.12. LEMMA (the homotopy category of a quasi-category). *If A is a quasi-category then its homotopy category $\mathbf{h}A$ has*

- the set of 0-simplices A_0 as its objects
- the set of homotopy classes of 1-simplices A_1 as its arrows
- the identity arrow at $a \in A_0$ represented by the degenerate 1-simplex $a \cdot \sigma_0 \in A_1$
- a composition relation $h = g \circ f$ in $\mathbf{h}A$ if and only if, for any choices of 1-simplices representing these arrows, there exists a 2-simplex with boundary

$$\begin{array}{ccc} & a_1 & \\ f \nearrow & & \searrow g \\ a_0 & \xrightarrow{h} & a_2 \end{array}$$

PROOF. Exercise 1.1.ii. \square

1.1.13. DEFINITION (isomorphisms in a quasi-category). A 1-simplex in a quasi-category is an **isomorphism** just when it represents an isomorphism in the homotopy category. By Lemma 1.1.12 this means that $f: a \rightarrow b$ is an isomorphism if and only if there exist a 1-simplex $f^{-1}: b \rightarrow a$ together with a pair of 2-simplices

$$\begin{array}{ccc} & b & \\ f \nearrow & & \searrow f^{-1} \\ a & \xlongequal{\quad} & a \end{array} \quad \begin{array}{ccc} & a & \\ f^{-1} \nearrow & & \searrow f \\ b & \xlongequal{\quad} & b \end{array}$$

³A relation on parallel pairs of arrows of a 1-category is a **congruence** if it is an equivalence relation that is closed under pre- and post-composition: if $f \sim g$ then $hfk \sim h g k$.

The properties of the isomorphisms in a quasi-category are most easily proved by arguing in a slightly different category where simplicial sets have the additional structure of a “marking” on a specified subset of the 1-simplices subject to the condition that all degenerate 1-simplices are marked; maps of these so-called **marked simplicial sets** must then preserve the markings. Because these objects will seldom appear outside of the proofs of certain combinatorial lemmas about the isomorphisms in quasi-categories, we save the details for Appendix D.

Let us now motivate the first of several results proven using marked techniques. Quasi-categories are defined to have extensions along all *inner horns*. But if in an outer horn $\Lambda^0[2] \rightarrow A$ or $\Lambda^2[2] \rightarrow A$, the initial or final edges, respectively, are isomorphisms, then intuitively a filler should exist

$$\begin{array}{ccc} & a_1 & \\ f \nearrow & & \searrow hf^{-1} \\ a_0 & \xrightarrow{h} & a_2 \end{array} \qquad \begin{array}{ccc} & a_1 & \\ g^{-1}h \nearrow & & \searrow g \\ a_0 & \xrightarrow{h} & a_2 \end{array}$$

and similarly for the higher-dimensional outer horns.

1.1.14. PROPOSITION (special outer horn lifting).

(i) Let A be a quasi-category. Then any outer horns

$$\begin{array}{ccc} \Lambda^0[n] & \xrightarrow{g} & A \\ \downarrow & \nearrow & \\ \Delta[n] & & \end{array} \qquad \begin{array}{ccc} \Lambda^n[n] & \xrightarrow{h} & A \\ \downarrow & \nearrow & \\ \Delta[n] & & \end{array}$$

in which the edges $g|_{\{0,1\}}$ and $h|_{\{n-1,n\}}$ are isomorphisms admit fillers.

(ii) Let A and B be quasi-categories and $f: A \rightarrow B$ a map that lifts against the inner horn inclusions. Then any outer horns

$$\begin{array}{ccc} \Lambda^0[n] & \xrightarrow{g} & A \\ \downarrow & \nearrow & \downarrow f \\ \Delta[n] & \longrightarrow & B \end{array} \qquad \begin{array}{ccc} \Lambda^n[n] & \xrightarrow{h} & A \\ \downarrow & \nearrow & \downarrow f \\ \Delta[n] & \longrightarrow & B \end{array}$$

in which the edges $g|_{\{0,1\}}$ and $h|_{\{n-1,n\}}$ are isomorphisms admit fillers.

The proof of Proposition 1.1.14 requires clever combinatorics, due to Joyal, and is deferred to Appendix D.⁴ Here, we enjoy its myriad consequences. Immediately:

1.1.15. COROLLARY. A quasi-category is a Kan complex if and only if its homotopy category is a groupoid.

PROOF. If the homotopy category of a quasi-category is a groupoid, then all of its 1-simplices are isomorphisms, and Proposition 1.1.14 then implies that all inner and outer horns have fillers. Thus, the quasi-category is a Kan complex. Conversely, in a Kan complex, all outer horns can be filled and in particular fillers for the horns $\Lambda^0[2]$ and $\Lambda^2[2]$ can be used to construct left and right inverses for any 1-simplex of the form displayed in Definition 1.1.13.⁵ \square

⁴The second statement subsumes the first, but the first is typically used to prove the second.

⁵In a quasi-category, any left and right inverses to a common 1-simplex are homotopic, but as Corollary 1.1.16 proves, any isomorphism in fact has a single two-sided inverse.

A quasi-category contains a canonical **maximal sub Kan complex**, the simplicial subset spanned by those 1-simplices that are isomorphisms. Just as the arrows in a quasi-category A are represented by simplicial maps $\mathbb{2} \rightarrow A$ whose domain is the nerve of the free-living arrow, the isomorphisms in a quasi-category are represented by diagrams $\mathbb{I} \rightarrow A$ whose domain is the free-living isomorphism:

1.1.16. COROLLARY. *An arrow f in a quasi-category A is an isomorphism if and only if it extends to a **homotopy coherent isomorphism***

$$\begin{array}{ccc} \mathbb{2} & \xrightarrow{f} & A \\ \downarrow & \nearrow & \\ \mathbb{I} & & \end{array}$$

PROOF. If f is an isomorphism, the map $f: \mathbb{2} \rightarrow A$ lands in the maximal sub Kan complex contained in A . The postulated extension also lands in this maximal sub Kan complex because the inclusion $\mathbb{2} \hookrightarrow \mathbb{I}$ can be expressed as a sequential composite of outer horn inclusions; see Exercise 1.1.iv. \square

The category of simplicial sets, like any category of presheaves, is cartesian closed. By the Yoneda lemma and the defining adjunction, an n -simplex in the exponential Y^X corresponds to a simplicial map $X \times \Delta[n] \rightarrow Y$, and its faces and degeneracies are computed by precomposing in the simplex variable. Our aim is now to show that the quasi-categories define an exponential ideal in the simplicially enriched category of simplicial sets: if X is a simplicial set and A is a quasi-category, then A^X is a quasi-category. We will deduce this as a corollary of the “relative” version of this result involving a class of maps called isofibrations that we now introduce.

1.1.17. DEFINITION (isofibrations between quasi-categories). A simplicial map $f: A \rightarrow B$ is a **isofibration** if it lifts against the inner horn inclusions, as displayed below left, and also against the inclusion of either vertex into the free-standing isomorphism \mathbb{I} .

$$\begin{array}{ccc} \Lambda^k[n] & \longrightarrow & A \\ \downarrow & \nearrow & \downarrow f \\ \Delta[n] & \longrightarrow & B \end{array} \qquad \begin{array}{ccc} \mathbb{I} & \longrightarrow & A \\ \downarrow & \nearrow & \downarrow f \\ \mathbb{I} & \longrightarrow & B \end{array}$$

To notationally distinguish the isofibrations, we depict them as arrows “ \twoheadrightarrow ” with two heads.

1.1.18. OBSERVATION.

- (i) For any simplicial set X , the unique map $X \rightarrow *$ whose codomain is the terminal simplicial set is an isofibration if and only if X is a quasi-category.
- (ii) Any class of maps characterized by a right lifting property is automatically closed under composition, product, pullback, retract, and limits of towers; see Lemma C.1.1.
- (iii) Combining (i) and (ii), if $A \twoheadrightarrow B$ is an isofibration, and B is a quasi-category, then so is A .
- (iv) The isofibrations generalize the eponymous categorical notion. The nerve of any functor $f: A \rightarrow B$ between categories defines a map of simplicial sets that lifts against the inner horn inclusions. This map then defines an isofibration if and only if given any isomorphism in B and specified object in A lifting either its domain or codomain, there exists an isomorphism in A with that domain or codomain lifting the isomorphism in B .

We typically only deploy the term “isofibration” for a map between quasi-categories because our usage of this class of maps intentionally parallels the classical categorical case.

Much harder to establish is the stability of the class of isofibrations under forming “Leibniz exponentials” as displayed in (1.1.20). The proof of this result is given in Proposition ?? in Appendix D.

1.1.19. PROPOSITION. *If $i: X \hookrightarrow Y$ is a monomorphism and $f: A \twoheadrightarrow B$ is an isofibration, then the induced Leibniz exponential map*

$$\begin{array}{ccc}
 A^Y & \xrightarrow{A^i} & A^X \\
 \downarrow f^Y & \searrow \widehat{i \pitchfork f} & \downarrow f^X \\
 & \bullet & \\
 & \downarrow & \\
 B^Y & \xrightarrow{B^i} & B^X
 \end{array}
 \quad (1.1.20)$$

*is again an isofibration.*⁶

1.1.21. COROLLARY. *If X is a simplicial set and A is a quasi-category, then A^X is a quasi-category. Moreover, a 1-simplex in A^X is an isomorphism if and only if its components at each vertex of X are isomorphisms in A .*

PROOF. The first statement is a special case of Proposition 1.1.19; see Exercise 1.1.vi. The second statement is proven similarly by arguing with marked simplicial sets. See Lemma ??. \square

1.1.22. DEFINITION (equivalences of quasi-categories). A map $f: A \rightarrow B$ between quasi-categories is an **equivalence** if it extends to the data of a “homotopy equivalence” with the free-living isomorphism \mathbb{I} serving as the interval: that is, if there exist maps $g: B \rightarrow A$ and

$$\begin{array}{ccc}
 & A & \\
 \nearrow & \uparrow \text{ev}_0 & \\
 A & \xrightarrow{\alpha} A^{\mathbb{I}} & \\
 \searrow & \downarrow \text{ev}_1 & \\
 & A &
 \end{array}
 \quad
 \begin{array}{ccc}
 & B & \\
 \nearrow fg & \uparrow \text{ev}_0 & \\
 B & \xrightarrow{\beta} B^{\mathbb{I}} & \\
 \searrow & \downarrow \text{ev}_1 & \\
 & B &
 \end{array}$$

We write “ \simeq ” to decorate equivalences and $A \simeq B$ to indicate the presence of an equivalence $A \simeq B$.

1.1.23. DEFINITION. A map $f: X \rightarrow Y$ between simplicial sets is a **trivial fibration** if it admits lifts against the boundary inclusions for all simplices

$$\begin{array}{ccc}
 \partial\Delta[n] & \longrightarrow & X \\
 \downarrow & \nearrow & \downarrow f \\
 \Delta[n] & \longrightarrow & Y
 \end{array}
 \quad n \geq 0
 \quad (1.1.24)$$

We write “ \twoheadrightarrow ” to decorate trivial fibrations.

1.1.25. REMARK. The simplex boundary inclusions $\partial\Delta[n] \hookrightarrow \Delta[n]$ “cellularly generate” the monomorphisms of simplicial sets — see Definition C.1.2 and Lemma D.1.2. Hence the dual of Lemma C.1.1

⁶Degenerate cases of this result, taking $X = \emptyset$ or $B = 1$, imply that the other six maps in this diagram are also isofibrations; see Exercise 1.1.vi.

implies that trivial fibrations lift against any monomorphism between simplicial sets. In particular, applying this to the map $\emptyset \rightarrow Y$, it follows that any trivial fibration $X \rightrightarrows Y$ is a split epimorphism.

The notation “ \rightrightarrows ” is suggestive: the trivial fibrations between quasi-categories are exactly those maps that are both isofibrations and equivalences. This can be proven by a relatively standard although rather technical argument in simplicial homotopy theory, given as Proposition ?? in Appendix D.

1.1.26. PROPOSITION. *For a map $f: A \rightarrow B$ between quasi-categories the following are equivalent:*

- (i) *f is a trivial fibration*
- (ii) *f is both an isofibration and an equivalence*
- (iii) *f is a **split fiber homotopy equivalence**: an isofibration admitting a section s that is also an equivalence inverse via a homotopy from sf to 1_A that composes with f to the constant homotopy from f to f .*

As a class characterized by a right lifting property, the trivial fibrations are also closed under composition, product, pullback, limits of towers, and contain the isomorphisms. The stability of these maps under Leibniz exponentiation will be verified along with Proposition 1.1.19 in Proposition ??.

1.1.27. PROPOSITION. *If $i: X \rightarrow Y$ is a monomorphism and $f: A \rightarrow B$ is an isofibration, then if either f is a trivial fibration or if i is in the class cellularly generated⁷ by the inner horn inclusions and the map $\mathbb{I} \hookrightarrow \mathbb{I}$ then the induced Leibniz exponential map*

$$A^Y \xrightarrow{i \hat{\cap} f} B^Y \times_{B^X} A^X$$

is a trivial fibration.

1.1.28. DIGRESSION (the Joyal model structure). The category of simplicial set bears a model structure (see Appendix D) whose fibrant objects are exactly the quasi-categories; all objects are cofibrant. The fibrations, weak equivalences, and trivial fibrations between fibrant objects are precisely the classes of isofibrations, equivalences, and trivial fibrations defined above. Proposition 1.1.26 proves that the trivial fibrations are the intersection of the classes of fibrations and weak equivalences. Propositions 1.1.19 and 1.1.27 reflect the fact that the Joyal model structure is a *closed monoidal model category* with respect to the cartesian closed structure on the category of simplicial sets.

We have declined to elaborate on the Joyal model structure for quasi-categories alluded to in Digression 1.1.28 because the only aspects of it that we will need are those described above. The results proven here suffice to show that the category of quasi-categories defines an ∞ -cosmos, a concept to which we now turn.

Exercises.

1.1.i. EXERCISE. Consider the set of 1-simplices in a quasi-category with initial vertex a_0 and final vertex a_1 .

- (i) Prove that the relation defined by $f \sim g$ if and only if there exists a 2-simplex with boundary

$$\begin{array}{ccc} & a_1 & \\ f \nearrow & & \searrow \\ a_0 & \xrightarrow{g} & a_1 \end{array} \quad \text{is an equivalence relation.}$$

⁷See Definition C.1.2.

- (ii) Prove that the relation defined by $f \sim g$ if and only if there exists a 2-simplex with boundary

$$\begin{array}{ccc} & a_0 & \\ \nearrow & & \searrow f \\ a_0 & \xrightarrow{g} & a_1 \end{array} \quad \text{is an equivalence relation.}$$

- (iii) Prove that the equivalence relations defined by (i) and (ii) are the same.

This proves Lemma 1.1.9.

1.1.ii. EXERCISE. Consider the free category on the reflexive directed graph

$$\begin{array}{ccc} & \xrightarrow{\delta_1} & \\ A_1 & \xleftarrow{\sigma_0} & A_0, \\ & \xrightarrow{\delta_0} & \end{array}$$

underlying a quasi-category A .

- (i) Consider the relation that identifies a pair of sequences of composable 1-simplices with common source and common target whenever there exists a simplex of A in which the sequences of 1-simplices define two paths from its initial vertex to its final vertex. Prove that this relation is stable under pre- and post-composition with 1-simplices and conclude that its transitive closure is a **congruence**: an equivalence relation that is closed under pre- and post-composition.⁸
- (ii) Consider the congruence relation generated by imposing a composition relation $h = g \circ f$ witnessed by 2-simplices

$$\begin{array}{ccc} & a_1 & \\ f \nearrow & & \searrow g \\ a_0 & \xrightarrow{h} & a_2 \end{array}$$

and prove that this coincides with the relation considered in (i).

- (iii) In the congruence relations of (i) and (ii), prove that every sequence of composable 1-simplices in A is equivalent to a single 1-simplex. Conclude that every morphism in the quotient of the free category by this congruence relation is represented by a 1-simplex in A .
- (iv) Prove that for any triple of 1-simplices f, g, h in A , $h = g \circ f$ in the quotient category if and only if there exists a 2-simplex with boundary

$$\begin{array}{ccc} & a_1 & \\ f \nearrow & & \searrow g \\ a_0 & \xrightarrow{h} & a_2 \end{array}$$

This proves Lemma 1.1.12.

1.1.iii. EXERCISE. Show that any quasi-category in which inner horns admit unique fillers is isomorphic to the nerve of its homotopy category.

1.1.iv. EXERCISE.

- (i) Prove that \mathbb{I} contains exactly two non-degenerate simplices in each dimension.

⁸Given a congruence relation on the hom-sets of a 1-category, the quotient category can be formed by quotienting each hom-set; see [39, §II.8].

- (ii) Inductively build \mathbb{I} from \mathbb{Z} by expressing the inclusion $\mathbb{Z} \hookrightarrow \mathbb{I}$ as a sequential composite of pushouts of outer horn inclusions⁹ $\Lambda^0[n] \hookrightarrow \Delta[n]$, one in each dimension starting with $n = 2$.¹⁰

1.1.v. EXERCISE. Prove the relative version of Corollary 1.1.16: for any isofibration $p: A \twoheadrightarrow B$ between quasi-categories and any isomorphism $f: \mathbb{Z} \rightarrow A$ any homotopy coherent isomorphism in B extending pf lifts to a homotopy coherent isomorphism in A extending f .

$$\begin{array}{ccc} \mathbb{Z} & \xrightarrow{f} & A \\ \downarrow & \nearrow & \downarrow p \\ \mathbb{I} & \longrightarrow & B \end{array}$$

1.1.vi. EXERCISE. Specialize Proposition 1.1.19 to prove the following:

- (i) If A is a quasi-category and X is a simplicial set then A^X is a quasi-category.
- (ii) If A is a quasi-category and $X \hookrightarrow Y$ is a monomorphism then $A^Y \twoheadrightarrow A^X$ is an isofibration.
- (iii) If $A \twoheadrightarrow B$ is an isofibration and X is a simplicial set then $A^X \twoheadrightarrow B^X$ is an isofibration.

1.1.vii. EXERCISE.

- (i) Prove that the equivalences defined in Definition 1.1.22 are closed under retracts.
- (ii) Prove that the equivalences defined in Definition 1.1.22 satisfy the 2-of-3 property.

1.2. ∞ -Cosmoi

In §1.1, we presented “analytic” proofs of a few of the basic facts about quasi-categories. The category theory of quasi-categories can be developed in a similar style, but we aim instead to develop the “synthetic” theory of infinite-dimensional categories, so that our results will apply to many models at once. To achieve this, our strategy is not to axiomatize what these infinite-dimensional categories *are*, but rather axiomatize the “universe” in which they *live*.

The following definition abstracts the properties of the quasi-categories and the classes of isofibrations, equivalences, and trivial fibrations introduced in §1.1. Firstly, the category of quasi-categories and simplicial maps is *enriched* over the category of simplicial sets — the set of morphisms from A to B coincides with the set of vertices of the simplicial set B^A — and moreover these hom-spaces are all quasi-categories. Secondly, a number of limit constructions that can be defined in the underlying 1-category of quasi-categories and simplicial maps satisfy universal properties relative to this simplicial enrichment. And finally, the classes of isofibrations, equivalences, and trivial fibrations satisfy properties that are familiar from abstract homotopy theory. In particular, the use of isofibrations in diagrams guarantees that their strict limits are equivalence invariant, so we can take advantage of up-to-isomorphism universal properties and strict functoriality of these constructions while still working “homotopically.”

As will be explained in Digression 1.2.9, there are a variety of models of infinite-dimensional categories for which the category of “ ∞ -categories,” as we will call them, and “functors” between them is

⁹By duality — the **opposite** of a simplicial set X is the simplicial set obtained by reindexing along the involution $(-)^{\text{op}}: \Delta \rightarrow \Delta$ that reverses the ordering in each ordinal — the outer horn inclusions $\Lambda^n[n] \hookrightarrow \Delta[n]$ can be used instead.

¹⁰This decomposition of the inclusion $\mathbb{Z} \hookrightarrow \mathbb{I}$ reveals which data can always be extended to a homotopy coherent isomorphism: for instance, the 1- and 2-simplices of Definition 1.1.13 together with a single 3-simplex that has these as its outer faces with its inner faces degenerate.

enriched over quasi-categories and admits classes of isofibrations, equivalences, and trivial fibrations satisfying analogous properties. This motivates the following axiomatization:

1.2.1. DEFINITION (∞ -cosmoi). An ∞ -cosmos \mathcal{K} is a category enriched over quasi-categories,¹¹ meaning that it has

- objects A, B , that we call ∞ -categories, and
- its morphisms define the vertices of **functor-spaces** $\mathbf{Fun}(A, B)$, which are quasi-categories,

that is also equipped with a specified class of maps that we call **isofibrations** and denote by “ \twoheadrightarrow .” From these classes, we define a map $f: A \rightarrow B$ to be an **equivalence** if and only the induced map $f_*: \mathbf{Fun}(X, A) \rightarrow \mathbf{Fun}(X, B)$ on functor-spaces is an equivalence of quasi-categories for all $X \in \mathcal{K}$, and we define f to be a **trivial fibration** just when f is both an isofibration and an equivalence; these classes are denoted by “ $\xrightarrow{\sim}$ ” and “ $\xrightarrow{\sim\sim}$ ” respectively. These classes must satisfy the following two axioms:

- (completeness) The simplicial category \mathcal{K} possesses a terminal object, small products, pullbacks of isofibrations, limits of countable towers of isofibrations, and cotensors with all simplicial sets, each of these limit notions satisfying a universal property that is enriched over simplicial sets.¹²
- (isofibrations) The class of isofibrations contains all isomorphisms and any map whose codomain is the terminal object; is closed under composition, product, pullback, forming inverse limits of towers, and Leibniz cotensors with monomorphisms of simplicial sets; and has the property that if $f: A \twoheadrightarrow B$ is an isofibration and X is any object then $\mathbf{Fun}(X, A) \twoheadrightarrow \mathbf{Fun}(X, B)$ is an isofibration of quasi-categories.

1.2.2. DIGRESSION (simplicial categories). A **simplicial category** \mathcal{A} is given by categories \mathcal{A}_n , with a common set of objects and whose arrows are called n -arrows, that assemble into a diagram $\Delta^{\text{op}} \rightarrow \mathbf{Cat}$ of identity-on-objects functors

$$\begin{array}{ccccccc} & & \begin{array}{c} \xrightarrow{\delta_3} \\ \xleftarrow{\sigma_2} \end{array} & & \begin{array}{c} \xrightarrow{\delta_2} \\ \xleftarrow{\sigma_1} \end{array} & & \begin{array}{c} \xrightarrow{\delta_1} \\ \xleftarrow{\sigma_0} \end{array} & & \\ \cdots & & \mathcal{A}_3 & \xleftarrow{\sigma_1} & \mathcal{A}_2 & \xleftarrow{\sigma_0} & \mathcal{A}_1 & \xleftarrow{\sigma_0} & \mathcal{A}_0, & =: \mathcal{A} & (1.2.3) \\ & & \begin{array}{c} \xleftarrow{\delta_1} \\ \xleftarrow{\sigma_0} \end{array} & & \begin{array}{c} \xleftarrow{\delta_0} \\ \xleftarrow{\sigma_0} \end{array} & & \begin{array}{c} \xleftarrow{\delta_0} \\ \xleftarrow{\sigma_0} \end{array} & & \end{array}$$

The data of a simplicial category can equivalently be encoded by a **simplicially enriched category** with a set of objects and a simplicial set $\mathcal{A}(x, y)$ of morphisms between each ordered pair of objects: an n -arrow in \mathcal{A}_n from x to y corresponds to an n -simplex in $\mathcal{A}(x, y)$ (see Exercise 1.2.i). Each endo-hom-space contains a distinguished identity 0-arrow (the degenerate images of which define the corresponding identity n -arrows) and composition is required to define a simplicial map

$$\mathcal{A}(y, z) \times \mathcal{A}(x, y) \xrightarrow{\circ} \mathcal{A}(x, z)$$

the single map encoding the compositions in each of the categories \mathcal{A}_n and also the functoriality of the diagram (1.2.3). The composition is required to be associative and unital, in a sense expressed by

¹¹This is to say \mathcal{K} is a simplicially enriched category whose hom-spaces are quasi-categories; this will be unpacked in 1.2.2.

¹²This will be elaborated upon in 1.2.4.

the commutative diagrams

$$\begin{array}{ccc}
\mathcal{A}(y, z) \times \mathcal{A}(x, y) \times \mathcal{A}(w, x) & \xrightarrow{\circ \times 1} & \mathcal{A}(x, z) \times \mathcal{A}(w, x) \\
1 \times \circ \downarrow & & \downarrow \circ \\
\mathcal{A}(y, z) \times \mathcal{A}(w, y) & \xrightarrow{\circ} & \mathcal{A}(w, z)
\end{array}
\quad
\begin{array}{ccc}
\mathcal{A}(x, y) & \xrightarrow{\text{id}_y \times 1} & \mathcal{A}(y, y) \times \mathcal{A}(x, y) \\
1 \times \text{id}_x \downarrow & \searrow & \downarrow \circ \\
\mathcal{A}(x, y) \times \mathcal{A}(x, x) & \xrightarrow{\circ} & \mathcal{A}(x, y)
\end{array}$$

the latter making use of natural isomorphisms $\mathcal{A}(x, y) \times 1 \cong \mathcal{A}(x, y) \cong 1 \times \mathcal{A}(x, y)$ in the domain vertex.

On account of the equivalence between these two presentations, the terms “simplicial category” and “simplicially-enriched category” are generally taken to be synonyms.¹³ The category \mathcal{A}_0 of 0-arrows is the **underlying category** of the simplicial category \mathcal{A} , which forgets the higher dimensional simplicial structure.

In particular, the underlying category of an ∞ -cosmos \mathcal{K} is the category whose objects are the ∞ -categories in \mathcal{K} and whose morphisms are the 0-arrows in the functor spaces. In all of the examples to appear below, this recovers the expected category of ∞ -categories in a particular model and functors between them.

1.2.4. DIGRESSION (simplicially enriched limits). Let \mathcal{A} be a simplicial category. The **cotensor** of an object $A \in \mathcal{A}$ by a simplicial set U is characterized by an isomorphism of simplicial sets

$$\mathcal{A}(X, A^U) \cong \mathcal{A}(X, A)^U \quad (1.2.5)$$

natural in $X \in \mathcal{A}$. Assuming such objects exist, the simplicial cotensor defines a bifunctor

$$\begin{aligned}
\mathcal{S}Set^{\text{op}} \times \mathcal{A} &\longrightarrow \mathcal{A} \\
(U, A) &\longmapsto A^U
\end{aligned}$$

in a unique way making the isomorphism (1.2.5) natural in U and A as well.

The other simplicial limit notions postulated by axiom 1.2.1(i) are **conical**, which is the term used for ordinary 1-categorical limit shapes that satisfy an enriched analog of the usual universal property; see Definition 7.1.14. When these limits exist they correspond to the usual limits in the underlying category, but the usual universal property is strengthened. Applying the covariant representable functor $\mathcal{A}(X, -): \mathcal{A}_0 \rightarrow \mathcal{S}Set$ to a limit cone $(\lim_{j \in J} A_j \rightarrow A_j)_{j \in J}$ in \mathcal{A}_0 , there is natural comparison map

$$\mathcal{A}(X, \lim_{j \in J} A_j) \rightarrow \lim_{j \in J} \mathcal{A}(X, A_j) \quad (1.2.6)$$

and we say that $\lim_{j \in J} A_j$ defines a **simplicially enriched limit** if and only if (1.2.6) is an isomorphism of simplicial sets for all $X \in \mathcal{A}$.

Considerably more details on the general theory of enriched categories can be found in [31] and in Appendix A. Enriched limits are the subject of §A.

1.2.7. REMARK (flexible weighted limits in ∞ -cosmoi). The axiom 1.2.1(i) implies that any ∞ -cosmos \mathcal{K} admits all *flexible limits* (see Corollary 7.3.3), a much larger class of simplicially enriched “weighted” limits that will be introduced in §7.2.

¹³The phrase “simplicial object in \mathcal{Cat} ” is reserved for the more general yet less common notion of a diagram $\Delta^{\text{op}} \rightarrow \mathcal{Cat}$ that is not necessarily comprised of identity-on-objects functors.

Using the results of Joyal discussed in §1.1, we can easily verify:

1.2.8. PROPOSITION. *The full subcategory $\mathcal{QCat} \subset \mathcal{SSet}$ of quasi-categories defines an ∞ -cosmos with the isofibrations, equivalences, and trivial fibrations of Definitions 1.1.17, 1.1.22, and 1.1.23.*

PROOF. The subcategory $\mathcal{QCat} \subset \mathcal{SSet}$ inherits its simplicial enrichment from the cartesian closed category of simplicial sets: note that for quasi-categories A and B , $\text{Fun}(A, B) := B^A$ is again a quasi-category.

The limits postulated in 1.2.1(i) exist in the ambient category of simplicial sets.¹⁴ The defining universal property of the simplicial cotensor is satisfied by the exponentials of simplicial sets. We now argue that the full subcategory of quasi-categories inherits all these limit notions.

Since the quasi-categories are characterized by a right lifting property, it is clear that they are closed under small products. Similarly, since the class of isofibrations is characterized by a right lifting property, Lemma C.1.1 implies that the fibrations are closed under all of the limit constructions of 1.2.1(ii) except for the last two: Leibniz closure and closure under exponentiation $(-)^X$. These last closure properties are established in Proposition 1.1.19. This completes the proof of 1.2.1(i) and 1.2.1(ii).

Remark 1.1.25 proves that trivial fibrations split once we verify that the classes of trivial fibrations and of equivalences coincide with those defined by 1.1.23 and 1.1.22. By Proposition 1.1.26 the former coincidence follows from the latter, so it remains only to show that the equivalences of 1.1.22 coincide with the **representably-defined equivalences**: those maps of quasi-categories $f: A \rightarrow B$ for which $A^X \rightarrow B^X$ is an equivalence of quasi-categories in the sense of 1.1.22. Taking $X = \Delta[0]$, we see immediately that representably-defined equivalences are equivalences, and the converse holds since the exponential $(-)^X$ preserves the data defining a simplicial homotopy. \square

We mention a common source of ∞ -cosmoi found in nature at the outside to help ground the intuition for readers familiar with Quillen’s model categories, a popular framework for “abstract homotopy theory,” but reassure others that model categories are not needed outside of Appendix E.

1.2.9. DIGRESSION (a source of ∞ -cosmoi in nature). As explained in Appendix E, certain easily described properties of a model category imply that the full subcategory of fibrant objects defines an ∞ -cosmos whose isofibrations, equivalences, and trivial fibrations are the fibrations, weak equivalences, and trivial fibrations between fibrant objects. Namely, any model category that is enriched as such over the Joyal model structure on simplicial sets and with the property that all fibrant objects are cofibrant has this property. This compatible enrichment in the Joyal model structure can be defined when the model category is cartesian closed and equipped with a right Quillen adjoint to the Joyal model structure on simplicial sets whose left adjoint preserves finite products. In this case, the right adjoint becomes the underlying quasi-category functor (see Proposition 1.3.3(ii)) and the ∞ -cosmoi so-produced will then be cartesian closed (see Definition 1.2.18). The ∞ -cosmoi listed in Example 1.2.19 all arise in this way.

The following results are consequences of the axioms of Definition 1.2.1. The first of these results tells us that the trivial fibrations enjoy all of the same stability properties satisfied by the isofibrations.

1.2.10. LEMMA (stability of trivial fibrations). *The trivial fibrations in an ∞ -cosmos define a subcategory containing the isomorphisms; are stable under product, pullback, forming inverse limits of towers; the Leibniz cotensors of any trivial fibration with a monomorphism of simplicial sets is a trivial fibration as is the Leibniz*

¹⁴Any category of presheaves is cartesian closed, complete, and cocomplete — a “cosmos” in the sense of Bénabou. Our ∞ -cosmoi are more similar to the fibrational cosmoi due to Street [57].

cotensor of an isofibration with a map in the class cellularly generated by the inner horn inclusions and the map $\mathbb{1} \hookrightarrow \mathbb{I}$; and if $E \rightrightarrows B$ is a trivial fibration then so is $\mathbf{Fun}(X, E) \rightrightarrows \mathbf{Fun}(X, B)$.

PROOF. We prove these statements in the reverse order. By axiom 1.2.1(ii) and the definition of the trivial fibrations in an ∞ -cosmos, we know that if $E \rightrightarrows B$ is a trivial fibration then is $\mathbf{Fun}(X, E) \rightrightarrows \mathbf{Fun}(X, B)$ is both an isofibration and an equivalence, and hence by Proposition 1.1.26 a trivial fibration. For stability under the remaining constructions, we know in each case that the maps in question are isofibrations in the ∞ -cosmos; it remains to show only that the maps are also equivalences. The equivalences in an ∞ -cosmos are defined to be the maps that $\mathbf{Fun}(X, -)$ carries to equivalences of quasi-categories, so it suffices to verify that trivial fibrations of quasi-categories satisfy the corresponding stability properties. This is established in Proposition 1.1.27 and the fact that that class is characterized by a right lifting property. \square

Additionally, every trivial fibration is “split” by a section.

1.2.11. LEMMA (trivial fibrations split). *Every trivial fibration admits a section*

$$\begin{array}{ccc} & & E \\ & \nearrow & \downarrow \\ B & \xlongequal{\quad} & B \end{array}$$

PROOF. If $p: E \rightrightarrows B$ is a trivial fibration, then by the final stability property of Lemma 1.2.10, so is $p_*: \mathbf{Fun}(B, E) \rightarrow \mathbf{Fun}(B, B)$. By Definition 1.1.23, we may solve the lifting problem

$$\begin{array}{ccc} \emptyset = \partial\Delta[0] & \longrightarrow & \mathbf{Fun}(B, E) \\ \downarrow & \nearrow s & \downarrow p_* \\ \Delta[0] & \xrightarrow{\text{id}_B} & \mathbf{Fun}(B, B) \end{array}$$

to find a map $s: B \rightarrow E$ so that $ps = \text{id}_B$. \square

A classical construction in abstract homotopy theory proves the following:

1.2.12. LEMMA (Brown factorization lemma). *Any functor $f: A \rightarrow B$ in an ∞ -cosmos may be factored as an equivalence followed by an isofibration, where this equivalence is constructed as a section of a trivial fibration.*

$$\begin{array}{ccc} & Pf & \\ q \nearrow & & \searrow p \\ A & \xrightarrow{s} & B \\ & \xrightarrow{f} & \end{array} \quad (1.2.13)$$

PROOF. The displayed factorization is constructed by the pullback of an isofibration formed by the simplicial cotensor of the inclusion $\mathbb{1} + \mathbb{1} \hookrightarrow \mathbb{I}$ into the ∞ -category B .

$$\begin{array}{ccccc}
 & & A^{\mathbb{I}} & & \\
 & \nearrow \Delta & & \searrow f^{\mathbb{I}} & \\
 A & \overset{\sim}{\dashrightarrow} Pf & \xrightarrow{\quad} & B^{\mathbb{I}} & \\
 \downarrow (A,f) & \downarrow (q,p) & \lrcorner & \downarrow (ev_0, ev_1) & \\
 & A \times B & \xrightarrow{f \times B} & B \times B &
 \end{array}$$

Note the map q is a pullback of the trivial fibration $ev_0: B^{\mathbb{I}} \rightrightarrows B$ and is hence a trivial fibration. Its section s , constructed by applying the universal property of the pullback to the displayed cone with summit A , is thus an equivalence. \square

1.2.14. REMARK (equivalences satisfy the 2-of-6 property). Exercise 1.1.vii proves that the equivalences between quasi-categories — and hence also the equivalences in any ∞ -cosmos — are closed under retracts and have the 2-of-3 property. Using this latter fact, we see that in the case where $f: A \rightarrow B$ is an equivalence, the map p of (1.2.13) is also a trivial fibration, and in particular has a section by Lemma 1.2.11. Combining these facts, a result of Blumberg and Mandell [7, 6.4] reproduced in Appendix C applies to prove that the equivalences in any ∞ -cosmos satisfy the stronger **2-of-6 property**: for any composable triple of morphisms

$$\begin{array}{ccccc}
 & & B & & \\
 & \nearrow f & & \searrow hg & \\
 A & \xrightarrow{hgf} & & \xrightarrow{\quad} & D \\
 & \searrow gf & & \nearrow h & \\
 & & C & &
 \end{array}$$

if gf and hg are equivalences then f , g , h , and hgf are too.

By a Yoneda-style argument, the “homotopy equivalence” characterization of the equivalences in the ∞ -cosmos of quasi-categories extends to an analogous characterization of the equivalences in any ∞ -cosmos:

1.2.15. LEMMA (equivalences are homotopy equivalences). *A map $f: A \rightarrow B$ between ∞ -categories in an ∞ -cosmos \mathcal{K} is an equivalence if and only if it extends to the data of a “homotopy equivalence” with the free-living isomorphism \mathbb{I} serving as the interval: that is, if there exist maps $g: B \rightarrow A$ and*

$$\begin{array}{ccc}
 \begin{array}{ccc}
 & A & \\
 & \parallel & \\
 A & \xrightarrow{\alpha} & A^{\mathbb{I}} \\
 & \searrow gf & \\
 & & A
 \end{array}
 &
 \begin{array}{ccc}
 & B & \\
 & \parallel & \\
 B & \xrightarrow{\beta} & B^{\mathbb{I}} \\
 & \searrow fg & \\
 & & B
 \end{array}
 & (1.2.16)
 \end{array}$$

in the ∞ -cosmos.

PROOF. By hypothesis, if $f: A \rightarrow B$ defines an equivalence in the ∞ -cosmos \mathcal{K} then the induced map on post-composition $f_*: \mathbf{Fun}(B, A) \rightleftarrows \mathbf{Fun}(B, B)$ is an equivalence of quasi-categories. Evaluating the equivalence inverse $\tilde{g}: \mathbf{Fun}(B, B) \rightleftarrows \mathbf{Fun}(B, A)$ and homotopy $\tilde{\beta}: \mathbf{Fun}(B, B) \rightarrow \mathbf{Fun}(B, B)^{\mathbb{I}}$ at the 0-arrow $1_B \in \mathbf{Fun}(B, B)$, we obtain a 0-arrow $g: B \rightarrow A$ together with an isomorphism $\mathbb{I} \rightarrow \mathbf{Fun}(B, B)$ from the composite fg to 1_B . By the defining universal property of the cotensor, this isomorphism internalizes to define the map $\beta: B \rightarrow B^{\mathbb{I}}$ in \mathcal{K} displayed on the right of (1.2.16).

Now the hypothesis that f is an equivalence also provides an equivalence of quasi-categories $f_*: \mathbf{Fun}(A, A) \rightleftarrows \mathbf{Fun}(A, B)$ and the map $\beta f: A \rightarrow B^{\mathbb{I}}$ represents an isomorphism in $\mathbf{Fun}(A, B)$ from fgf to f . Since f_* is an equivalence, we can conclude that 1_A and gf are isomorphic in the quasi-category $\mathbf{Fun}(A, A)$: such an isomorphism may be defined by applying the inverse equivalence $\tilde{h}: \mathbf{Fun}(A, B) \rightarrow \mathbf{Fun}(A, A)$ and composing with the components at $1_A, gf \in \mathbf{Fun}(A, A)$ of the isomorphism $\tilde{\alpha}: \mathbf{Fun}(A, A) \rightarrow \mathbf{Fun}(A, A)^{\mathbb{I}}$ from $1_{\mathbf{Fun}(A, A)}$ to $\tilde{h}f_*$. Now by Corollary 1.1.16 this isomorphism is represented by a map $\mathbb{I} \rightarrow \mathbf{Fun}(A, A)$ from 1_A to gf , which internalizes to a map $\alpha: A \rightarrow A^{\mathbb{I}}$ in \mathcal{K} displayed on the left of (1.2.16).

The converse is easy: the simplicial cotensor construction commutes with $\mathbf{Fun}(X, -)$ so homotopy equivalences are preserved and by Definition 1.1.22 homotopy equivalences of quasi-categories define equivalences of quasi-categories. \square

One of the key advantages of the ∞ -cosmological approaches to abstract category theory is that there are a myriad varieties of “fibered” ∞ -cosmoi that can be built from a given ∞ -cosmos, which means that any theorem proven in this axiomatic framework specializes and generalizes to those contexts. The most basic of these derived ∞ -cosmos is the ∞ -cosmos of isofibrations over a fixed base, which we introduce now. Other examples of ∞ -cosmoi will be introduced in §7.4, once we have developed a greater facility with the simplicial limits of axiom 1.2.1(i).

1.2.17. PROPOSITION (sliced ∞ -cosmoi). *For any ∞ -cosmos \mathcal{K} and any object $B \in \mathcal{K}$ there is an ∞ -cosmos \mathcal{K}_B of isofibrations over B whose*

- (i) *objects are isofibrations $p: E \twoheadrightarrow B$ with codomain B*
- (ii) *functor-spaces, say from $p: E \twoheadrightarrow B$ to $q: F \twoheadrightarrow B$, are defined by pullback*

$$\begin{array}{ccc} \mathbf{Fun}_B(p: E \twoheadrightarrow B, q: F \twoheadrightarrow B) & \longrightarrow & \mathbf{Fun}(E, F) \\ \downarrow & \lrcorner & \downarrow q_* \\ \mathbb{1} & \xrightarrow{p} & \mathbf{Fun}(E, B) \end{array}$$

and abbreviated to $\mathbf{Fun}_B(E, F)$ when the specified isofibrations are clear from context

- (iii) *isofibrations are commutative triangles of isofibrations over B*

$$\begin{array}{ccc} E & \xrightarrow{r} & F \\ p \searrow & & \swarrow q \\ & B & \end{array}$$

(iv) terminal object is $1: B \rightarrow B$ and products are defined by the pullback along the diagonal

$$\begin{array}{ccc} \times_i^B E_i & \longrightarrow & \prod_i E_i \\ \downarrow & \lrcorner & \downarrow \\ B & \xrightarrow{\Delta} & \prod_i B \end{array}$$

(v) pullbacks and limits of towers of isofibrations are created by the forgetful functor $\mathcal{K}_B \rightarrow \mathcal{K}$

(vi) simplicial cotensors $p: E \rightrightarrows B$ by $U \in \mathcal{SSet}$ are denoted $U \pitchfork_B p$ and constructed by the pullback

$$\begin{array}{ccc} U \pitchfork_B p & \longrightarrow & E^U \\ \downarrow & \lrcorner & \downarrow p^U \\ B & \xrightarrow{\Delta} & B^U \end{array}$$

(vii) and in which a map

$$\begin{array}{ccc} E & \xrightarrow{f} & F \\ p \searrow & & \swarrow q \\ & B & \end{array}$$

over B is an equivalence in the ∞ -cosmos \mathcal{K}_B if and only if f is an equivalence in \mathcal{K} .

PROOF. Note first that the functor spaces are quasi-categories since axiom 1.2.1(ii) asserts that for any isofibration $q: F \rightrightarrows B$ in \mathcal{K} the map $q_*: \text{Fun}(E, F) \rightrightarrows \text{Fun}(E, B)$ is an isofibration of quasi-categories. Other parts of this axiom imply that each of the limit constructions define isofibrations over B . The closure properties of the isofibrations in \mathcal{K}_B follow from the corresponding ones in \mathcal{K} . The most complicated of these is the Leibniz cotensor stability of the isofibrations in \mathcal{K}_B , which follows from the corresponding property in \mathcal{K} , since for a monomorphism of simplicial sets $i: X \hookrightarrow Y$ and an isofibration r over B as above, the map $i \widehat{\pitchfork}_B r$ is constructed by pulling back $i \widehat{\pitchfork} r$ along $\Delta: B \rightarrow B^Y$.

The fact that the above constructions define simplicially enriched limits in a simplicially enriched slice category are standard from enriched category theory. It remains only to verify that the equivalences in the ∞ -cosmos of isofibrations are created by the forgetful functor $\mathcal{K}_B \rightarrow \mathcal{K}$. First note that if $f: E \rightarrow F$ defines an equivalence in \mathcal{K} , then for any isofibration $s: A \rightrightarrows B$ the induced equivalence on functor-spaces in \mathcal{K} pulls back to define an equivalence on corresponding functor spaces in \mathcal{K}_B .

$$\begin{array}{ccccc} \text{Fun}_B(A, E) & \xrightarrow{\quad} & \text{Fun}(A, E) & & \\ \downarrow & \searrow f_* & \downarrow p_* & \searrow f_* & \\ & \text{Fun}_B(A, F) & \xrightarrow{\quad} & \text{Fun}(A, F) & \\ & \downarrow & & \downarrow q_* & \\ \mathbb{1} & \xleftarrow{\quad} & \text{Fun}(A, B) & & \end{array}$$

This can be verified either by appealing to Lemmas 1.2.10 and 1.2.12 and using standard techniques from simplicial homotopy theory¹⁵ or by appealing to Lemma 1.2.15 and using the fact that pullback along r defines a simplicial functor.

For the converse implication, we appeal to Lemma 1.2.15. If $f: E \rightarrow F$ is an equivalence in \mathcal{K}_B then it admits a homotopy inverse in \mathcal{K}_B . The inverse equivalence $g: F \rightarrow E$ also defines an inverse equivalence in \mathcal{K} and the required simplicial homotopies in \mathcal{K} are defined by composing

$$E \xrightarrow{\alpha} \mathbb{I} \pitchfork_B E \longrightarrow E^{\mathbb{I}} \quad F \xrightarrow{\beta} \mathbb{I} \pitchfork_B F \rightarrow F^{\mathbb{I}}$$

with the top horizontal leg of the pullback defining the cotensor in \mathcal{K}_B . \square

1.2.18. DEFINITION (cartesian closed ∞ -cosmoi). An ∞ -cosmos \mathcal{K} is **cartesian closed** if the product bifunctor $- \times -: \mathcal{K} \times \mathcal{K} \rightarrow \mathcal{K}$ extends to a simplicially enriched two-variable adjunction

$$\mathrm{Fun}(A \times B, C) \cong \mathrm{Fun}(A, C^B) \cong \mathrm{Fun}(B, C^A)$$

in which the right adjoint $(-)^A$ preserve the class of isofibrations.

For instance, the ∞ -cosmos of quasi-categories is cartesian closed, with the exponentials defined as (special cases of) simplicial cotensors. This is one of the reasons that we use the same notation for cotensor and for exponential.¹⁶

1.2.19. EXAMPLE (∞ -cosmoi of $(\infty, 1)$ -categories). The following models of $(\infty, 1)$ -categories define cartesian closed ∞ -cosmoi:

- (i) Rezk’s **complete Segal spaces** define the objects of an ∞ -cosmos **CSS**, in which the isofibrations, equivalences, and trivial fibrations are the corresponding classes of the model structure of [45].¹⁷
- (ii) The **Segal categories** defined by Dwyer, Kan, and Smith [18] and developed by Hirschowitz and Simpson [23] define the objects of an ∞ -cosmos **Segal**, in which the isofibrations, equivalences and trivial fibrations are the corresponding classes of the model structure of [43] and [3].¹⁸
- (iii) The **1-complicial sets** of [61], equivalently the “naturally marked quasi-categories” of [36], define the objects of an ∞ -cosmos **1-Comp** in which the isofibrations, equivalences and trivial fibrations are the corresponding classes of the model structure from either of these sources.

Proofs of these facts can be found in Appendix E.

Appendix E also proves that certain models of (∞, n) -categories or even (∞, ∞) -categories define ∞ -cosmoi.

¹⁵In more detail: any functor between the 1-categories underlying ∞ -cosmoi that preserves trivial fibrations also preserves equivalences

¹⁶Another reason for this convenient notational conflation will be explained in §2.3.

¹⁷Warning: the model category of complete Segal spaces is enriched over simplicial sets in two distinct “directions” — one enrichment makes the simplicial set of maps between two complete Segal spaces into a Kan complex that probes the “spacial” structure while another enrichment makes the simplicial set of maps into a quasi-category that probes the “categorical” structure [26]. It is this latter enrichment that we want.

¹⁸Here we reserve the term “Segal category” for those simplicial objects with a discrete set of objects that are Reedy fibrant and satisfy the Segal condition. The traditional definition does not include the Reedy fibrancy condition because it is not satisfied by the simplicial object defined as the nerve of a Kan complex enriched category. Since Kan complex enriched categories are not among our preferred models of $(\infty, 1)$ -categories this does not bother us.

1.2.20. EXAMPLE (\mathcal{Cat} as an ∞ -cosmos). The category \mathcal{Cat} of 1-categories defines a cartesian closed ∞ -cosmos, inheriting its structure as a full subcategory $\mathcal{Cat} \hookrightarrow \mathcal{QCat}$ of the ∞ -cosmos of quasi-categories via the nerve embedding, which preserves all limits and also exponentials: the nerve of the functor category B^A is the exponential of the nerves.

In the ∞ -cosmos of categories, the isofibrations are the **isofibrations**: functors satisfying the displayed right lifting property:

$$\begin{array}{ccc} \mathbb{I} & \longrightarrow & A \\ \downarrow & \nearrow & \downarrow f \\ \mathbb{I} & \longrightarrow & B \end{array}$$

The equivalences are the equivalences of categories and the trivial fibrations are **surjective equivalences**: equivalences of categories that are also surjective on objects.

1.2.21. DEFINITION (discrete ∞ -categories). An object E in an ∞ -cosmos \mathcal{K} is **discrete** just when for all $X \in \mathcal{K}$ the functor-space $\mathbf{Fun}(X, E)$ is a Kan complex.

In the ∞ -cosmos of quasi-categories, the discrete objects are exactly the Kan complexes: by Proposition ?? the Kan complexes also define an exponential ideal in the category of simplicial sets. Similarly, in the ∞ -cosmoi of Example 1.2.19 whose ∞ -categories are $(\infty, 1)$ -categories in some model, the discrete objects are the ∞ -groupoids.

1.2.22. PROPOSITION (∞ -cosmos of discrete objects). *The full subcategory $\mathcal{Disc}(\mathcal{K}) \hookrightarrow \mathcal{K}$ spanned by the discrete objects in any ∞ -cosmos form an ∞ -cosmos.*

PROOF. We first establish this result for the ∞ -cosmos of quasi-categories. By Proposition 1.1.14 an isofibration between Kan complexes is a **Kan fibration**: a map with the right lifting property with respect to all horn inclusions. Conversely, all Kan fibrations define isofibrations. Since Kan complexes are closed under simplicial cotensor (which coincides with exponentiation), It follows that the full subcategory $\mathcal{Kan} \hookrightarrow \mathcal{QCat}$ is closed under all of the limit constructions of axiom 1.2.1(i). The remaining axiom 1.2.1(ii) is inherited from the analogous properties established for quasi-categories in Proposition 1.2.8.

In a generic ∞ -cosmos \mathcal{K} we need only show that the discrete objects are closed in \mathcal{K} under the limit constructions of 1.2.1(i). The definition natural isomorphism (1.2.6) characterizing these simplicial limits expresses the functor-space $\mathbf{Fun}(X, \lim_{j \in J} A_j)$ as an analogous limit of functor space $\mathbf{Fun}(X, A_j)$. If each A_j is discrete then these objects are Kan complexes and the previous paragraph then establishes that the limit is a Kan complex as well. This holds for all objects $X \in \mathcal{K}$ so it follows that $\lim_{j \in J} A_j$ is discrete as required. \square

Exercises.

1.2.i. EXERCISE. Prove that the following are equivalent:

- (i) a simplicial category, as in 1.2.2,
- (ii) a category enriched over simplicial sets.

1.2.ii. EXERCISE. Elaborate on the proof of Proposition 1.2.8 by proving that the simplicially enriched category \mathcal{QCat} admits conical products satisfying the universal property of Digression 1.2.4. That is:

- (i) For quasi-categories A, B, X , form the cartesian product $A \times B$ and prove that the projection maps $\pi_A: A \times B \rightarrow A$ and $\pi_B: A \times B \rightarrow B$ induce an isomorphism of quasi-categories

$$(A \times B)^X \xrightarrow{\cong} A^X \times B^X.$$

- (ii) Explain how this relates to the universal property of Digression 1.2.4.
 (iii) Express the usual 1-categorical universal property of the product $A \times B$ as the “0-dimensional aspect” of the universal property of (i).

1.2.iii. EXERCISE. Prove that any object in an ∞ -cosmos has a **path object**

$$\begin{array}{ccc} & B^{\mathbb{I}} & \\ \swarrow \scriptstyle \sim & \searrow \scriptstyle (ev_0, ev_1) & \\ B & \xrightarrow{\Delta} & B \times B \end{array}$$

constructed by cotensoring with the free-living isomorphism.

1.2.iv. EXERCISE.

- (i) Use Exercise 1.1.iv and results from Appendix D to prove that a quasi-category Q is a Kan complex if and only if the map $Q^{\mathbb{I}} \rightrightarrows Q^2$ induced by the inclusion $2 \hookrightarrow \mathbb{I}$ is a trivial fibration.
 (ii) Conclude that an ∞ -category A is discrete if and only if $A^{\mathbb{I}} \rightrightarrows A^2$ is a trivial fibration.

1.3. Cosmological functors

Certain “right adjoint type” constructions define maps between ∞ -cosmoi that preserve all of the structures axiomatized in Definition 1.2.1. The simple observation that such constructions define *cosmological functors* between ∞ -cosmoi will streamline many proofs.

1.3.1. DEFINITION (cosmological functor). A **cosmological functor** is a simplicial functor $F: \mathcal{K} \rightarrow \mathcal{L}$ that preserves the specified classes of isofibrations and all of the simplicial limits enumerated in 1.2.1(i).

1.3.2. LEMMA. *Any cosmological functor also preserves the equivalences and the trivial fibrations.*

PROOF. By Lemma 1.2.15 the equivalences in an ∞ -cosmos coincide with the homotopy equivalences defined relative to cotensoring with the free-living isomorphism. Since a cosmological functor preserves simplicial cotensors, it preserves the data displayed in (1.2.16) and hence carries equivalences to equivalences. The statement about trivial fibrations follows. \square

In general, cosmological functors preserve any ∞ -categorical notion that can be characterized internally to the ∞ -cosmos — for instance, as a property of a certain map — as opposed to externally — for instance, in a statement that involves a universal quantifier. From Definition 1.2.21 it is not clear whether cosmological functors preserve discrete objects, but using the internal characterization of Exercise 1.2.iv — an ∞ -category A is discrete if and only if $A^{\mathbb{I}} \rightrightarrows A^2$ is at trivial fibration — this follows easily: cosmological functors preserve simplicial cotensors and trivial fibrations.

1.3.3. PROPOSITION.

- (i) For any object A in an ∞ -cosmos \mathcal{K} , $\text{Fun}(A, -): \mathcal{K} \rightarrow \mathcal{QCat}$ defines a cosmological functor.
 (ii) Specializing, each ∞ -cosmos has an *underlying quasi-category functor*

$$(-)_0 := \text{Fun}(1, -): \mathcal{K} \rightarrow \mathcal{QCat}.$$

- (iii) For any ∞ -cosmos \mathcal{K} and any simplicial set U , the simplicial cotensor defines a cosmological functor $(-)^U: \mathcal{K} \rightarrow \mathcal{K}$.
- (iv) For any object A in a cartesian closed ∞ -cosmos \mathcal{K} , exponentiation defines a cosmological functor $(-)^A: \mathcal{K} \rightarrow \mathcal{K}$.
- (v) For any map $f: A \rightarrow B$ in an ∞ -cosmos \mathcal{K} , pullback defines a cosmological functor $f^*: \mathcal{K}_B \rightarrow \mathcal{K}_A$.
- (vi) For any cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ and any $A \in \mathcal{K}$, the induced map on slices $F: \mathcal{K}_A \rightarrow \mathcal{L}_{/A}$ defines a cosmological functor.

PROOF. The first four of these statements are nearly immediate, the preservation of isofibrations being asserted explicitly as a hypothesis in each case and the preservation of limits following from standard categorical arguments.

For (v), pullback in an ∞ -cosmos \mathcal{K} is a simplicially enriched limit construction; one consequence of this is that $f^*: \mathcal{K}_B \rightarrow \mathcal{K}_A$ defines a simplicial functor. The action of the functor f^* on a 0-arrow g in \mathcal{K}_B is also defined by a pullback square: since the front and back squares in the displayed diagram are pullbacks the top square is as well

$$\begin{array}{ccc}
 f^*E & \xrightarrow{\quad} & E \\
 \downarrow f^*(g) & \lrcorner & \downarrow p \\
 A & \xrightarrow{\quad f \quad} & B
 \end{array}
 \quad
 \begin{array}{ccc}
 & & E \\
 & \searrow g & \\
 & & F \\
 & \swarrow q & \\
 & & B
 \end{array}$$

Since isofibrations are stable under pullback, it follows that $f^*: \mathcal{K}_B \rightarrow \mathcal{K}_A$ preserves isofibrations. It remains to prove that this functor preserves the simplicial limits constructed in Proposition 1.2.17. In the case of connected limits, which are created by the forgetful functors to \mathcal{K} , this is clear. For products and simplicial cotensors, this follows from the commutative cubes

$$\begin{array}{ccc}
 \times_i^A f^* E_i & \xrightarrow{\quad} & \prod_i f^* E_i \\
 \downarrow \lrcorner & \searrow & \downarrow \lrcorner \\
 \times_i^B E_i & \xrightarrow{\quad} & \prod_i E_i \\
 \downarrow & \searrow & \downarrow \\
 A & \xrightarrow{\quad \Delta \quad} & \prod_i A \\
 \downarrow f & \searrow & \downarrow \Pi_i f \\
 B & \xrightarrow{\quad \Delta \quad} & \prod_i B
 \end{array}
 \quad
 \begin{array}{ccc}
 U \pitchfork_A f^*(p) & \xrightarrow{\quad} & (f^*E)^U \\
 \downarrow \lrcorner & \searrow & \downarrow \lrcorner \\
 U \pitchfork_B p & \xrightarrow{\quad} & E^U \\
 \downarrow & \searrow & \downarrow \\
 A & \xrightarrow{\quad \Delta \quad} & A^U \\
 \downarrow f & \searrow & \downarrow f^U \\
 B & \xrightarrow{\quad \Delta \quad} & B^U
 \end{array}$$

Since the front, back, and right faces are pullbacks, the left is as well, which is what we wanted to show.

The final statement (vi) is left as Exercise 1.3.i. □

1.3.4. NON-EXAMPLE. The forgetful functor $\mathcal{K}_B \rightarrow \mathcal{K}$ is simplicial and preserves the class of isofibrations but does *not* define a cosmological functor, failing to preserve cotensors and products. However, by Proposition 1.3.3(v), $- \times B: \mathcal{K} \rightarrow \mathcal{K}_B$ does define a cosmological functor.

1.3.5. DEFINITION (biequivalences). A cosmological functor defines a *biequivalence* $F: \mathcal{K} \rightleftarrows \mathcal{L}$ if additionally it

- (i) is **essentially surjective on objects up to equivalence**: for all $C \in \mathcal{L}$ there exists $A \in \mathcal{K}$ so that $FA \simeq C$ and
- (ii) it defines a **local equivalence**: for all $A, B \in \mathcal{K}$, the action of F on functor quasi-categories defines an equivalence

$$\mathrm{Fun}(A, B) \xrightarrow{\sim} \mathrm{Fun}(FA, FB).$$

1.3.6. REMARK. Cosmological biequivalences will be studied more systematically in Chapter 13, where we think of them as “change-of-model” functors. A basic fact is that any biequivalence of ∞ -cosmoi not only preserves equivalences but also *creates* them: a pair of objects in an ∞ -cosmos are equivalent if and only if their images in any biequivalent ∞ -cosmos are equivalent (Exercise 1.3.ii). It follows that the cosmological biequivalences satisfy the 2-of-3 property.

1.3.7. EXAMPLE (biequivalences between ∞ -cosmoi of $(\infty, 1)$ -categories).

- (i) The underlying quasi-category functors defined on the ∞ -cosmoi of complete Segal spaces, Segal categories, and 1-complicial sets

$$\mathbf{CSS} \xrightarrow[\sim]{(-)_0} \mathbf{QCat} \quad \mathbf{Segal} \xrightarrow[\sim]{(-)_0} \mathbf{QCat} \quad \mathbf{1-Comp} \xrightarrow[\sim]{(-)_0} \mathbf{QCat}$$

are all biequivalences. In the first two cases these are defined by “evaluating at the 0th row” and in the last case this is defined by “forgetting the markings.”

- (ii) There is also a cosmological biequivalence $\mathbf{QCat} \simeq \mathbf{CSS}$ defined by Joyal and Tierney [26].
- (iii) The functor $\mathbf{CSS} \simeq \mathbf{Segal}$ defined by Bergner [5] that “discretizes” a complete Segal spaces also defines a cosmological biequivalence.
- (iv) There is a further cosmological biequivalence $(-)^{\natural}: \mathbf{QCat} \rightarrow \mathbf{1-Comp}$ that gives each quasi-category its “natural marking,” with all invertible 1-simplices and all simplices in dimension greater than 1 marked.

Proofs of these facts can be found in Appendix E.

Exercises.

1.3.i. EXERCISE. Prove that for any cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ and any $A \in \mathcal{K}$, the induced map $F: \mathcal{K}_{/A} \rightarrow \mathcal{L}_{/FA}$ defines a cosmological functor.

1.3.ii. EXERCISE. Let $F: \mathcal{K} \simeq \mathcal{L}$ be a cosmological biequivalence and let $A, B \in \mathcal{K}$. Sketch a proof that if $FA \simeq FB$ in \mathcal{L} then $A \simeq B$ in \mathcal{K} (and see Exercise 1.4.i).

1.4. The homotopy 2-category

Small 1-categories define the objects of a strict 2-category¹⁹ \mathbf{Cat} of categories, functors, and natural transformations. Many basic categorical notions — those defined in terms of categories, functors, and natural transformations and their various composition operations — can be defined internally to the 2-category \mathbf{Cat} . This suggests a natural avenue for generalization: reinterpreting these same

¹⁹A comprehensive introduction to strict 2-categories appears as Appendix B. Succinctly, in parallel with Digression 1.2.2, 2-categories can be understood equally as

- “two-dimensional” categories, with objects, 0-arrows (typically called **1-cells**), and 1-arrows (typically called **2-cells**)
- or as categories enriched over \mathbf{Cat} .

definitions in a generic 2-category using its objects in place of small categories, its 1-cells in place of functors, and its 2-cells in place of natural transformations.

In Chapter 2, we will develop a non-trivial portion of the theory of ∞ -categories in any fixed ∞ -cosmos following exactly this outline, working internally to a strict 2-category that we refer to as the *homotopy 2-category* that we associate to any ∞ -cosmos. The homotopy 2-category of an ∞ -cosmos is a quotient of the full ∞ -cosmos, replacing each quasi-categorical functor-space by its homotopy category. Surprisingly, this rather destructive quotienting operation preserves quite a lot of information. Indeed, essentially all of the work in Part I will take place in the homotopy 2-category of an ∞ -cosmos. This said, we caution the reader against becoming overly seduced by homotopy 2-categories, for that structure is more of a technical convenience for reducing the complexity of our arguments than a fundamental notion of ∞ -category theory.

The homotopy 2-category for the ∞ -cosmos of quasi-categories was first introduced by Joyal in his work on the foundations of quasi-category theory.

1.4.1. DEFINITION (homotopy 2-category). Let \mathcal{K} be an ∞ -cosmos. Its **homotopy 2-category** is the strict 2-category $\mathbf{h}\mathcal{K}$ whose

- objects are the ∞ -categories, i.e., the objects A, B of \mathcal{K} ;
- 1-cells $f: A \rightarrow B$ are the 0-arrows in the functor space $\mathbf{Fun}(A, B)$ of \mathcal{K} , i.e., the ∞ -functors; and
- 2-cells $A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B$ are homotopy classes of 1-simplices in $\mathbf{Fun}(A, B)$, which we call **∞ -natural transformations**.

Put another way $\mathbf{h}\mathcal{K}$ is the 2-category with the same objects as \mathcal{K} and with hom-categories defined by

$$\mathbf{hFun}(A, B) := \mathbf{h}(\mathbf{Fun}(A, B)),$$

that is, as the homotopy category of the quasi-category $\mathbf{Fun}(A, B)$.

The **underlying category** of a 2-category is defined by simply forgetting its 2-cells. Note that an ∞ -cosmos \mathcal{K} and its homotopy 2-category $\mathbf{h}\mathcal{K}$ share the same underlying category of ∞ -categories and ∞ -functors in \mathcal{K} .

1.4.2. DIGRESSION. The homotopy category functor $\mathbf{h}: \mathcal{S}\mathcal{S}\mathcal{e}\mathcal{t} \rightarrow \mathcal{C}\mathcal{a}\mathcal{t}$ preserves finite products, as of course does its right adjoint. It follows that the adjunction of Proposition 1.1.11 induces a change-of-base adjunction

$$\begin{array}{ccc} & \xleftarrow{\mathbf{h}_*} & \\ \mathbf{2}\text{-}\mathcal{C}\mathcal{a}\mathcal{t} & \perp & \mathcal{S}\mathcal{S}\mathcal{e}\mathcal{t}\text{-}\mathcal{C}\mathcal{a}\mathcal{t} \\ & \xrightarrow{\quad} & \end{array}$$

whose left and right adjoints change the enrichment by applying the homotopy category functor or the nerve functor to the hom objects of the enriched category. Here $\mathbf{2}\text{-}\mathcal{C}\mathcal{a}\mathcal{t}$ and $\mathcal{S}\mathcal{S}\mathcal{e}\mathcal{t}\text{-}\mathcal{C}\mathcal{a}\mathcal{t}$ can each be understood as 2-categories — of enriched categories, enriched functors, and enriched natural transformations — and both change of base constructions define 2-functors [10, 6.4.3].

1.4.3. OBSERVATION (functors representing (invertible) 2-cells). By definition, 2-cells in the homotopy category $\mathbf{h}\mathcal{K}$ are represented by maps $\mathbf{2} \rightarrow \mathbf{Fun}(A, B)$ valued in the appropriate functor space and two such maps represent the same 2-cell if and only if their images are homotopic as 1-simplices in $\mathbf{Fun}(A, B)$ in the sense defined by Lemma 1.1.9.

Now a 2-cell in a 2-category is **invertible** if and only if it defines an isomorphism in the appropriate hom-category $\mathbf{hFun}(A, B)$. By Definition 1.1.13 and Corollary 1.1.16 it follows that each invertible 2-cell in $\mathbf{h}\mathcal{K}$ is represented by a map $\mathbb{I} \rightarrow \mathbf{Fun}(A, B)$.

1.4.4. LEMMA. *Any simplicial functor $F: \mathcal{K} \rightarrow \mathcal{L}$ between ∞ -cosmoi induces a 2-functor $F: \mathbf{h}\mathcal{K} \rightarrow \mathbf{h}\mathcal{L}$ between their homotopy 2-categories.*

PROOF. This follows immediately from the remarks on change of base in Digression 1.4.2 but we can also argue directly. The action of the induced 2-functor $F: \mathbf{h}\mathcal{K} \rightarrow \mathbf{h}\mathcal{L}$ on objects and 1-cells is given by the corresponding action of $F: \mathcal{K} \rightarrow \mathcal{L}$; recall an ∞ -cosmos and its homotopy 2-category have the same underlying 1-category. Each 2-cell in $\mathbf{h}\mathcal{K}$ is represented by a 1-simplex in $\mathbf{Fun}(A, B)$ which is mapped via

$$\begin{array}{ccc} \mathbf{Fun}(A, B) & \xrightarrow{F} & \mathbf{Fun}(FA, FB) \\ \begin{array}{ccc} A & \xrightarrow{f} & B \\ \Downarrow \alpha & & \\ g & & \end{array} & \longmapsto & \begin{array}{ccc} FA & \xrightarrow{Ff} & FB \\ \Downarrow F\alpha & & \\ Fg & & \end{array} \end{array}$$

to a 1-simplex representing a 2-cell in $\mathbf{h}\mathcal{L}$. Since the action $F: \mathbf{Fun}(A, B) \rightarrow \mathbf{Fun}(FA, FB)$ on functor spaces defines a morphism of simplicial sets, it preserves faces and degeneracies. In particular, homotopic 1-simplices in $\mathbf{Fun}(A, B)$ are carried to homotopic 1-simplices in $\mathbf{Fun}(FA, FB)$ so the action on 2-cells just described is well-defined. The 2-functoriality of these mappings follows from the simplicial functoriality of the original mapping. \square

We now begin to relate the simplicially enriched structures of an ∞ -cosmos to the 2-categorical structures in its homotopy 2-category. The first result proves that homotopy 2-categories inherit products from their ∞ -cosmoi, which satisfy a 2-categorical universal property. To illustrate, recall that the terminal ∞ -category $1 \in \mathcal{K}$ has the universal property $\mathbf{Fun}(X, 1) \cong \mathbb{1}$ for all $X \in \mathcal{K}$. Applying the homotopy category functor we see that $1 \in \mathbf{h}\mathcal{K}$ has the universal property $\mathbf{hFun}(X, 1) \cong \mathbb{1}$ for all $X \in \mathbf{h}\mathcal{K}$. This 2-categorical universal property has both a 1-dimensional and a 2-dimensional aspect. Since $\mathbf{hFun}(X, 1) \cong \mathbb{1}$ is a category with a single object, there exists a unique morphism $X \rightarrow 1$ in \mathcal{K} . And since $\mathbf{hFun}(X, 1) \cong \mathbb{1}$ has only a single identity morphism, we see that the only 2-cells in $\mathbf{h}\mathcal{K}$ with codomain 1 are identities.

1.4.5. PROPOSITION (cartesian (closure)).

- (i) *The homotopy 2-category of any ∞ -cosmos has 2-categorical products.*
- (ii) *The homotopy 2-category of a cartesian closed ∞ -cosmos is cartesian closed as a 2-category.*

PROOF. While the functor $\mathbf{h}: \mathbf{SSet} \rightarrow \mathbf{Cat}$ only preserves finite products, the restricted functor $\mathbf{h}: \mathbf{QCat} \rightarrow \mathbf{Cat}$ preserves *all* products on account of the simplified description of the homotopy category of a quasi-category given in Lemma 1.1.12. Thus for any set I and family of ∞ -categories $(A_i)_{i \in I}$ in \mathcal{K} , the homotopy category functor carries the isomorphism of quasi-categories displayed below left to an isomorphism of hom-categories displayed below right

$$\mathbf{Fun}(X, \prod_{i \in I} A_i) \xrightarrow{\cong} \prod_{i \in I} \mathbf{Fun}(X, A_i) \xrightarrow{\mathbf{h}} \mathbf{hFun}(X, \prod_{i \in I} A_i) \xrightarrow{\cong} \prod_{i \in I} \mathbf{hFun}(X, A_i).$$

This proves that the homotopy 2-category $\mathbf{h}\mathcal{K}$ has products whose universal properties have both a 1- and 2-dimensional component, as described for terminal objects above.

If \mathcal{K} is a cartesian closed ∞ -cosmos, then for any triple of ∞ -categories $A, B, C \in \mathcal{K}$ there exist exponential objects $C^A, C^B \in \mathcal{K}$ characterized by natural isomorphisms

$$\mathrm{Fun}(A \times B, C) \cong \mathrm{Fun}(A, C^B) \cong \mathrm{Fun}(B, C^A).$$

Passing to homotopy categories we have natural isomorphisms

$$\mathrm{hFun}(A \times B, C) \cong \mathrm{hFun}(A, C^B) \cong \mathrm{hFun}(B, C^A),$$

which demonstrates that $\mathrm{h}\mathcal{K}$ is cartesian closed as a 1-category: functors $A \times B \rightarrow C$ transpose to define functors $A \rightarrow C^B$ and $B \rightarrow C^A$, and 2-cells transpose similarly. \square

There is a standard definition of *isomorphism* between two objects in any 1-category. Similarly, there is a standard definition of *equivalence* between two objects in any 2-category:

1.4.6. DEFINITION (equivalence). An **equivalence** in a 2-category is given by

- a pair of objects A and B
- a pair of 1-cells $f: A \rightarrow B$ and $g: B \rightarrow A$
- a pair of invertible 2-cells

$$\begin{array}{ccc} A & \xrightleftharpoons[\cong \Downarrow \alpha]{\quad} & A \\ & \scriptstyle gf & \end{array} \qquad \begin{array}{ccc} B & \xrightleftharpoons[\cong \Downarrow \beta]{fg} & B \end{array}$$

When A and B are **equivalent**, we write $A \simeq B$ and refer to the 1-cells f and g as **equivalences**, denoted by “ \simeq .”

In the case of the homotopy 2-category of an ∞ -cosmos we have a competing definition of equivalence from 1.2.1: namely a 1-cell $f: A \rightrightarrows B$ that induces an equivalence $f_*: \mathrm{Fun}(X, A) \rightrightarrows \mathrm{Fun}(X, B)$ on functor-spaces — or equivalently, by Lemma 1.2.15, a homotopy equivalence defined relative to the interval \mathbb{I} . Crucially, these two notions of equivalence coincide:

1.4.7. THEOREM (equivalences are equivalences). A functor $f: A \rightarrow B$ between ∞ -categories defines an equivalence in the ∞ -cosmos \mathcal{K} if and only if it defines an equivalence in its homotopy 2-category $\mathrm{h}\mathcal{K}$.

PROOF. Given an equivalence $f: A \rightrightarrows B$ in the ∞ -cosmos \mathcal{K} , Lemma 1.2.15 provides an inverse equivalence $g: B \rightrightarrows A$ and homotopies $\alpha: A \rightarrow A^{\mathbb{I}}$ and $\beta: B \rightarrow B^{\mathbb{I}}$ in \mathcal{K} . By Observation 1.4.3 this data represents an equivalence in the homotopy 2-category $\mathrm{h}\mathcal{K}$.

For the converse, first note that if parallel 1-cells $h, k: A \rightrightarrows B$ in the homotopy 2-category are connected by an invertible 2-cell as displayed below left, then h is an equivalence in the ∞ -cosmos \mathcal{K} if and only if k is:

$$\begin{array}{ccc} A & \xrightleftharpoons[\cong \Downarrow \gamma]{h} & B \\ & \scriptstyle k & \end{array} \qquad \begin{array}{ccccc} & & A & & \\ & \swarrow h & \downarrow \gamma & \searrow k & \\ B & \xleftarrow[\sim]{\mathrm{ev}_0} & B^{\mathbb{I}} & \xrightarrow[\sim]{\mathrm{ev}_1} & B \end{array}$$

By Observation 1.4.3, the invertible 2-cell can be represented by a map $\gamma: A \rightarrow B^{\mathbb{I}}$ in \mathcal{K} as displayed above right; now apply the 2-of-3 property for the equivalences in \mathcal{K} .

Now it follows immediately from the 2-of-6 property of the equivalences in any ∞ -cosmos established in Remark 1.2.14 and the fact that the equivalences contain the identities that any 2-categorical

equivalence defines an equivalence in the ∞ -cosmos: since gf and fg are isomorphic to identities, they must be equivalences in \mathcal{K} , and hence so must f and g . \square

1.4.8. DIGRESSION (on the importance of Theorem 1.4.7). It is hard to overstate the importance of Theorem 1.4.7 to the work that follows. The categorical constructions that we will introduce for ∞ -categories, ∞ -functors, and ∞ -natural transformations are invariant under 2-categorical equivalence in the homotopy 2-category and the universal properties we develop similarly characterize a 2-categorical equivalence class of ∞ -categories. Theorem 1.4.7 then asserts that such constructions are “homotopically correct”: both invariant under equivalence in the ∞ -cosmos and precisely identifying equivalence classes of objects.

The equivalence invariance of the functor space in the codomain variable is axiomatic, but equivalence invariance in the domain variable is not.²⁰ But using 2-categorical techniques, there is now a short proof:

1.4.9. COROLLARY. *Equivalences of ∞ -categories $A' \simeq A$ and $B \simeq B'$ induce an equivalence of functor spaces $\mathbf{Fun}(A, B) \simeq \mathbf{Fun}(A', B')$.*

PROOF. The simplicial functors $\mathbf{Fun}(A, -): \mathcal{K} \rightarrow \mathbf{QCat}$ and $\mathbf{Fun}(-, B): \mathcal{K}^{\mathrm{op}} \rightarrow \mathbf{QCat}$ induce 2-functors $\mathbf{Fun}(A, -): \mathbf{hK} \rightarrow \mathbf{hQCat}$ and $\mathbf{Fun}(-, B): \mathbf{hK}^{\mathrm{op}} \rightarrow \mathbf{hQCat}$, which preserve the 2-categorical equivalences of Definition 1.4.6. By Theorem 1.4.7 this is what we wanted to show. \square

Similarly, there is a standard 2-categorical notion of an isofibration, defined in the statement of Proposition 1.4.10, and any isofibration in an ∞ -cosmos defines an isofibration in its homotopy 2-category.²¹

1.4.10. PROPOSITION (isofibrations define isofibrations). *Any isofibration $p: E \twoheadrightarrow B$ in an ∞ -cosmos \mathcal{K} , also defines an isofibration in the homotopy 2-category \mathbf{hK} : given any invertible 2-cell as displayed below left abutting to B with a specified lift of one of its boundary 1-cells through p , there exists an invertible 2-cell abutting to E with this boundary 1-cell as displayed below right that whiskers with p to the original 2-cell.*

$$\begin{array}{ccc} X & \xrightarrow{e} & E \\ & \searrow \cong \Downarrow \beta & \downarrow p \\ & & B \end{array} \quad b \searrow \quad = \quad \begin{array}{ccc} X & \xrightarrow{e} & E \\ & \searrow \cong \Downarrow \gamma & \downarrow p \\ & & B \end{array}$$

PROOF. Put another way, the universal property of the statement says that the functor

$$p_*: \mathbf{hFun}(X, E) \twoheadrightarrow \mathbf{hFun}(X, B)$$

is an isofibration of categories in the sense defined in Example 1.2.20. By axiom 1.2.1(ii), since $p: E \twoheadrightarrow B$ is an isofibration in \mathcal{K} , the induced map $p_*: \mathbf{Fun}(X, E) \twoheadrightarrow \mathbf{Fun}(X, B)$ is an isofibration of quasi-categories. So it suffices to show that the functor $\mathbf{h}: \mathbf{QCat} \rightarrow \mathbf{Cat}$ carries isofibrations of quasi-categories to isofibrations of categories.²²

²⁰Lemma 1.3.2 does not apply since $\mathbf{Fun}(-, B)$ is not cosmological.

²¹In this case, the converse does not hold, nor is it the case that a representably-defined isofibration of quasi-categories is necessarily an isofibration in the ∞ -cosmos; consider the case of sliced ∞ -cosmoi for instance.

²²Alternately, argue directly using Observation 1.4.3.

So let us now consider an isofibration $p: E \twoheadrightarrow B$ between quasi-categories. By Corollary 1.1.16, every isomorphism β in the homotopy category $\mathbf{h}B$ of the quasi-category B is represented by a simplicial map $\beta: \mathbb{I} \rightarrow B$. By Definition 1.1.17, the lifting problem

$$\begin{array}{ccc} \mathbb{I} & \xrightarrow{e} & E \\ \downarrow & \nearrow \gamma & \downarrow p \\ \mathbb{I} & \xrightarrow{\beta} & B \end{array}$$

can be solved, and the map $\gamma: \mathbb{I} \rightarrow E$ so-produced represents a lift of the isomorphism from $\mathbf{h}B$ to an isomorphism in $\mathbf{h}E$ with domain e . \square

1.4.11. CONVENTION (on “isofibrations” in homotopy 2-categories). Since the converse to Proposition 1.4.10 does not hold, there is a potential ambiguity when using the term “isofibration” to refer to a map in the homotopy 2-category of an ∞ -cosmos. We adopt the convention that when we declare that a map in $\mathbf{h}\mathcal{K}$ is an isofibration we always mean this is the stronger sense of defining an isofibration in \mathcal{K} . This stronger condition gives us access to the 2-categorical lifting property of Proposition 1.4.10 but also to the many homotopical properties axiomatized in Definition 1.2.1, which guarantee that the strictly defined limits of 1.2.1(i) are automatically equivalence invariant constructions.

The 1- and 2-cells in the homotopy 2-category from the terminal ∞ -category $1 \in \mathcal{K}$ to a generic ∞ -category $A \in \mathcal{K}$ define the objects and morphisms in the *homotopy category* of A .

1.4.12. DEFINITION (homotopy category of an ∞ -category). The **homotopy category** of an ∞ -category A in an ∞ -cosmos \mathcal{K} is defined to be the homotopy category of its underlying quasi-category, that is:

$$\mathbf{h}A := \mathbf{hFun}(1, A) := \mathbf{h}(Fun(1, A)).$$

As we shall discover, homotopy categories generally bear “derived” analogues of structures present at the level of ∞ -categories. See the remark after the statement Proposition 2.1.7 for an early example of this.

Exercises.

1.4.i. EXERCISE. Let $F: \mathcal{K} \simeq \mathcal{L}$ be a cosmological biequivalence and let $A, B \in \mathcal{K}$. Prove that if $FA \simeq FB$ in \mathcal{L} then $A \simeq B$ in \mathcal{K} and ruminate on why this exercise is considerably easier than Exercise 1.3.ii).

1.4.ii. EXERCISE.

- (i) What is the homotopy 2-category of the ∞ -cosmos \mathcal{Cat} of 1-categories?
- (ii) Prove that the nerve defines a 2-functor $\mathcal{Cat} \hookrightarrow \mathbf{h}QCat$ that is *locally fully faithful*.

1.4.iii. EXERCISE. Let B be an ∞ -category in the ∞ -cosmos \mathcal{K} and let $\mathbf{h}\mathcal{K}_B$ denote the 2-category whose

- objects are isofibrations $E \twoheadrightarrow B$ in \mathcal{K} with codomain B
- 1-cells are 1-cells in $\mathbf{h}\mathcal{K}$ over B

$$\begin{array}{ccc} E & \longrightarrow & F \\ & \searrow & \swarrow \\ & B & \end{array}$$

- 2-cells are 2-cells in $\mathfrak{h}\mathcal{K}$ over B

$$\begin{array}{ccc}
 & f & \\
 E & \xrightarrow{\quad} & F \\
 & \Downarrow \alpha & \\
 & g & \\
 p \searrow & B & \swarrow q
 \end{array}$$

in the sense that $q\alpha = \text{id}_p$.

Argue that the homotopy 2-category $\mathfrak{h}(\mathcal{K}_B)$ of the sliced ∞ -cosmos has the same underlying 1-category but different 2-cells. How do these compare with the 2-cells of $\mathfrak{h}\mathcal{K}_B$?²³

²³A more systematic comparison will be given in Proposition 3.5.3.

CHAPTER 2

Adjunctions, limits, and colimits I

Heuristically, ∞ -categories generalize ordinary 1-categories by adding in higher dimensional morphisms and weakening the composition law. The dream is that proofs establishing the theory of 1-categories similarly generalize to give proofs for ∞ -categories, just by adding a prefix “ ∞ -” everywhere. In this chapter, we make this dream a reality — at least for a library of basic propositions concerning equivalences, adjunctions, limits, and colimits and the relationships between these notions.

Recall that categories, functors, and natural transformations assemble into a 2-category \mathbf{Cat} . Similarly, the ∞ -categories, ∞ -functors, and ∞ -natural transformations in any ∞ -cosmos assemble into a 2-category, namely the *homotopy 2-category* of the ∞ -cosmos, introduced in §1.4. By Exercise 1.4.ii, \mathbf{Cat} can be regarded as a special case of a homotopy 2-category. In this chapter, we will use strict 2-categorical techniques to define *adjunctions* between ∞ -categories and *limits* and *colimits* of diagrams valued in an ∞ -category and prove that these notions interact in the expected ways. In the homotopy 2-category of categories, these recover the classical results from 1-category theory. As these proofs are equally valid in any homotopy 2-category, our arguments also establish the desired generalizations by simply appending the prefix “ ∞ -.”

2.1. Adjunctions and equivalences

In §1.4, we encountered the definition of an *equivalence* between a pair of objects in a 2-category. In the case where the ambient 2-category is the homotopy 2-category of an ∞ -cosmos, we observed in Theorem 1.4.7 that the 2-categorical notion of equivalence precisely recaptures the notion of equivalence introduced in Definition 1.2.1 between ∞ -categories in the full ∞ -cosmos. In each of the examples of ∞ -cosmoi we have considered, the representably-defined equivalences in the ∞ -cosmos coincide with the standard notion of equivalences between ∞ -categories as presented in that particular model.¹ Thus, the 2-categorical notion of equivalence is the “correct” notion of equivalence between ∞ -categories.

Similarly, there is a standard definition of an *adjunction* between a pair of objects in a 2-category, which, when interpreted in the homotopy 2-category of ∞ -categories, functors, and natural transformations in an ∞ -cosmos, will define the correct notion of adjunction between ∞ -categories.

2.1.1. DEFINITION (adjunction). An **adjunction** between ∞ -categories is comprised of:

- a pair of ∞ -categories A and B ,
- a pair of functors $u: A \rightarrow B$ and $f: B \rightarrow A$,
- and a pair of natural transformations $\eta: 1_B \Rightarrow uf$ and $\epsilon: fu \Rightarrow 1_A$, called the **unit** and **counit** respectively,

¹For instance, as outlined in Digression 1.2.9, the equivalences in the ∞ -cosmoi of Example 1.2.19 recapture the weak equivalences between fibrant-cofibrant objects in the usual model structure.

so that the triangle equalities hold:²

$$\begin{array}{c}
 \begin{array}{ccc}
 & B & \\
 u \nearrow & & \searrow f \\
 A & \Downarrow \epsilon & B \\
 & \searrow f & \nearrow u \\
 & A &
 \end{array}
 & = &
 \begin{array}{ccc}
 & B & \\
 & \left(= \right) & \\
 & A &
 \end{array}
 & &
 \begin{array}{ccc}
 B & & B \\
 \searrow f & \Downarrow \eta & \nearrow u \\
 A & \Downarrow \epsilon & A \\
 & \searrow f & \nearrow u \\
 & A &
 \end{array}
 & = &
 \begin{array}{ccc}
 & B & \\
 & \left(= \right) & \\
 & A &
 \end{array}
 \end{array}$$

The functor f is called the **left adjoint** and u is called the **right adjoint**, a relationship that is denoted symbolically in text by writing $f \dashv u$ or in a displayed diagram such as³

$$\begin{array}{ccc}
 & f & \\
 A & \xleftarrow{\quad} & B \\
 & \perp & \\
 & u &
 \end{array}$$

2.1.2. DIGRESSION (why this is the right definition). For readers who find Definition 2.1.1 implausible — perhaps too simple to be trusted — we offer a few words of justification. Firstly, the correct notion of *adjunction* between quasi-categories is well established, though the definition appearing in [36, §5.2] takes a quite different form. In Appendix F, we prove that in the ∞ -cosmos of quasi-categories, our definition of adjunction precisely recovers Lurie’s. As explained in Part IV, each of the models of $(\infty, 1)$ -categories described in Example 1.2.19 “has the same category theory,” so Definition 2.1.1 agrees with the community consensus notion of adjunction between $(\infty, 1)$ -categories.

But what about those ∞ -cosmoi whose objects model (∞, n) - or (∞, ∞) -categories? For instance in the ∞ -cosmos of complicial sets, the adjunctions defined in the homotopy 2-category are the “pseudo-style” adjunctions. While these are not the most general adjunctions that might be considered — for instance, one could have (op)lax units and counits — they are an important class of adjunctions. One reason for the relevance of Definition 2.1.1 in all ∞ -cosmoi is its formal properties vis-a-vis the related notion of equivalence, which Theorem 1.4.7 has established is morally “correct,” and with the notions of limits and colimits to be introduced.

Finally, a reasonable objection is that Definition 2.1.1 appears too “low dimensional,” comprised of data found entirely in the homotopy 2-category and ignoring the higher dimensional morphisms in an ∞ -cosmos. This deficiency will be addressed in Chapter 8, when we prove that any adjunction between ∞ -categories extends to a *homotopy coherent adjunction*, and moreover such extensions are homotopically unique.

The definition of an adjunction given in Definition 2.1.1 is “equational” in character: stated in terms of the objects, 1-cells, and 2-cells of a 2-category and their composites. Immediately:

2.1.3. LEMMA. *Adjunctions in a 2-category are preserved by any 2-functor.* □

Lemma 2.1.3 provides an easy source of examples of adjunctions between quasi-categories. The 2-functors underlying the cosmological functors of Example 1.3.7 then transfer adjunctions defined in one model of $(\infty, 1)$ -categories to adjunctions defined in each of the other models.

2.1.4. EXAMPLE (adjunctions between 1-categories). Via the nerve embedding $\mathbf{Cat} \hookrightarrow \mathbf{hQCat}$, any adjunction between 1-categories induces an adjunction between their nerves regarded as quasi-categories.

²The left-hand equality of pasting diagrams asserts the composition relation $u\epsilon \cdot \eta u = \text{id}_u$ in the hom-category $\mathbf{hFun}(A, B)$, while the right-hand equality asserts that $\epsilon f \cdot f\eta = \text{id}_f$ in $\mathbf{hFun}(B, A)$.

³Some authors contort adjunction diagrams so that the left adjoint is always on the left; we instead use the turnstile symbol “ \dashv ” to indicate which adjoint is the left adjoint.

2.1.5. EXAMPLE (adjunctions between topological categories). The *homotopy coherent nerve* defines a 2-functor $\mathfrak{N}: \mathcal{K}an\text{-}Cat \rightarrow \mathfrak{h}QCat$ from the 2-category of Kan complex enriched categories, simplicially enriched functors, and simplicial natural transformations, to the homotopy 2-category $\mathfrak{h}QCat$. In this way, topologically enriched adjunctions define adjunctions between quasi-categories.

2.1.6. REMARK. Topologically enriched adjunctions are relatively rare. More prevalent are “up-to-homotopy” topologically enriched adjunctions, such as those given by Quillen adjunctions between simplicial model categories. These also define adjunctions between quasi-categories, though the proof will have to wait until Part II.

The preservation of adjunctions by 2-functors proves:

2.1.7. PROPOSITION. Given any adjunction $A \begin{smallmatrix} \xleftarrow{f} \\ \perp \\ \xrightarrow{u} \end{smallmatrix} B$ between ∞ -categories then:

(i) for any ∞ -category X ,

$$\text{Fun}(X, A) \begin{smallmatrix} \xleftarrow{f_*} \\ \perp \\ \xrightarrow{u_*} \end{smallmatrix} \text{Fun}(X, B)$$

defines an adjunction between quasi-categories;

(ii) for any ∞ -category X ,

$$\text{hFun}(X, A) \begin{smallmatrix} \xleftarrow{f_*} \\ \perp \\ \xrightarrow{u_*} \end{smallmatrix} \text{hFun}(X, B)$$

defines an adjunction between categories;

(iii) for any simplicial set U ,

$$A^U \begin{smallmatrix} \xleftarrow{f^U} \\ \perp \\ \xrightarrow{u^U} \end{smallmatrix} B^U$$

defines an adjunction between ∞ -categories;

(iv) and if the ambient ∞ -cosmos is cartesian closed, then for any ∞ -category C ,

$$A^C \begin{smallmatrix} \xleftarrow{f^C} \\ \perp \\ \xrightarrow{u^C} \end{smallmatrix} B^C$$

defines an adjunction between ∞ -categories.

For instance, taking $X = 1$ in (ii) yields a “derived” adjunction between the homotopy categories of the ∞ -categories A and B .

PROOF. Any adjunction $f \dashv u$ in the homotopy 2-category $\mathfrak{h}\mathcal{K}$ is preserved by the 2-functors $\text{Fun}(X, -): \mathfrak{h}\mathcal{K} \rightarrow \mathfrak{h}QCat$, $\text{hFun}(X, -): \mathfrak{h}\mathcal{K} \rightarrow Cat$, $(-)^U: \mathfrak{h}\mathcal{K} \rightarrow \mathfrak{h}\mathcal{K}$, and $(-)^C: \mathfrak{h}\mathcal{K} \rightarrow \mathfrak{h}\mathcal{K}$. \square

2.1.8. REMARK. There are contravariant versions of each of the adjunction-preservation results of Proposition 2.1.7, the first of which we explain in detail. Fixing the codomain variable of the functor-space at any ∞ -category $C \in \mathcal{K}$ defines a 2-functor

$$\mathrm{Fun}(-, C): \mathfrak{h}\mathcal{K}^{\mathrm{op}} \rightarrow \mathfrak{h}\mathcal{QCat}$$

that is contravariant on 1-cells and covariant on 2-cells.⁴ Similarly, the cotensor or exponential $C^{(-)}$ is contravariant on 1-cells and covariant on 2-cells.⁵ Such 2-functors preserve adjunctions, but exchange left and right adjoints: for instance, given $f \dashv u$ in \mathcal{K} , we obtain an adjunction

$$\mathrm{Fun}(A, C) \quad \begin{array}{c} \xleftarrow{u^*} \\ \perp \\ \xrightarrow{f^*} \end{array} \quad \mathrm{Fun}(B, C)$$

between the functor-spaces.

2.1.9. PROPOSITION. *Adjunctions compose: given adjoint functors*

$$C \begin{array}{c} \xrightarrow{f'} \\ \perp \\ \xleftarrow{u'} \end{array} B \begin{array}{c} \xrightarrow{f} \\ \perp \\ \xleftarrow{u} \end{array} A \quad \rightsquigarrow \quad C \begin{array}{c} \xrightarrow{ff'} \\ \perp \\ \xleftarrow{u'u} \end{array} A$$

the composite functors are adjoint.

PROOF. Writing $\eta: \mathrm{id}_B \Rightarrow uf$, $\epsilon: fu \Rightarrow \mathrm{id}_A$, $\eta': \mathrm{id}_C \Rightarrow u'f'$, and $\epsilon': f'u' \Rightarrow \mathrm{id}_B$ for the respective units and counits, the pasting diagrams

$$\begin{array}{ccc} C & \xlongequal{\quad} & C \\ f' \searrow & \Downarrow \eta' & \nearrow u' \\ B & \xlongequal{\quad} & B \\ f \searrow & \Downarrow \eta & \nearrow u \\ A & & A \end{array} \quad \begin{array}{ccc} C & & C \\ u' \nearrow & \Downarrow \epsilon' & \searrow f' \\ B & \xlongequal{\quad} & B \\ u \nearrow & \Downarrow \epsilon & \searrow f \\ A & \xlongequal{\quad} & A \end{array}$$

define the unit and counit of $ff' \dashv u'u$ so that the triangle equalities

$$\begin{array}{ccc} C & \xlongequal{\quad} & C \\ f' \searrow & \Downarrow \eta' & \nearrow u' \\ B & \xlongequal{\quad} & B \\ f \searrow & \Downarrow \eta & \nearrow u \\ A & \xlongequal{\quad} & A \end{array} = \begin{array}{c} C \\ \left(\begin{array}{c} = \end{array} \right) \\ A \end{array} \begin{array}{c} ff' \\ \left(\begin{array}{c} = \end{array} \right) \\ A \end{array} = \begin{array}{ccc} C & \xlongequal{\quad} & C \\ u' \nearrow & \Downarrow \epsilon' & \searrow f' \\ B & \xlongequal{\quad} & B \\ u \nearrow & \Downarrow \epsilon & \searrow f \\ A & \xlongequal{\quad} & A \end{array} = \begin{array}{c} C \\ \left(\begin{array}{c} = \end{array} \right) \\ A \end{array} \begin{array}{c} u'u \\ \left(\begin{array}{c} = \end{array} \right) \\ A \end{array}$$

hold. □

⁴On a strict 2-category, the superscript “op” is used to signal that the 1-cells should be reversed but not the 2-cells, the superscript “co” is used to signal that the 2-cells should be reversed but not the 1-cells, and the superscript “coop” is used to signal that both the 1- and 2-cells should be reversed; see Chapter B.

⁵In the case of the simplicial cotensor, the domain can safely be restricted to the homotopy 2-category of quasi-categories or can be regarded as an analogously-defined homotopy 2-category of simplicial sets.

An adjoint to a given functor is unique up to natural isomorphism:

2.1.10. PROPOSITION (uniqueness of adjoints).

- (i) If $f \dashv u$ and $f' \dashv u$, then $f \cong f'$.
- (ii) Conversely, if $f \dashv u$ and $f \cong f'$ then $f' \dashv u$.

PROOF. Writing $\eta: \text{id}_B \Rightarrow uf$, $\epsilon: fu \Rightarrow \text{id}_A$, $\eta': \text{id}_B \Rightarrow uf'$, and $\epsilon': f'u \Rightarrow \text{id}_B$ for the respective units and counits, the pasting diagrams

$$\begin{array}{ccc} B & \xlongequal{\quad} & B \\ & \searrow f' \quad \Downarrow \eta' \quad \nearrow u \quad \Downarrow \epsilon \quad \searrow f & \\ & A & \xlongequal{\quad} A \end{array} \qquad \begin{array}{ccc} B & \xlongequal{\quad} & B \\ & \searrow f \quad \Downarrow \eta \quad \nearrow u \quad \Downarrow \epsilon' \quad \searrow f' & \\ & A & \xlongequal{\quad} A \end{array}$$

define 2-cells $f \Rightarrow f'$ and $f' \Rightarrow f$. The composites $f \Rightarrow f' \Rightarrow f$ and $f' \Rightarrow f \Rightarrow f$ are computed by pasting these diagrams together horizontally on one side or the other. Applying the triangle equalities for the adjunctions $f \dashv u$ and $f' \dashv u$ both composites are easily seen to be identities. Hence $f \cong f'$ as functors from B to A .

Part (ii) is left as Exercise 2.1.i. □

We will make repeated use of the following standard 2-categorical result, which says that any equivalence in a 2-category can be promoted to an equivalence that also defines an adjunction:

2.1.11. PROPOSITION (adjoint equivalences). *Any equivalence can be promoted to an **adjoint equivalence** by modifying one of the 2-cells. That is, the invertible 2-cells in an equivalence can be chosen so as to satisfy the triangle equalities. Hence, if f and g are inverse equivalences then $f \dashv g$ and $g \dashv f$.*

PROOF. Consider an equivalence comprised of functors $f: A \rightarrow B$ and $g: B \rightarrow A$ and invertible 2-cells

$$\begin{array}{ccc} A & \xrightleftharpoons[\cong]{\Downarrow \alpha} & A \\ & \searrow gf & \\ & & \end{array} \qquad \begin{array}{ccc} B & \xrightleftharpoons[\cong]{\Downarrow \beta} & B \\ & \searrow fg & \\ & & \end{array}$$

We will construct an adjunction $f \dashv g$ with unit $\eta := \alpha$ by modifying β . The “triangle identity composite”

$$\phi := f \xrightarrow{f\alpha} f g f \xrightarrow{\beta f} f$$

is an isomorphism, though likely not an identity. Define

$$\epsilon := f g \xrightarrow{\phi^{-1} g} f g \xrightarrow{\beta} \text{id}_B := f g \xrightarrow{\beta^{-1} f g} f g f g \xrightarrow{f \alpha^{-1} g} f g \xrightarrow{\beta} \text{id}_B$$

This “corrects” the counit so that now the composite $\epsilon f \cdot f \eta$, displayed on the top of the diagram

$$\begin{array}{ccccc} & & fgf & & \\ & f\alpha \nearrow & & \searrow \epsilon f & \\ f & & & & fgf = \beta f \rightrightarrows f \\ & \searrow \phi^{-1} & \nearrow f\alpha & \nearrow \phi & \\ & & f & & \end{array}$$

which agrees with the bottom composite by “naturality of whiskering,” is the identity id_f .

Now by another diagram chase, the other triangle composite $g\epsilon \cdot \eta g$ is an idempotent:

$$\begin{array}{ccccc}
 g & \xrightarrow{\eta g} & gfg & \xrightarrow{g\epsilon} & g \\
 \eta g \downarrow & & \downarrow \eta gfg & & \downarrow \eta g \\
 gfg & \xrightarrow{gf\eta g} & gfgfg & \xrightarrow{gf g\epsilon} & gfg \\
 & \searrow & \downarrow g\epsilon fg & & \downarrow g\epsilon \\
 & & gfg & \xrightarrow{g\epsilon} & g
 \end{array}$$

By cancelation, any idempotent isomorphism is the identity, proving that $g\epsilon \cdot \eta g = \text{id}_g$. \square

One use of Proposition 2.1.10 is to show that adjunctions are equivalence invariant:

2.1.12. PROPOSITION (equivalence-invariance of adjunctions). *A functor $u: A \rightarrow B$ between ∞ -categories admits a left adjoint if and only if, for any pair of equivalent ∞ -categories $A' \simeq A$ and $B' \simeq B$, the equivalent functor $u: A' \rightarrow B'$ admits a right adjoint.*

PROOF. Exercise 2.1.ii. \square

As we will discover, all of ∞ -category theory is equivalence invariant in this way.

2.1.13. LEMMA. *For any ∞ -category A , the “composition” functor*

$$\begin{array}{ccc}
 & \xleftarrow{(-, \text{id}_{\text{dom}}(-))} & \\
 A^2 \times_A A^2 & \xrightarrow[\perp]{\perp} & A^2 \\
 & \xleftarrow{(\text{id}_{\text{cod}}(-), -)} &
 \end{array} \tag{2.1.14}$$

admits left and right adjoints, which, respectively, “extend an arrow into a composable pair” by pairing it with the identities at its domain or its codomain.

PROOF. There is a dual adjunction in \mathbf{Cat} whose functors we describe using notation for simplicial operators introduced in 1.1.1; the full subcategory of \mathbf{Cat} spanned by the finite non-empty ordinals is isomorphic to Δ .

$$\begin{array}{ccc}
 \mathfrak{3} & \begin{array}{c} \xleftarrow{s^0} \\ \top \\ \xleftarrow{d^1} \\ \top \\ \xleftarrow{s^1} \end{array} & 2 \\
 & \rightsquigarrow & \\
 A^3 & \begin{array}{c} \xleftarrow{A^{s^0}} \\ \perp \\ \xleftarrow{A^{d^1}} \\ \perp \\ \xleftarrow{A^{s^1}} \end{array} & A^2
 \end{array}$$

Any ∞ -category A in an ∞ -cosmos \mathcal{K} defines a 2-functor $A^{(-)}: \mathbf{Cat}^{\text{op}} \rightarrow \mathbf{h}\mathcal{K}$ carrying the adjoint triple displayed above-left to the one displayed above-right.

Now we claim there is a trivial fibration $A^3 \twoheadrightarrow A^2 \times_A A^2$ constructed as follows. The pushout diagram of simplicial sets displayed below-left is carried by the simplicial cotensor $A^{(-)}: \mathbf{SSet}^{\text{op}} \rightarrow \mathcal{K}$ to a pullback diagram displayed below-right; since the legs of the pushout square are monomorphisms,

the legs of the pullback square are isofibrations

$$\begin{array}{ccc}
 \Lambda^1[2] & \longleftarrow & \mathbf{2} \\
 \uparrow & \lrcorner & \uparrow d^1 \\
 \mathbf{2} & \xleftarrow{d^0} & \mathbf{1}
 \end{array}
 \qquad
 \begin{array}{ccc}
 A^{\Lambda^1[2]} & \longrightarrow & A^2 \\
 \downarrow & \lrcorner & \downarrow \text{ev}_0 \\
 A^2 & \xrightarrow{\text{ev}_1} & A
 \end{array}$$

Lemma 1.2.10 tells us that the cotensor of the inner horn inclusion $\Lambda^1[2] \hookrightarrow \mathbf{3}$ with the ∞ -category A defines a trivial fibration $A^{\mathbf{3}} \simeq A^{\Lambda^1[2]}$ and the pullback square above left recognizes its codomain as the desired ∞ -category of “composable pairs.” Any section s to $q: A^{\mathbf{3}} \simeq A^2 \times_A A^2$ can be made into an equivalence inverse. By Proposition 2.1.11, these functors are both left and right adjoints. Composing the adjunction $q \dashv s \dashv q$ with the adjunction constructed above defines the desired adjunction. \square

Note that the adjoint functors of (2.1.14) commute with the “endpoint evaluation” functors to $A \times A$. In fact, the units and counits can similarly be fibered over $A \times A$; see Example 3.5.12.

Exercises.

2.1.i. EXERCISE. Prove Proposition 2.1.10(ii).

2.1.ii. EXERCISE. Prove Proposition 2.1.12: given an adjunction $A \begin{smallmatrix} \xleftarrow{f} \\ \perp \\ \xrightarrow{u} \end{smallmatrix} B$ and equivalences $A \simeq A'$ and $B \simeq B'$ construct an adjunction between A' and B' .

2.2. Initial and terminal elements

Employing the tactic used to define the homotopy category of A in Definition 1.4.12, we use the terminal ∞ -category $\mathbf{1}$ to probe inside the ∞ -category A . The objects $a \in \mathbf{h}A$ of the homotopy category of A were defined to be maps of ∞ -categories $a: \mathbf{1} \rightarrow A$, but to avoid the proliferation of the term “objects” we refer to maps $a: \mathbf{1} \rightarrow A$ as **elements** of the ∞ -category A instead.

Before introducing limits and colimits of general diagram shapes, we warm up by defining initial and terminal elements in an ∞ -category A .

2.2.1. DEFINITION (initial/terminal element). An **initial element** in an ∞ -category A is a left adjoint to the unique functor $!: A \rightarrow \mathbf{1}$, as displayed below left, while a **terminal element** in an ∞ -category A is a right adjoint, as displayed below right.

$$\begin{array}{ccc}
 \mathbf{1} & \begin{smallmatrix} \xrightarrow{i} \\ \perp \\ \xleftarrow{!} \end{smallmatrix} & A
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathbf{1} & \begin{smallmatrix} \xleftarrow{!} \\ \perp \\ \xrightarrow{t} \end{smallmatrix} & A
 \end{array}$$

Let us unpack the definition of an initial element; dual remarks apply to terminal elements.

2.2.2. LEMMA (the minimal data required to present an initial element). *To define an initial element in A , it suffices to specify*

- an element $i: \mathbf{1} \rightarrow A$ and

- a natural transformation

$$\begin{array}{ccc} & 1 & \\ ! \nearrow & \Downarrow \epsilon & \searrow i \\ A & \xlongequal{\quad} & A \end{array}$$

so that the component $\epsilon i: i \Rightarrow i$ is the identity in $\mathbf{h}A$.

PROOF. Proposition 1.4.5 demonstrates that the ∞ -category $1 \in \mathcal{K}$ is terminal in the homotopy 2-category $\mathbf{h}\mathcal{K}$. The 1-dimensional aspect of this universal property implies that i defines a section of the unique map $A \rightarrow 1$ and from the 2-dimensional aspects, we see that there exist no non-identity 2-cells with codomain 1. In particular, the unit of the adjunction $i \dashv !$ is necessarily an identity and one of the triangle equalities comes for free. The data enumerated above is what remains of Definition 2.1.1 in this setting. \square

Put more concisely, an initial element i defines a **left adjoint right inverse** to the functor $!: A \rightarrow 1$. Such adjunctions are studied more systematically in §B.4. In fact, it suffices to assume that the counit component ϵi is an isomorphism, not necessarily the identity; see Lemma B.4.1.

2.2.3. REMARK. Applying the 2-functor $\text{Fun}(X, -): \mathbf{h}\mathcal{K} \rightarrow \mathbf{h}QCat$ to an initial or terminal element of an ∞ -category $A \in \mathcal{K}$ yields adjunctions

$$\begin{array}{ccc} & i_* & \\ \text{Fun}(X, 1) & \xrightarrow{\quad} & \text{Fun}(X, A) \\ & ! & \end{array} \quad \text{and} \quad \begin{array}{ccc} & ! & \\ \text{Fun}(X, 1) & \xleftarrow{\quad} & \text{Fun}(X, A) \\ & t_* & \end{array}$$

Via the isomorphisms $\text{Fun}(X, 1) \cong \mathbb{1}$ that express the universal property of the terminal ∞ -category 1, we see that initial or terminal elements of A define initial or terminal elements of the functor-space $\text{Fun}(X, A)$, namely the composite functors

$$X \xrightarrow{!} 1 \xrightarrow{i} A \quad \text{or} \quad X \xrightarrow{!} 1 \xrightarrow{t} A .$$

In particular, initial or terminal elements are representably initial or terminal at the level of the ∞ -cosmos.

This representable universal property is also captured at the level of the homotopy 2-category. The next lemma shows that the initial element $i: 1 \rightarrow A$ is initial among all *generalized elements* $f: X \rightarrow A$ in the following precise sense.

2.2.4. LEMMA. *An element $i: 1 \rightarrow A$ is initial if and only if for all $f: X \rightarrow A$ there exists a unique 2-cell with boundary*

$$\begin{array}{ccc} & 1 & \\ ! \nearrow & \Downarrow \exists! & \searrow i \\ X & \xrightarrow{\quad f \quad} & A \end{array}$$

PROOF. If $i: 1 \rightarrow A$ is initial, then the adjunction of Definition 2.2.1 is preserved by the 2-functor $\mathbf{hFun}(X, -): \mathbf{hK} \rightarrow \mathbf{Cat}$, defining an adjunction

$$\begin{array}{ccc} & i_* & \\ \curvearrowright & & \curvearrowleft \\ \mathbb{1} \cong \mathbf{hFun}(X, 1) & \perp & \mathbf{hFun}(X, A) \\ \curvearrowleft & & \curvearrowright \\ & ! & \end{array}$$

Via the isomorphism $\mathbf{hFun}(X, 1) \cong \mathbb{1}$, this adjunction proves that the element $i!: X \rightarrow A$ is initial in $\mathbf{hFun}(X, A)$ and thus has the universal property of the statement.

Conversely, if $i: 1 \rightarrow A$ satisfies the universal property of the statement, applying this to the generic element of A (the identity map $\text{id}_A: A \rightarrow A$) easily produces the data of Lemma 2.2.2. \square

2.2.5. REMARK. Lemma 2.2.4 says that initial elements are *representably initial* in the homotopy 2-category. Specializing the generalized elements to ordinary elements, we see that initial and terminal elements in A respectively define initial and terminal elements in the homotopy category $\mathbf{h}A$.

2.2.6. LEMMA. *If A has an initial element and $A \simeq A'$ then A' has an initial element and these elements are preserved up to isomorphism by the equivalences.*

PROOF. By Proposition 2.1.11, the equivalence $A \simeq A'$ can be promoted to an adjoint equivalence, which can immediately be composed with the adjunction characterizing an initial element i of A :

$$\begin{array}{ccccc} 1 & \xrightarrow{i} & A & \xrightarrow{\sim} & A' \\ & \perp & & \perp & \\ & \curvearrowright & & \curvearrowright & \\ & ! & & \sim & \end{array}$$

The composite adjunction provided by Proposition 2.1.9 proves that the image of i defines an initial element of A' , which by construction is preserved by the equivalence $A \simeq A'$.

To see that the equivalence $A' \simeq A$ also preserves initial elements, we can use the invertible 2-cells of the equivalence to see that i is isomorphic to the image of the image of i in A' . In case the initial objects in mind are not the ones being considered here, we can appeal to the uniqueness of initial elements proven in Exercise 2.2.ii. \square

Exercises.

2.2.i. EXERCISE. Prove that initial elements are preserved by left adjoints and terminal elements are preserved by right adjoints.

2.2.ii. EXERCISE. Prove that any two initial elements in an ∞ -category A are isomorphic in $\mathbf{h}A$.

2.3. Limits and colimits

Our aim is now to introduce limits and colimits of diagram valued *inside* an ∞ -category A in some ∞ -cosmos. We will consider two varieties of diagrams:

- In a generic ∞ -cosmos \mathcal{K} , we shall consider diagrams indexed by a simplicial set J and valued in an ∞ -category A .

- In a cartesian closed ∞ -cosmos \mathcal{K} , we shall also consider diagram indexed by an ∞ -category J and valued in an ∞ -category A .⁶

2.3.1. DEFINITION (diagram ∞ -categories). For a simplicial set J — or possibly, in the case of a cartesian closed ∞ -cosmos, an ∞ -category J — and an ∞ -category A , we refer to A^J as the **∞ -category of J -shaped diagrams in A** . Both constructions define bifunctors

$$\begin{array}{ccc} \mathcal{S}Set^{\text{op}} \times \mathcal{K} & \longrightarrow & \mathcal{K} \\ (J, A) & \longmapsto & A^J \end{array} \qquad \begin{array}{ccc} \mathcal{K}^{\text{op}} \times \mathcal{K} & \longrightarrow & \mathcal{K} \\ (J, A) & \longmapsto & A^J \end{array}$$

In either indexing context, there is a terminal object 1 with the property that $A^1 \cong A$ for any ∞ -category A . Restriction along the unique map $! : J \rightarrow 1$, induces the **constant diagram functor** $\Delta : A \rightarrow A^J$.

We are deliberately conflating the notation for ∞ -categories of diagrams indexed by a simplicial set or by another ∞ -category because all of the results we will prove in Part I about the former case will also apply to the latter. For economy of language, we refer only to simplicial set indexed diagrams for the remainder of this section.

2.3.2. DEFINITION. An ∞ -category A **admits all colimits** of shape J if the constant diagram functor $\Delta : A \rightarrow A^J$ admits a left adjoint, while A **admits all limits** of shape J if the constant diagram functor admits a right adjoint:

$$\begin{array}{ccc} & \xrightarrow{\text{colim}} & \\ & \perp & \\ A^J & \xleftarrow{\Delta} & A \\ & \perp & \\ & \xrightarrow{\text{lim}} & \end{array}$$

2.3.3. WARNING. Limits or colimits of set-indexed diagrams — the case where the indexing shape is a coproduct of the terminal object 1 indexed by a set J — are called **products** or **coproducts**, respectively. In this case the ∞ -category of diagrams itself decomposes as a product $A^J \cong \prod_J A$. As the functor

$$\begin{array}{ccc} \mathbf{h}\mathcal{K} & \xrightarrow{\mathbf{h}\text{Fun}(1, -)} & \mathbf{Cat} \\ A & \longmapsto & \mathbf{h}A \end{array}$$

that carries an ∞ -category to its homotopy category preserves products, when J is a set there is a chain of isomorphisms

$$\mathbf{h}(A^J) \cong \mathbf{h}(\prod_J A) \cong \prod_J \mathbf{h}A \cong (\mathbf{h}A)^J$$

Thus, in this special case the adjunctions of Definition 2.3.2 that define products or coproducts in an ∞ -category descend to the adjunctions that define products or coproducts in its homotopy category.

However, this argument does *not* extend to more general limit or colimit notions, and such ∞ -categorical limits or colimits are generally not limits or colimits in the homotopy category.⁷ In §3.2, we

⁶In Proposition 13.3.4 proven in Part IV, we shall discover that in the case of the ∞ -cosmoi of $(\infty, 1)$ -categories, there is no essential difference between these notions: in \mathbf{QCat} they are tautologically the same, and in all biequivalent ∞ -cosmoi the ∞ -category of diagrams indexed by an ∞ -category A is equivalent to the ∞ -category of diagrams indexed by its underlying quasi-category, regarded as a simplicial set.

⁷This sort of behavior is expected in abstract homotopy theory: homotopy limits and colimits are not generally limits or colimits in the homotopy category.

shall see that the homotopy category construction fails to preserve more complicated cotensors, even in the relatively simple case of $J = \mathbf{2}$.

The problem with Definition 2.3.2 is that it is insufficiently general: many ∞ -categories will have certain, but not all, limits of diagrams of a particular indexing shape. So it would be desirable to re-express Definition 2.3.2 in a form that allows us to define the limit of a single diagram $d: 1 \rightarrow A^I$ or of a family of diagrams. To achieve this, we make use of the following 2-categorical notion that op-dualizes the more familiar absolute extension diagrams.

2.3.4. DEFINITION (absolute lifting diagrams). Given a cospan $C \xrightarrow{g} A \xleftarrow{f} B$ in a 2-category, an **absolute left lifting** of g through f is given by a 1-cell and 2-cell as displayed below-left

$$\begin{array}{ccc} & B & \\ \ell \nearrow & \downarrow f & \\ C & \xrightarrow{g} & A \end{array} \quad \begin{array}{ccc} X & \xrightarrow{b} & B \\ c \downarrow & \uparrow \chi & \downarrow f \\ C & \xrightarrow{g} & A \end{array} = \begin{array}{ccc} X & \xrightarrow{b} & B \\ c \downarrow & \exists! \uparrow \zeta & \downarrow f \\ C & \xrightarrow{g} & A \end{array}$$

so that any 2-cell as displayed above-center factors uniquely through (ℓ, λ) as displayed above-right.

Dually, an **absolute right lifting** of g through f is given by a 1-cell and 2-cell as displayed below-left

$$\begin{array}{ccc} & B & \\ r \nearrow & \downarrow f & \\ C & \xrightarrow{g} & A \end{array} \quad \begin{array}{ccc} X & \xrightarrow{b} & B \\ c \downarrow & \Downarrow \chi & \downarrow f \\ C & \xrightarrow{g} & A \end{array} = \begin{array}{ccc} X & \xrightarrow{b} & B \\ c \downarrow & \exists! \Downarrow \zeta & \downarrow f \\ C & \xrightarrow{g} & A \end{array}$$

so that any 2-cell as displayed above-center factors uniquely through (r, ρ) as displayed above-right.

The adjectives “left” and “right” refer to the handedness of the adjointness of these constructions: left and right liftings respectively define left and right adjoints to the composition functor $f_*: \mathbf{hFun}(C, B) \rightarrow \mathbf{hFun}(C, A)$, with the 2-cells defining the components of the unit and counit of these adjunctions, respectively, at the object g . The adjective “absolute” refers to the following stability property.

2.3.5. LEMMA. *Absolute left or right lifting diagrams are stable under restriction of their domain object: if (ℓ, λ) defines an absolute left lifting of g through f , then for any $c: X \rightarrow C$, the restricted diagram $(\ell c, \lambda c)$ defines an absolute left lifting of gc through f .*

$$X \xrightarrow{c} C \begin{array}{ccc} & B & \\ \ell \nearrow & \downarrow f & \\ & \xrightarrow{g} & A \end{array}$$

PROOF. Exercise 2.3.i. □

Units and counits of adjunctions provide important examples of absolute left and right lifting diagrams respectively:

2.3.6. LEMMA. A 2-cell $\eta: \text{id}_B \Rightarrow uf$ defines the unit of an adjunction $f \dashv u$ if and only if (f, η) defines an absolute left lifting diagram, displayed below-left.

$$\begin{array}{ccc} & A & \\ f \nearrow & & \downarrow u \\ B & \xlongequal{\quad} & B \end{array} \qquad \begin{array}{ccc} & B & \\ u \nearrow & & \downarrow f \\ A & \xlongequal{\quad} & A \end{array}$$

Dually a 2-cell $\epsilon: fu \Rightarrow \text{id}_A$ defines the counit of an adjunction if and only if (u, ϵ) defines an absolute right lifting diagram, displayed above-right.

PROOF. We prove the universal property of the counit. Given a 2-cell $\alpha: fb \Rightarrow a$ as displayed below left

$$\begin{array}{ccc} X & \xrightarrow{b} & B \\ a \downarrow & \Downarrow \alpha & \downarrow f \\ A & \xlongequal{\quad} & A \end{array} = \begin{array}{ccc} X & \xrightarrow{b} & B \\ a \downarrow & \Downarrow \beta & \nearrow u \\ A & \xlongequal{\quad} & A \end{array}$$

there exists a unique transpose $\beta: b \Rightarrow ua$ as displayed above-right across the induced adjunction

$$\begin{array}{ccc} & f_* & \\ \text{hFun}(X, B) & \perp & \text{hFun}(X, A) \\ & u_* & \end{array}$$

between the hom-categories of the homotopy 2-category; see Proposition 2.1.7(ii). From right to left, transposes are composed by pasting with the counit; hence the left-hand side above equals the right-hand side. The converse is left as Exercise 2.3.ii. \square

In particular, the unit of the adjunction $\text{colim} \dashv \Delta$ of Definition 2.3.2 defines an absolute left lifting diagram

$$\begin{array}{ccc} & A & \\ \text{colim} \nearrow & & \downarrow \Delta \\ A^J & \xlongequal{\quad} & A^J \end{array}$$

By Lemma 2.3.5, this universal property is retained upon restricting to any subobject of the ∞ -category of diagrams. This motivates the following definitions:

2.3.7. DEFINITION. A **colimit** of a family of diagrams $d: D \rightarrow A^J$ indexed by J in an ∞ -category A is given by an absolute left lifting diagram

$$\begin{array}{ccc} & A & \\ \text{colim} \nearrow & & \downarrow \Delta \\ D & \xrightarrow{d} & A^J \end{array}$$

comprised of a **colimit functor** $\text{colim}: D \rightarrow A$ and a **colimit cone** $\eta: d \Rightarrow \Delta \text{colim}$.

Dually, a **limit** of a family of diagrams $d: D \rightarrow A^J$ indexed by J in an ∞ -category A is given by an absolute right lifting diagram

$$\begin{array}{ccc} & & A \\ & \nearrow \text{lim} & \downarrow \Delta \\ D & \xrightarrow{d} & A^J \end{array}$$

comprised of a **limit functor** $\text{lim}: D \rightarrow A$ and a **limit cone** $\epsilon: \Delta \text{lim} \Rightarrow d$.

2.3.8. REMARK. If A has all limits of shape J , then Lemma 2.3.5 implies that any family of diagrams $d: D \rightarrow A^J$ has a limit, defined by evaluating the limit functor $\text{lim}: A^J \rightarrow A$ at d , i.e., by restricting lim along d . In certain ∞ -cosmoi, such as \mathcal{QCat} , if every diagram $d: 1 \rightarrow A^J$ has a limit, then A has all J -indexed limits, because the quasi-category 1 generates the ∞ -cosmos of quasi-categories in a suitable sense, but this result is not true for all ∞ -cosmoi.

For example, a 2-categorical lemma enables general proof of a classical result from homotopy theory that computes geometric realizations of “split” simplicial objects. Before proving this, we introduce the indexing shapes involved.

2.3.9. DEFINITION (split augmented (co)simplicial objects). Recall Δ is the simplex category of finite non-empty ordinals and order-preserving maps introduced in 1.1.1. It defines a full subcategory of a category Δ_+ which freely appends the empty ordinal “[−1]” as an initial object. This in turn defines a wide subcategory of a category Δ_\perp , which adds an “extra” degeneracy $\sigma^{-1}: [n+1] \twoheadrightarrow [n]$ between each pair of consecutive ordinals, including $\sigma^{-1}: [0] \twoheadrightarrow [-1]$.

Diagrams indexed by $\Delta \subset \Delta_+ \subset \Delta_\perp$ are respectively called **cosimplicial objects**, **coaugmented cosimplicial objects**, and **split coaugmented cosimplicial objects**, if they are covariant, and **simplicial objects**, **augmented simplicial objects**, and **split augmented simplicial objects**, if they are contravariant.

A simplicial object $d: 1 \rightarrow A^{\Delta^{\text{op}}}$ in an ∞ -category A **admits an augmentation** or **admits a splitting**, if it lifts along the restriction functors

$$\begin{array}{ccc} & & A^{\Delta_\perp^{\text{op}}} \\ & \nearrow \text{dotted} & \downarrow \\ & & A^{\Delta_+^{\text{op}}} \\ & \nearrow \text{dashed} & \downarrow \\ 1 & \xrightarrow{d} & A^{\Delta^{\text{op}}} \end{array}$$

The family of simplicial objects admitting an augmentation and splitting is then represented by the generic element $A^{\Delta_\perp^{\text{op}}} \twoheadrightarrow A^{\Delta^{\text{op}}}$. The following proposition proves that for any simplicial object admitting a splitting, the augmentation defines the colimit cone; dual results apply to colimits of split cosimplicial objects. The limit and colimit cones are defined by cotensoring with the unique natural transformation

$$\begin{array}{ccc} \Delta & \xrightarrow{\quad} & \Delta_+ \\ \downarrow ! & \uparrow \nu & \uparrow [-1] \\ & \mathbb{1} & \end{array} \quad (2.3.10)$$

that exists because $[-1]: \mathbb{1} \rightarrow \Delta_+$ is initial; see Lemma 2.2.4.

2.3.11. PROPOSITION (geometric realizations). *Let A be any ∞ -category. For every cosimplicial object in A that admits a coaugmentation and a splitting, the coaugmentation defines a limit cone. Dually, for every simplicial object in A that admits an augmentation and a splitting, the augmentation defines a colimit cone. That is, there exist absolute right and left lifting diagrams*

$$\begin{array}{ccc}
 & & A \\
 & \nearrow \text{ev}[-1] & \downarrow \Delta \\
 A^{\Delta_{\perp}} & \xrightarrow{\text{res}} A^{\Delta_+} & \xrightarrow{\text{res}} A^{\Delta} \\
 & \Downarrow A^{\vee} & \\
 & & A \\
 & \nwarrow \text{ev}[-1] & \downarrow \Delta \\
 A^{\Delta_{\perp}^{\text{op}}} & \xrightarrow{\text{res}} A^{\Delta_+^{\text{op}}} & \xrightarrow{\text{res}} A^{\Delta^{\text{op}}} \\
 & \Uparrow A^{\vee^{\text{op}}} &
 \end{array}$$

in which the 2-cells are obtained as restrictions of the cotensor of the 2-cell (2.3.10) with A . Moreover, such limits and colimits are **absolute**, preserved by any functor $f: A \rightarrow B$ of ∞ -categories.

PROOF. By Example B.5.2, the inclusion $\Delta \hookrightarrow \Delta_{\perp}$ admits a right adjoint, which can automatically be regarded as an adjunction “over” $\mathbb{1}$ since $\mathbb{1}$ is 2-terminal. The initial element $[-1] \in \Delta_+ \subset \Delta_{\perp}$ defines a left adjoint to the constant functor:

$$\begin{array}{ccccc}
 & & \top & & \\
 & \swarrow & & \searrow & \\
 \Delta & \xrightarrow{\quad} & \Delta_+ & \hookrightarrow & \Delta_{\perp} \\
 \downarrow \text{!} & & \uparrow & & \downarrow \text{!} \\
 \mathbb{1} & & & &
 \end{array}$$

with the counit of this adjunction (2.3.10) defining the colimit cone under the constant functor at the initial element. These adjunctions are preserved by the 2-functor $A^{(-)}: \text{Cat}^{\text{op}} \rightarrow \mathfrak{h}\mathcal{K}$, yielding a diagram

$$\begin{array}{ccc}
 & & A \\
 & \nearrow \text{ev}[-1] & \downarrow \Delta \\
 A^{\Delta_{\perp}} & \xrightarrow{\text{res}} A^{\Delta_+} & \xrightarrow{\text{res}} A^{\Delta} \\
 & \Downarrow A^{\vee} & \\
 & & A \\
 & \nwarrow \text{ev}[-1] & \downarrow \Delta \\
 & & A
 \end{array}$$

By Lemma B.5.1 these adjunctions witness the fact that evaluation at $[-1]$ and the 2-cell from (2.3.10) define an absolute right lifting of the canonical restriction functor $A^{\Delta_{\perp}} \rightarrow A^{\Delta}$ through the constant diagram functor, as claimed. The colimit case is proven similarly by applying the composite 2-functor

$$\text{Cat}^{\text{coop}} \xrightarrow{(-)^{\text{op}}} \text{Cat}^{\text{op}} \xrightarrow{A^{(-)}} \mathfrak{h}\mathcal{K}$$

Finally, by the 2-functoriality of the simplicial cotensor, any $f: A \rightarrow B$ commutes with the 2-cells defined by cotensoring with \vee or its opposite.

$$\begin{array}{ccc}
 & & A \xrightarrow{f} B \\
 & \nearrow \text{ev}[-1] & \downarrow \Delta \\
 A^{\Delta_{\perp}} & \xrightarrow{\text{res}} A^{\Delta_+} & \xrightarrow{\text{res}} A^{\Delta} \xrightarrow{f^{\Delta}} B^{\Delta} \\
 & \Downarrow A^{\vee} & \\
 & & B \\
 & \nwarrow \text{ev}[-1] & \downarrow \Delta \\
 & & B
 \end{array} = \begin{array}{ccc}
 & & B \\
 & \nearrow \text{ev}[-1] & \downarrow \Delta \\
 A^{\Delta_{\perp}} & \xrightarrow{f^{\Delta_{\perp}}} B^{\Delta_{\perp}} & \xrightarrow{\text{res}} B^{\Delta_+} & \xrightarrow{\text{res}} B^{\Delta} \\
 & \Downarrow A^{\vee} & \\
 & & B
 \end{array}$$

Since the right-hand composite is an absolute right lifting diagram, so is the left-hand composite, which says that $f: A \rightarrow B$ preserves the totalization of any split coaugmented cosimplicial object in A . \square

Exercises.

2.3.i. EXERCISE. Prove Lemma 2.3.5.

2.3.ii. EXERCISE. Re-prove the forwards implication of Lemma 2.3.6 by following your nose through a pasting diagram calculation and prove the converse similarly.

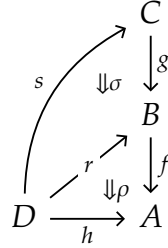
2.4. Preservation of limits and colimits

Famously, right adjoint functors preserve limits and left adjoints preserve colimits. Our aim in this section is to prove this in the ∞ -categorical context and exhibit the first examples of initial and final functors, in the sense introduced in Definition 2.4.6 below.

The commutativity of right adjoints and limits is very easily established in the case where the ∞ -categories in question admit *all* limits of a given shape: under these hypotheses, the limit functor is right adjoint to the constant diagram functor, which commutes with all functors between the base ∞ -categories. Since the left adjoints commute, the uniqueness of adjoints (Proposition 2.1.10) implies that the right adjoints do as well. This outline gives a hint for Exercise 2.4.i.

A slightly more delicate argument is needed in the general case, involving, say the preservation of a single limit diagram without a priori assuming that any other limits exist. This follows easily from a general lemma about composition and cancelation of absolute lifting diagrams:

2.4.1. LEMMA (composition and cancelation of absolute lifting diagrams). *Suppose (r, ρ) defines an absolute right lifting of h through f :*



Then (s, σ) defines an absolute right lifting of r through g if and only if $(s, \rho \cdot f\sigma)$ defines an absolute right lifting of h through fg .

PROOF. Exercise 2.4.ii. □

2.4.2. THEOREM (RAPL/LAPC). *Right adjoints preserve limits and left adjoints preserve colimits.*

The usual argument that right adjoints preserve limits proceeds like this: a cone over a J -shaped diagram in the image of u transposes across the adjunction $f^J \dashv u^J$ to a cone over the original diagram, which factors through the designated limit cone. This factorization transposes across the adjunction $f \dashv u$ to define the sought-for unique factorization through the image of the limit cone. The use of absolute lifting diagrams to express the universal properties of limits and colimits (Definition 2.3.7) and adjoint transposition (Lemma 2.3.6) allows us to economize on the usual proof by suppressing consideration of a generic test cone that must be shown to uniquely factor through the limit cone.

PROOF. We prove that right adjoints preserve limits. By taking “co” duals the same argument demonstrates that left adjoints preserve colimits.

Suppose $u: A \rightarrow B$ admits a left adjoint $f: B \rightarrow A$ with unit $\eta: \text{id}_B \Rightarrow uf$ and counit $\epsilon: fu \Rightarrow \text{id}_A$. Our aim is to show that any absolute right lifting diagram as displayed below-left is carried to an absolute right lifting diagram as displayed below-right:

$$\begin{array}{ccc}
 & A & \\
 \lim \nearrow & \Downarrow \rho & \downarrow \Delta \\
 D & \xrightarrow{d} & A^J
 \end{array}
 \qquad
 \begin{array}{ccccc}
 & A & \xrightarrow{u} & B & \\
 \lim \nearrow & \Downarrow \rho & \downarrow \Delta & & \downarrow \Delta \\
 D & \xrightarrow{d} & A^J & \xrightarrow{u^J} & B^J
 \end{array}
 \tag{2.4.3}$$

The cotensor $(-)^J: \mathbf{h}\mathcal{K} \rightarrow \mathbf{h}\mathcal{K}$ carries the adjunction $f \dashv u$ to an adjunction $f^J \dashv u^J$ with unit η^J and counit ϵ^J . In particular, by Lemma 2.3.6, (u^J, ϵ^J) defines an absolute right lifting of the identity through f^J , which is then preserved by restriction along the functor d . Thus, by Lemma 2.4.1, the diagram on the right of (2.4.3) is an absolute right lifting diagram if and only if the pasted composite displayed below-left

$$\begin{array}{ccccc}
 & A & \xrightarrow{u} & B & \\
 \lim \nearrow & \Downarrow \rho & \downarrow \Delta & & \downarrow \Delta \\
 D & \xrightarrow{d} & A^J & \xrightarrow{u^J} & B^J \\
 & & \Downarrow \epsilon^J & \downarrow f^J & \\
 & & A^J & &
 \end{array}
 =
 \begin{array}{ccccc}
 & A & \xrightarrow{u} & B & \\
 \lim \nearrow & \Downarrow \rho & \downarrow \Delta & & \downarrow \Delta \\
 D & \xrightarrow{d} & A^J & \xrightarrow{u^J} & B^J \\
 & & \Downarrow \epsilon^J & \downarrow f^J & \\
 & & A^J & &
 \end{array}
 =
 \begin{array}{ccccc}
 & A & \xrightarrow{u} & B & \\
 \lim \nearrow & \Downarrow \rho & \downarrow \Delta & & \downarrow \Delta \\
 D & \xrightarrow{d} & A^J & \xrightarrow{u^J} & B^J \\
 & & \Downarrow \epsilon^J & \downarrow f^J & \\
 & & A^J & &
 \end{array}$$

defines an absolute right lifting diagram. Pasting the 2-cell on the right of (2.4.3) with the counit in this way amounts to transposing the cone under $u \lim$ across the adjunction $f^J \dashv u^J$.

We'll now observe that this transposed cone factors through the limit cone (\lim, ρ) in a canonical way. From the 2-functoriality of the simplicial cotensor in its exponent variable, $f^J \Delta = \Delta f$ and $\epsilon^J \Delta = \Delta \epsilon$. Hence, the pasting diagram displayed above-left equals the one displayed above-center and hence also, by naturality of whiskering, the diagram above-right.⁸ This latter diagram is a pasted composite of two absolute right lifting diagrams, and is hence an absolute right lifting diagram in its own right; this universal property says that any cone over d whose summit factors through f factors uniquely through the limit cone (\lim, ρ) through a map that then transposes along the adjunction $f \dashv u$. Hence all of the diagrams in the statement are absolute right lifting diagrams, including in particular the one on the right-hand side of (2.4.3). \square

By combining Theorem 2.4.2 with Proposition 2.1.11, we have immediately that:

2.4.4. COROLLARY. *Equivalences preserve limits and colimits.* \square

We can also prove a more refined result:

2.4.5. PROPOSITION. *If $A \simeq B$, then any family of diagrams in A admitting a limit or colimit in B also admits a limit or colimit in A that is preserved by the equivalence.*

PROOF. By Proposition 2.1.11 the equivalence $B \simeq A$ is both left and right adjoint to its equivalence inverse, preserving both limits and colimits of the composite family of diagrams $D \rightarrow A^J \simeq B^J$. Via the invertible 2-cells of the equivalence $A^J \simeq B^J$ constructed by applying $(-)^J: \mathbf{h}\mathcal{K} \rightarrow \mathbf{h}\mathcal{K}$ to the equivalence $A \simeq B$, the preserved diagram $D \rightarrow A^J \simeq B^J \simeq A^J$ is isomorphic to the original family

⁸By naturality of whiskering, $\epsilon^J d \cdot f^J u^J \rho = \rho \cdot \epsilon^J \Delta \lim$, and since $\epsilon^J \Delta = \Delta \epsilon$, this composite equals $\rho \cdot \Delta \epsilon \lim$.

of diagrams $D \rightarrow A^J$. Thus, we conclude that a family of diagrams in A has a limit or colimit if and only if its image in an equivalent ∞ -category B does, and such limits and colimits are preserved by the equivalence. \square

The following definition makes sense between small quasi-categories or equally between arbitrary ∞ -categories in a cartesian closed ∞ -cosmos.

2.4.6. DEFINITION (initial and final functor). A functor $k: I \rightarrow J$ is **final** if J -indexed colimits exist if and only if, and in such cases coincide with, the restricted I -indexed colimits. That is, $k: I \rightarrow J$ is final if and only if for any ∞ -category A , the square

$$\begin{array}{ccc} A & \xlongequal{\quad} & A \\ \Delta \downarrow & & \downarrow \Delta \\ A^J & \xrightarrow{A^k} & A^I \end{array}$$

preserves and reflects all absolute left lifting diagrams.

Dually a functor $k: I \rightarrow J$ is **initial** if this square preserves and reflects all absolute right lifting diagrams: or informally, if a generalized element defines a limit of a J -indexed diagram if and only if it defines a limit of the restricted I -indexed diagrams.

Historically, final functors were called “cofinal” with no obvious name for the dual notion. Our preferred terminology hinges on the following mnemonic: the inclusion of an initial element defines an initial functor, while the inclusion of a terminal (aka final) element defines a final functor. These results are special cases of a more general result we now establish, using exactly the same tactics as taken to prove Theorem 2.4.2.

2.4.7. PROPOSITION. *Left adjoints define initial functors and right adjoints define final functors.*

PROOF. If $k \dashv r$ with unit $\eta: \text{id}_I \Rightarrow rk$ and counit $\epsilon: kr \Rightarrow \text{id}_J$, then cotensoring into A yields an adjunction

$$\begin{array}{ccc} & A^r & \\ A^J & \xleftarrow{\quad} & A^I \\ & \perp & \\ & A^k & \end{array}$$

with unit $A^\eta: \text{id}_{A^I} \Rightarrow A^k A^r$ and counit $A^\epsilon: A^r A^k \Rightarrow \text{id}_{A^J}$.

To prove that k is initial we must show that for any (d, lim, ρ) as displayed below-left,

$$\begin{array}{ccc} & A & \\ \text{lim} \nearrow & \downarrow \Delta & \\ D & \xrightarrow{d} & A^J \end{array} \qquad \begin{array}{ccccc} & A & \xlongequal{\quad} & A & \\ \text{lim} \nearrow & \downarrow \Delta & & \downarrow \Delta & \\ D & \xrightarrow{d} & A^J & \xrightarrow{A^k} & A^I \end{array}$$

the left-hand diagram is an absolute right lifting diagram if and only if the right-hand diagram is an absolute right lifting diagram.

By Lemmas 2.3.6 and 2.4.1, the right-hand diagram is an absolute right lifting diagram if and only if the pasted composite displayed below-left

$$\begin{array}{ccc}
 & A & \xlongequal{\quad} A \\
 \lim \nearrow & \downarrow \Delta & \downarrow \Delta \\
 D & \xrightarrow[d]{} A^J & \xrightarrow{A^k} A^I \\
 & \searrow \Downarrow A^\epsilon & \downarrow A^r \\
 & & A^J
 \end{array}
 =
 \begin{array}{ccc}
 & A & \\
 \lim \nearrow & \downarrow \Delta & \\
 D & \xrightarrow[d]{} A^J &
 \end{array}$$

is also an absolute right lifting diagram. On noting that $A^r \Delta = \Delta$ and $A^\epsilon \Delta = \text{id}_\Delta$, the left-hand side reduces to the right-hand side, which proves the claim. \square

Exercises.

2.4.i. EXERCISE. Show that any left adjoint $f: B \rightarrow A$ between ∞ -categories admitting all J -shaped colimits preserves them in the sense that the square of functors

$$\begin{array}{ccc}
 B^J & \xrightarrow{f^J} & A^J \\
 \text{colim} \downarrow & \cong & \downarrow \text{colim} \\
 B & \xrightarrow{f} & A
 \end{array}$$

commutes up to isomorphism.

2.4.ii. EXERCISE. Prove Lemma 2.4.1.

2.4.iii. EXERCISE. Given a proof of Theorem 2.4.2 that does not appeal to Lemma 2.4.1 by directly verifying that the diagram on the right of (2.4.3) is an absolute right lifting diagram.

2.4.iv. EXERCISE. Use Lemma 2.4.1 to give a new proof of Proposition 2.1.9.

CHAPTER 3

Weak 2-limits in the homotopy 2-category

In Chapter 2, we introduced adjunctions between ∞ -categories and limits and colimits of diagrams valued within an ∞ -category through definitions that are particularly expedient for establishing the expected interrelationships. But neither 2-categorical definition clearly articulates the universal properties of these notions. Definition 2.3.7 does not obviously express the expected universal property of the limit cone: namely, that the limit cone over a diagram d defines the terminal element of the ∞ -category of cones over d , yet-to-be-defined. Nor have we understood how an adjunction $f \dashv u$ induces an equivalence on as-yet-to-be-defined hom-spaces $\mathbf{Hom}_A(fb, a) \simeq \mathbf{Hom}_B(b, ua)$ for a pair of generalized elements.¹ In this section, we make use of the completeness axiom in the definition of an ∞ -cosmos to exhibit a general construction that will specialize to give a definition of this ∞ -category of cones and also specialize to define these hom-spaces. This construction will also permit us to represent a functor between ∞ -categories as an ∞ -category, in dual “left” or “right” fashions. Using this, we can redefine an adjunction to consist of a pair of functors $f: B \rightarrow A$ and $u: A \rightarrow B$ so that the left representation of f is equivalent to the right representation of u over $A \times B$.

Our vehicle for all of these new definitions is the *comma ∞ -category* associated to a cospan

$$C \xrightarrow{g} A \xleftarrow{f} B \quad \rightsquigarrow \quad \begin{array}{c} \mathbf{Hom}_A(f, g) \\ \downarrow (p_1, p_0) \\ C \times B \end{array}$$

Our aim in this chapter is to develop the general theory of comma constructions from the point of view of the homotopy 2-category of an ∞ -cosmos. Our first payoff for this work will occur in Chapter 4 where we study the universal properties of adjunctions, limits, and colimits in the sense of the ideas just outlined. The comma construction will also provide the essential vehicle for establishing the model-independence of the categorical notions we will introduce throughout this text.

There is a standard definition of a “comma object” that can be stated in any strict 2-category, defined as a particular weighted limit (see Example 7.1.17). Comma ∞ -categories do *not* satisfy this universal property in the homotopy 2-category, however. Instead, they satisfy a somewhat peculiar “weak” variant of the usual 2-categorical universal property that to our knowledge has not been discovered elsewhere in the categorical or homotopical literature, expressed in terms of something we call a *smothering functor*. To introduce these universal properties in a concrete rather than abstract framework, we start in §3.1 by considering smothering functors involving homotopy categories of quasi-categories. The intrepid and impatient reader may skip the entirety of §3.1 if they wish to instead first encounter these notions in their full generality.

¹A 2-categorical version of this result — exhibiting a bijection between *sets* of 2-cells — appears as Lemma 2.3.6, but in an ∞ -category we’d hope for a similar equivalence of hom-spaces.

3.1. Smothering functors

Let Q be a quasi-category. Recall from Lemma 1.1.12 that its homotopy category hQ has

- the elements $1 \rightarrow Q$ of Q as its objects;
- the set of homotopy classes of 1-simplices of Q as its arrows, where parallel 1-simplices are homotopic just when they bound a 2-simplex with the remaining outer edge degenerate; and
- a composition relation if and only if any chosen 1-simplices representing the three arrows bound a 2-simplex.

For a 1-category J , it is well-known in classical homotopy theory that the homotopy category of diagrams $h(Q^J)$ is not equivalent to the category $(hQ)^J$ of diagrams in the homotopy category — except in very special cases, such as when J is a set (see Warning 2.3.3). The objects of $h(Q^J)$ are *homotopy coherent diagrams* of shape J in Q , while the objects of $(hQ)^J$ are mere *homotopy commutative diagrams*. There is, however, a canonical comparison functor

$$h(Q^J) \rightarrow (hQ)^J$$

defined by applying $h: \mathbf{QCat} \rightarrow \mathbf{Cat}$ to the evaluation functor $Q^J \times J \rightarrow Q$ and then transposing; a homotopy coherent diagram is in particular homotopy commutative.

Our first aim in this section is to better understand the relationship between the arrows in the homotopy category hQ and what we'll refer to as the **arrows of Q** , namely, the 1-simplices in the quasi-category. To study this we'll be interested in the quasi-category in which the arrows of Q live as elements, namely Q^2 , where $2 = \Delta[1]$ is the nerve of the “walking” arrow. Our notation deliberately imitates the notation commonly used for the **category of arrows**: if C is a 1-category, then C^2 is the category whose objects are arrows in C and whose morphisms are commutative squares, regarded as a morphism from the arrow displayed vertically on the left-hand side to the arrow displayed vertically on the right-hand side. This notational conflation suggests our first motivating question: how does the homotopy category of Q^2 relate to the category of arrows in the homotopy category of Q ?

3.1.1. LEMMA. *The canonical functor $h(Q^2) \rightarrow (hQ)^2$ is*

- *surjective on objects,*
- *full, and*
- *conservative, i.e., reflects invertibility of morphisms,*

but not injective on objects nor faithful.

PROOF. Surjectivity on objects asserts that every arrow in the homotopy category hQ is represented by a 1-simplex in Q . This is the conclusion of Exercise 1.1.ii(iii) which outlines the proof of Lemma 1.1.12.

To prove fullness, consider a commutative square in hQ and choose arbitrary 1-simplices representing each morphism and their common composite:

$$\begin{array}{ccc} \bullet & \xrightarrow{h} & \bullet \\ f \downarrow & \searrow \ell & \downarrow g \\ \bullet & \xrightarrow{k} & \bullet \end{array}$$

By Lemma 1.1.12, every composition relation in hQ is witnessed by a 2-simplex in Q ; choosing a pair of such 2-simplices defines a diagram $2 \rightarrow Q^2$, which represents a morphism from f to g in $h(Q^2)$, proving fullness.

Surjectivity on objects and fullness of the functor $\mathbf{h}(Q^2) \rightarrow \mathbf{h}(Q)^2$ are special properties having to do with the diagram shape **2**. Conservativity is much more general as a consequence of the second statement of Corollary 1.1.21. \square

The properties of the canonical functor $\mathbf{h}(Q^2) \rightarrow \mathbf{h}(Q)^2$ will reappear frequently so are worth giving a name:

3.1.2. DEFINITION. A functor $f: A \rightarrow B$ between 1-categories is **smothering** if it is surjective on objects, full, and conservative. That is, a functor is smothering if and only if it has the right lifting property with respect to the set of functors:

$$\left\{ \begin{array}{ccc} \emptyset & \mathbf{1} + \mathbf{1} & \mathbf{2} \\ \downarrow & \downarrow & \downarrow \\ \mathbf{1} & \mathbf{2} & \mathbf{1} \end{array} \right\}$$

Some elementary properties of smothering functors are established in Exercise 3.1.i. The most important of these is:

3.1.3. LEMMA. *Each fibre of a smothering functor is a non-empty connected groupoid.*

PROOF. Suppose $f: A \rightarrow B$ is smothering and consider the fiber

$$\begin{array}{ccc} A_b & \longrightarrow & A \\ \downarrow & \lrcorner & \downarrow f \\ \mathbf{1} & \xrightarrow{b} & B \end{array}$$

over an object b of B . By surjectivity on objects, the fiber is non-empty. Its morphisms are defined to be arrows between objects in the fiber of b that map to the identity on b . By fullness, any two objects in the fiber are connected by a morphism, indeed, by morphisms pointing in both directions. By conservativity, all the morphisms in the fiber are necessarily invertible. \square

The argument used to prove Lemma 3.1.1 generalizes to:

3.1.4. LEMMA. *If J is a 1-category that is free on a reflexive directed graph and Q is a quasi-category, then the canonical functor $\mathbf{h}(Q^J) \rightarrow (\mathbf{h}Q)^J$ is smothering.*

PROOF. Exercise 3.1.ii. \square

Cotensors are one of the simplicial limit constructions enumerated in axiom 1.2.1(i). Other limit constructions listed there also give rise to smothering functors.

3.1.5. LEMMA. *For any pullback diagram of quasi-categories in which p is an isofibration*

$$\begin{array}{ccc} E \times_B A & \longrightarrow & E \\ \downarrow & \lrcorner & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

the canonical functor $\mathbf{h}(E \times_B A) \rightarrow \mathbf{h}E \times_{\mathbf{h}B} \mathbf{h}A$ is smothering.

PROOF. As $\mathbf{h}: \mathbf{QCat} \rightarrow \mathbf{Cat}$ does not preserve pullbacks, the canonical comparison functor of the statement is not an isomorphism. It is however bijective on objects since the composite functor

$$\mathbf{QCat} \xrightarrow{\mathbf{h}} \mathbf{Cat} \xrightarrow{\text{obj}} \mathbf{Set}$$

is given by evaluation on the set of vertices of each quasi-category, and this functor *does* preserve pullbacks.

For fullness, note that a morphism in $\mathbf{h}E \times_{\mathbf{h}B} \mathbf{h}A$ is represented by a pair of 1-simplices $\alpha: a \rightarrow a'$ and $\epsilon: e \rightarrow e'$ in A and E whose images in B are homotopic, a condition that implies in particular that $f(a) = p(e)$ and $f(a') = p(e')$. By Lemma 1.1.9, we can arrange this homotopy however we like, and thus we choose a 2-simplex witness β so as to define a lifting problem

$$\begin{array}{ccc} \Lambda^1[2] & \longrightarrow & E \\ \downarrow & \nearrow & \downarrow p \\ \Delta[2] & \xrightarrow{\beta} & B \end{array} \quad \ni \quad \begin{array}{ccc} & e & \\ & \parallel & \searrow \epsilon \\ e & & e' \end{array} \quad \Downarrow \quad \begin{array}{ccc} & p(e) & \\ & \parallel & \searrow p(\epsilon) \\ f(a) & \xrightarrow{f(\alpha)} & f(a') = p(e') \end{array}$$

Since p is an isofibration, a solution exists, defining an arrow $\tilde{\epsilon}: e \rightarrow e'$ in E in the same homotopy class as ϵ so that $p(\tilde{\epsilon}) = f(\alpha)$. The pair $(\alpha, \tilde{\epsilon})$ now defines the lifted arrow in $\mathbf{h}(E \times_B A)$.

Finally, consider an arrow $\mathbb{2} \rightarrow E \times_B A$ whose image in $\mathbf{h}E \times_{\mathbf{h}B} \mathbf{h}A$ is an isomorphism, which is the case just when the projections to E and A define isomorphisms. By Corollary 1.1.16, we may choose a homotopy coherent isomorphism $\mathbb{I} \rightarrow A$ extending the given isomorphism $\mathbb{2} \rightarrow A$. This data presents us with a lifting problem

$$\begin{array}{ccccc} \mathbb{2} & \longrightarrow & E \times_B A & \longrightarrow & E \\ \downarrow & \nearrow & \downarrow & \nearrow & \downarrow p \\ \mathbb{I} & \longrightarrow & A & \xrightarrow{f} & B \end{array}$$

which Exercise 1.1.v tells us we can solve. This proves that $\mathbf{h}(E \times_B A) \rightarrow \mathbf{h}E \times_{\mathbf{h}B} \mathbf{h}A$ is conservative and hence also smothering. \square

A similar argument proves:

3.1.6. LEMMA. *For any tower of isofibrations between quasi-categories*

$$\cdots \longrightarrow E_n \longrightarrow E_{n-1} \longrightarrow \cdots \longrightarrow E_2 \longrightarrow E_1 \longrightarrow E_0$$

the canonical functor $\mathbf{h}(\lim_n E_n) \rightarrow \lim_n \mathbf{h}E_n$ is smothering.

PROOF. Exercise 3.1.iii. \square

3.1.7. LEMMA. For any cospan between quasi-categories $C \xrightarrow{g} A \xleftarrow{f} B$ consider the quasi-category defined by the pullback

$$\begin{array}{ccc} \mathrm{Hom}_A(f, g) & \longrightarrow & A^2 \\ (p_1, p_0) \downarrow & \lrcorner & \downarrow (\mathrm{cod}, \mathrm{dom}) \\ C \times B & \xrightarrow{g \times f} & A \times A \end{array}$$

The canonical functor $\mathrm{hHom}_A(f, g) \rightarrow \mathrm{Hom}_{\mathrm{h}A}(\mathrm{h}f, \mathrm{h}g)$ is smothering.

PROOF. Here, the codomain is the category defined by an analogous pullback

$$\begin{array}{ccc} \mathrm{Hom}_{\mathrm{h}A}(\mathrm{h}f, \mathrm{h}g) & \longrightarrow & (\mathrm{h}A)^2 \\ \downarrow & \lrcorner & \downarrow (\mathrm{cod}, \mathrm{dom}) \\ \mathrm{h}C \times \mathrm{h}B & \xrightarrow{\mathrm{h}g \times \mathrm{h}f} & \mathrm{h}A \times \mathrm{h}A \end{array}$$

in \mathbf{Cat} and the canonical functor factors as

$$\mathrm{hHom}_A(f, g) \rightarrow \mathrm{h}(A^2) \times_{\mathrm{h}A \times \mathrm{h}A} (\mathrm{h}C \times \mathrm{h}B) \rightarrow (\mathrm{h}A)^2 \times_{\mathrm{h}A \times \mathrm{h}A} (\mathrm{h}C \times \mathrm{h}B)$$

By Lemma 3.1.5 the first of these functors is smothering. By Lemma 3.1.1 the second is a pullback of a smothering functor. By Exercise 3.1.i(i) it follows that the composite functor is smothering. \square

In the sections that follow, we will discover that the smothering functors just constructed express particular “weak” universal properties of arrow, pullback, and comma constructions in the homotopy 2-category of any ∞ -cosmos. It is to the first of these that we now turn.

Exercises.

3.1.i. EXERCISE. Prove that:

- (i) The class of smothering functors is closed under composition, retract, product, and pullback.
- (ii) The class of smothering functors contains all surjective equivalences of categories.
- (iii) All smothering functors are isofibrations, that is, maps that have the right lifting property with respect to $\mathbf{1} \hookrightarrow \mathbf{I}$.
- (iv) Prove that if f and g are smothering functors, then g is a smothering functor.²

3.1.ii. EXERCISE. Prove Lemma 3.1.4.

3.1.iii. EXERCISE. Prove Lemma 3.1.6.

3.2. ∞ -categories of arrows

In this section, we replicate the discussion from the start of the previous section using an arbitrary ∞ -category A in place of the quasi-category Q . The analysis of the previous section could have been developed natively in this general setting but at the cost of an extra layer of abstraction and more confusing notation — with a functor space $\mathbf{Fun}(X, A)$ replacing the quasi-category Q .

Recall an **element** of an ∞ -category is defined to be a functor $\mathbf{1} \rightarrow A$. Tautologically, the elements of A are the vertices of the **underlying quasi-category** $\mathbf{Fun}(\mathbf{1}, A)$ of A . In this section, we will define

²It suffices, in fact, to merely assume that f is surjective on objects and arrows.

and study an ∞ -category A^2 whose elements are the 1-simplices in the underlying quasi-category of A . We refer to A^2 as the ∞ -category of arrows in A and call its elements simply *arrows* of A .

In fact, we've tacitly introduced this construction already. Recall $\mathbf{2}$ is our preferred notation for the quasi-category $\Delta[1]$, as this coincides with the nerve of the 1-category $\mathbf{2}$ with a single non-identity morphism $0 \rightarrow 1$.

3.2.1. DEFINITION (arrow ∞ -category). Let A be an ∞ -category. The ∞ -category of arrows in A is the simplicial cotensor A^2 together with the canonical endpoint-evaluation isofibration

$$A^2 := A^{\Delta[1]} \xrightarrow{(p_1, p_0)} A^{\partial\Delta[1]} \cong A \times A$$

induced by the inclusion $\partial\Delta[1] \hookrightarrow \Delta[1]$. For conciseness, we write $p_0: A^2 \rightarrow A$ for the domain-evaluation induced by the inclusion $0: \mathbf{1} \hookrightarrow \mathbf{2}$ and write $p_1: A^2 \rightarrow A$ for the codomain-evaluation induced by $1: \mathbf{1} \hookrightarrow \mathbf{2}$.

As an object of the homotopy 2-category \mathbf{hK} , the ∞ -category of arrows comes equipped with a canonical 2-cell that we now construct.

3.2.2. LEMMA. For any ∞ -category A , the ∞ -category of arrows comes equipped with a canonical 2-cell

$$A^2 \begin{array}{c} \xrightarrow{p_0} \\ \Downarrow \kappa \\ \xrightarrow{p_1} \end{array} A \quad (3.2.3)$$

that we refer to as the **generic arrow** with codomain A .

PROOF. The simplicial cotensor has a strict universal property described in Digression 1.2.4: namely A^2 is characterized by the natural isomorphism

$$\mathrm{Fun}(X, A^2) \cong \mathrm{Fun}(X, A)^2. \quad (3.2.4)$$

By the Yoneda lemma, the data of the natural isomorphism (3.2.4) is encoded by its “universal element”, which is defined to be the image of the identity at the representing object. Here the identity functor $\mathrm{id}: A^2 \rightarrow A^2$ is mapped to an element of $\mathrm{Fun}(A^2, A)^2$, a 1-simplex in $\mathrm{Fun}(A^2, A)$ which represents a 2-cell in the homotopy 2-category defining (3.2.3).

To see that its source and target must be the domain-evaluation and codomain-evaluation maps, note that the action of the simplicial cotensor $A^{(-)}$ on morphisms of simplicial sets is defined so that the isomorphism (3.2.4) is natural in the cotensor variable as well. Thus, by restricting along the endpoint inclusion $\mathbf{1} + \mathbf{1} \hookrightarrow \mathbf{2}$, we may regard the isomorphism (3.2.4) as lying over $\mathrm{Fun}(X, A \times A) \cong \mathrm{Fun}(X, A) \times \mathrm{Fun}(X, A)$. \square

There is a 2-categorical limit notion that is analogous to Definition 3.2.1, which constructs, for any object A , the universal 2-cell with codomain A : namely the cotensor with the 1-category $\mathbf{2}$. Its universal property is analogous to (3.2.4) but with the hom-categories of the 2-category in place of the functor spaces. In *Cat* this constructs the arrow category associated to a 1-category.

In the homotopy 2-category \mathbf{hK} , by the Yoneda lemma again, the data (3.2.3) encodes a natural transformation

$$\mathbf{hFun}(X, A^2) \rightarrow \mathbf{hFun}(X, A)^2$$

of categories but this is *not* a natural isomorphism, nor even a natural equivalence of categories but does express the arrow ∞ -category as a “weak” arrow object with a universal property of the following form:

3.2.5. PROPOSITION (the weak universal property of the arrow ∞ -category). *The generic arrow (3.2.3) with codomain A has a weak universal property in the homotopy 2-category given by three operations:*

(i) *1-cell induction: Given a 2-cell over A as below-left*

$$\begin{array}{c} X \\ \begin{array}{c} \swarrow t \\ \searrow s \end{array} \\ \begin{array}{c} \alpha \\ \Leftarrow \end{array} \\ A \end{array} = \begin{array}{c} X \\ \begin{array}{c} \downarrow a \\ \swarrow p_1 \quad \searrow p_0 \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \kappa \\ \searrow \end{array} \\ A \end{array}$$

there exists a 1-cell $a: X \rightarrow A^2$ so that $s = p_0 a$, $t = p_1 a$, and $\alpha = \kappa a$.

(ii) *2-cell induction: Given a pair of functors $a, a': X \rightrightarrows A^2$ and a pair of 2-cells τ_0 and τ_1 so that*

$$\begin{array}{c} X \\ \begin{array}{c} \swarrow a' \\ \searrow a \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \tau_1 \\ \searrow p_1 \end{array} \\ A \end{array} \quad \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \kappa \\ \searrow p_0 \end{array} \\ A \end{array} = \begin{array}{c} X \\ \begin{array}{c} \swarrow a' \\ \searrow a \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \tau_0 \\ \searrow p_0 \end{array} \\ A \end{array} \quad \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \kappa \\ \searrow p_1 \end{array} \\ A \end{array}$$

there exists a 2-cell $\tau: a \Rightarrow a'$ so that

$$\begin{array}{c} X \\ \begin{array}{c} \swarrow a' \\ \searrow a \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \tau_1 \\ \searrow p_1 \end{array} \\ A \end{array} = \begin{array}{c} X \\ \begin{array}{c} \swarrow a' \\ \searrow a \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \tau \\ \searrow p_1 \end{array} \\ A \end{array} \quad \text{and} \quad \begin{array}{c} X \\ \begin{array}{c} \swarrow a' \\ \searrow a \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \tau \\ \searrow p_0 \end{array} \\ A \end{array} = \begin{array}{c} X \\ \begin{array}{c} \swarrow a' \\ \searrow a \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \tau_0 \\ \searrow p_0 \end{array} \\ A \end{array}$$

(iii) *2-cell conservativity: Any 2-cell*

$$\begin{array}{c} X \\ \begin{array}{c} \swarrow a' \\ \searrow a \end{array} \\ \begin{array}{c} A^2 \\ \begin{array}{c} \swarrow \tau \\ \searrow \end{array} \\ A^2 \end{array}$$

with the property that both $p_1 \tau$ and $p_0 \tau$ are isomorphisms is an isomorphism.

PROOF. Let $Q = \mathbf{Fun}(X, A)$ and apply Lemma 3.1.1 to observe that the natural map of hom-categories

$$\begin{array}{ccc} \mathbf{hFun}(X, A^2) & \xrightarrow{\quad} & \mathbf{hFun}(X, A)^2 \\ & \searrow \scriptstyle ((p_1)_*, (p_0)_*) & \swarrow \scriptstyle (ev_1, ev_0) \\ & \mathbf{hFun}(X, A) \times \mathbf{hFun}(X, A) & \end{array}$$

over $\mathbf{hFun}(X, A \times A) \cong \mathbf{hFun}(X, A) \times \mathbf{hFun}(X, A)$ is a smothering functor. Surjectivity on objects is expressed by 1-cell induction, fullness by 2-cell induction, and conservativity by 2-cell conservativity. \square

Note that the functors $X \rightarrow A^2$ that represent a fixed 2-cell with domain X and codomain A are not unique. However, they are unique up to “fibered” isomorphisms that whisker with $(p_1, p_0): A^2 \rightarrow A \times A$ to an identity 2-cell:

3.2.6. PROPOSITION. *Whiskering with (3.2.3) induces a bijection between 2-cells with domain X and codomain A as displayed below-left*

$$\left\{ X \begin{array}{c} \xrightarrow{s} \\ \Downarrow \alpha \\ \xrightarrow{t} \end{array} A \right\} \quad \longleftrightarrow \quad \left\{ \begin{array}{ccccc} & & X & & \\ & \swarrow t & & \searrow s & \\ A & & & & A \\ & \nwarrow p_1 & \downarrow a & \nearrow p_0 & \\ & & A^2 & & \end{array} \right\} / \cong$$

and fibered isomorphism classes of functors $X \rightarrow A^2$ as displayed above-right, where the fibered isomorphisms are given by invertible 2-cells

$$\begin{array}{ccccc} & & X & & \\ & \swarrow t & & \searrow s & \\ A & & & & A \\ & \nwarrow p_1 & \downarrow \gamma \cong & \nearrow p_0 & \\ & & A^2 & & \end{array}$$

so that $p_0\gamma = \text{id}_s$ and $p_1\gamma = \text{id}_t$.

PROOF. Lemma 3.1.3 proves that the fibers of the smothering functor of Proposition 3.2.5 are connected groupoids. The objects of these fibers are functors $X \rightarrow A^2$ and the morphisms are invertible 2-cells that whisker with $(p_1, p_0): A^2 \rightarrow A \times A$ to an identity 2-cell. The action of the smothering functor defines a bijection between the objects of its codomain and their corresponding fibers. \square

Our final task is to observe that the universal property of Proposition 3.2.5 is also enjoyed by any object $(e_1, e_0): E \rightarrow A \times A$ that is equivalent to the arrow ∞ -category $(p_1, p_0): A^2 \rightarrow A \times A$ in the slice ∞ -cosmos $\mathcal{K}_{/A \times A}$. We have special terminology to allow us to concisely express the type of equivalence we have in mind.

3.2.7. DEFINITION (fibered equivalence). A **fibered equivalence** over an ∞ -category B in an ∞ -cosmos \mathcal{K} is an equivalence

$$\begin{array}{ccc} E & \xrightarrow{\sim} & F \\ & \searrow & \swarrow \\ & B & \end{array} \quad (3.2.8)$$

in the sliced ∞ -cosmos \mathcal{K}_B . We write $E \simeq_B F$ to indicate that that specified isofibrations with these domains are equivalent **over** B .

By Proposition 1.2.17(vii), a fibered equivalence is just a map between a pair of isofibrations over a common base that defines an equivalence in the underlying ∞ -cosmos: the forgetful functor $\mathcal{K}_B \rightarrow \mathcal{K}$ preserves and reflects equivalences. Note, however, that it does not create them: it is possible for two ∞ -categories E and F to be equivalent without there existing any equivalence compatible with a pair of specified isofibration $E \rightarrow B$ and $F \rightarrow B$.

3.2.9. REMARK. At this point, there is some ambiguity about the 2-categorical data that presents a fibered equivalence related to the question posed in Exercise 1.4.iii. But since Proposition 1.2.17(vii) tells us that a mere equivalence in $\mathbf{h}\mathcal{K}$ involving a functor of the form (3.2.8) is sufficient to guarantee that this as-yet-unspecified 2-categorical data exists, we defer a careful analysis of this issue to §3.5.

3.2.10. PROPOSITION (uniqueness of arrow ∞ -categories). *For any isofibration $(e_1, e_0): E \twoheadrightarrow A \times A$ equipped with a fibered equivalence $e: E \xrightarrow{\sim} A^2$, the corresponding 2-cell*

$$E \begin{array}{c} \xrightarrow{e_0} \\ \Downarrow \epsilon \\ \xrightarrow{e_1} \end{array} A$$

satisfies the weak universal property of Proposition 3.2.5. Conversely, if $(d_1, d_0): D \twoheadrightarrow A \times A$ and $(e_1, e_0): E \twoheadrightarrow A \times A$ are equipped with 2-cells

$$D \begin{array}{c} \xrightarrow{d_0} \\ \Downarrow \delta \\ \xrightarrow{d_1} \end{array} A \quad \text{and} \quad E \begin{array}{c} \xrightarrow{e_0} \\ \Downarrow \epsilon \\ \xrightarrow{e_1} \end{array} A$$

satisfying the weak universal property of Proposition 3.2.5, then D and E are fibered equivalent over $A \times A$.

PROOF. We prove the first statement. By the definition equation of 1-cell induction $\epsilon = \kappa e$, where κ is the canonical 2-cell of (3.2.3). Hence, pasting with ϵ induces a functor

$$\begin{array}{ccccc} \mathbf{hFun}(X, E) & \xrightarrow{e_*} & \mathbf{hFun}(X, A^2) & \xrightarrow{\quad} & \mathbf{hFun}(X, A)^2 \\ & \searrow & & \swarrow & \\ & ((p_1)_*, (p_0)_*) & \mathbf{hFun}(X, A) \times \mathbf{hFun}(X, A) & & (ev_1, ev_0) \end{array}$$

and our task is to prove that this composite functor is smothering. We see that the first functor, defined by post-composing with the equivalence $e: E \xrightarrow{\sim} A^2$, is an equivalence of categories, and the second functor is smothering. Thus, the composite is clearly full and conservative. To see that it is also surjective on objects, note first that by 1-cell induction any 2-cell

$$X \begin{array}{c} \xrightarrow{s} \\ \Downarrow \alpha \\ \xrightarrow{t} \end{array} A$$

is represented by a functor $a: X \rightarrow A^2$ over $A \times A$. Composing with any fibered inverse equivalence e' to e yields a functor

$$\begin{array}{ccccc} X & \xrightarrow{a} & A^2 & \xrightarrow[e']{\sim} & E \\ & \searrow & \downarrow (p_1, p_0) & \swarrow & \\ & (t, s) & A \times A & & (e_1, e_0) \end{array}$$

whose image after post-composing with e is isomorphic to a over $A \times A$. Because this isomorphism is fibered (see Proposition 3.2.6), the image of ae' under the functor $\mathbf{hFun}(X, E) \rightarrow \mathbf{hFun}(X, A)^2$ returns the 2-cell α . This proves that this mapping is surjective on objects and hence defines a smothering functor as claimed.

The converse is left to Exercise 3.2.ii and proven in a more general context in Proposition 3.3.11. \square

3.2.11. CONVENTION. On account of Proposition 3.2.10, we extend the appellation “ ∞ -category of arrows” from the strict model constructed in Definition 3.2.1 to any ∞ -category that is fibered equivalent to it.

Via Lemma 3.1.4, the discussion of this section extends to establish corresponding weak universal properties for the cotensors A^I of an ∞ -category A with a free category I . We leave the exploration of this to the reader.

Exercises.

3.2.i. EXERCISE.

- (i) Prove that a parallel pair of 1-simplices in a quasi-category Q are homotopic if and only if they are isomorphic as elements of Q^2 via an isomorphism that projects to an identity along $(p_1, p_0): Q^2 \rightarrow Q \times Q$.
- (ii) Conclude that a parallel pair of 1-arrows in the functor space $\mathbf{Fun}(X, A)$ between two ∞ -categories X and A in any ∞ -cosmos represent the same natural transformation if and only if they are isomorphic as elements of $\mathbf{Fun}(X, A)^2 \cong \mathbf{Fun}(X, A^2)$ via an isomorphism whose domain and codomain components are an identity.
- (iii) Conclude that a parallel pair of 1-arrows in the functor space $\mathbf{Fun}(X, A)$, which may be encoded as functors $X \rightrightarrows A^2$, represent the same natural transformation if and only if they are connected by a fibered isomorphism:

$$\begin{array}{ccc}
 X & \begin{array}{c} \xrightarrow{\quad} \\ \text{||} \\ \xrightarrow{\quad} \end{array} & A^2 \\
 & \searrow \quad \swarrow & \\
 & A \times A & \quad (p_1, p_0)
 \end{array}$$

3.2.ii. EXERCISE. Prove the second statement of Proposition 3.2.10.

3.3. The comma construction

The *comma ∞ -category* is defined by restricting the domain and codomain of the ∞ -category of arrows A^2 along specified functors with codomain A .

3.3.1. DEFINITION (comma ∞ -category). Let $C \xrightarrow{g} A \xleftarrow{f} B$ be a diagram of ∞ -categories. The **comma ∞ -category** is constructed as a pullback of the simplicial cotensor A^2 along $g \times f$

$$\begin{array}{ccc}
 \mathbf{Hom}_A(f, g) & \xrightarrow{\phi} & A^2 \\
 (p_1, p_0) \downarrow & \lrcorner & \downarrow (p_1, p_0) \\
 C \times B & \xrightarrow{g \times f} & A \times A
 \end{array} \tag{3.3.2}$$

This construction equips the comma ∞ -category with a specified isofibration $(p_1, p_0): \text{Hom}_A(f, g) \twoheadrightarrow C \times B$ and a canonical 2-cell

$$\begin{array}{ccc}
 & \text{Hom}_A(f, g) & \\
 p_1 \swarrow & & \searrow p_0 \\
 C & \xleftarrow{\phi} & B \\
 g \searrow & & \swarrow f \\
 & A &
 \end{array} \tag{3.3.3}$$

in the homotopy 2-category called the **comma cone**.

3.3.4. EXAMPLE (arrow ∞ -categories as comma ∞ -categories). The arrow ∞ -category arises as a special case of the comma construction applied to the identity span. This provides us with alternate notation for the generic arrow of (3.2.3), which may be regarded as a particular instance of a comma cone.

$$\begin{array}{ccc}
 & \text{Hom}_A & \\
 p_1 \swarrow & & \searrow p_0 \\
 A & \xleftarrow{\phi} & A \\
 \parallel \searrow & & \swarrow \parallel \\
 & A &
 \end{array}$$

The following proposition encodes the homotopical properties of the comma construction. The proof is by a standard argument in abstract homotopy theory, which can be found in Appendix C. A hint for this proof is given in Exercise 3.3.i.

3.3.5. PROPOSITION (maps between commas). *A commutative diagram*

$$\begin{array}{ccccc}
 C & \xrightarrow{g} & A & \xleftarrow{f} & B \\
 r \downarrow & & \downarrow p & & \downarrow q \\
 \bar{C} & \xrightarrow{\bar{g}} & \bar{A} & \xleftarrow{\bar{f}} & \bar{B}
 \end{array}$$

induces a map between the comma ∞ -categories

$$\begin{array}{ccc}
 \text{Hom}_A(f, g) & \xrightarrow{\text{Hom}_p(q, r)} & \text{Hom}_{\bar{A}}(\bar{f}, \bar{g}) \\
 (p_1, p_0) \downarrow & & \downarrow (p_1, p_0) \\
 C \times B & \xrightarrow{r \times q} & \bar{C} \times \bar{B}
 \end{array}$$

Moreover, if p , q , and r are all

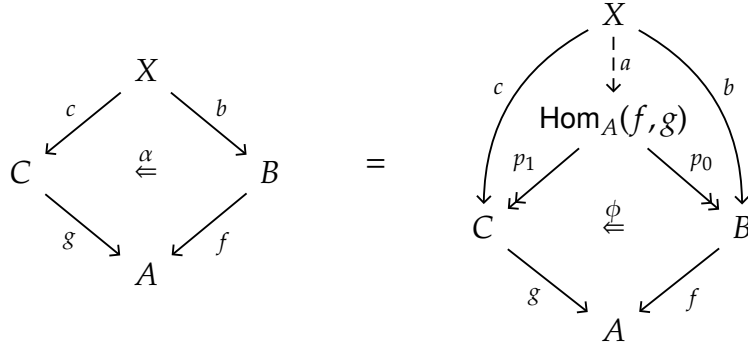
- (i) equivalences,
- (ii) isofibrations, or
- (iii) trivial fibrations

then the induced map is again an equivalence, isofibration, or trivial fibration, respectively.

There is a 2-categorical limit notion that is analogous to Definition 3.3.1, which constructs the universal 2-cell inhabiting a square over a specified cospan. In \mathbf{Cat} the category so-constructed is referred to as a *comma category*, from when we borrow the name. As with the case of ∞ -categories of arrow, comma ∞ -categories do *not* satisfy this 2-universal property strictly. Instead:

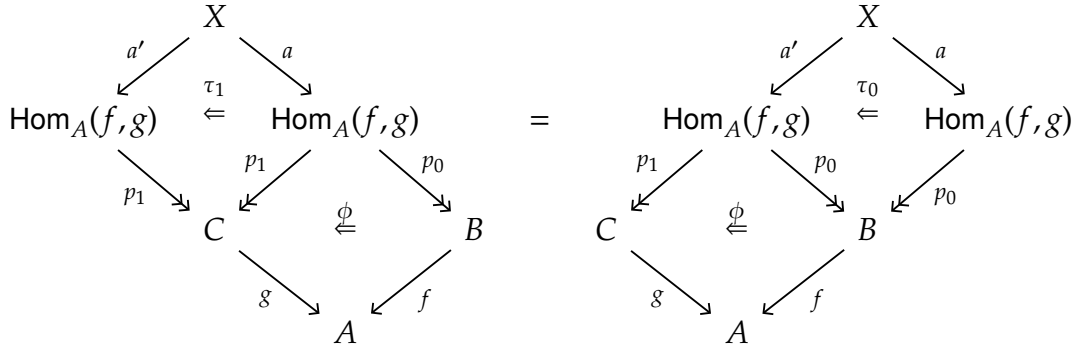
3.3.6. PROPOSITION (the weak universal property of the comma ∞ -category). *The comma cone (3.3.3) has a weak universal property in the homotopy 2-category given by three operations:*

(i) *1-cell induction: Given a 2-cell over $C \xrightarrow{g} A \xleftarrow{f} B$ as below-left*

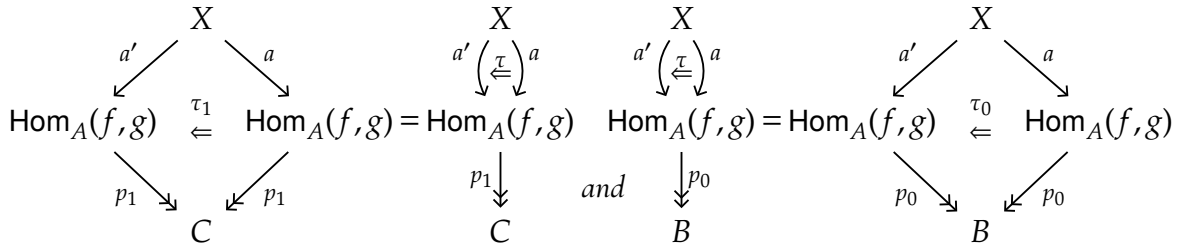


there exists a 1-cell $a: X \rightarrow \mathrm{Hom}_A(f, g)$ so that $b = p_0 a$, $c = p_1 a$, and $\alpha = \phi a$.

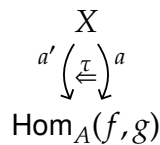
(ii) *2-cell induction: Given a pair of functors $a, a': X \rightrightarrows \mathrm{Hom}_A(f, g)$ and a pair of 2-cells τ_0 and τ_1 so that*



there exists a 2-cell $\tau: a \Rightarrow a'$ so that



(iii) *2-cell conservativity: Any 2-cell*



with the property that both $p_1\tau$ and $p_0\tau$ are isomorphisms is an isomorphism.

PROOF. The cosmological functor $\text{Fun}(X, -): \mathcal{K} \rightarrow \mathcal{QCat}$ carries the pullback (3.3.2) to a pullback

$$\begin{array}{ccc} \text{Fun}(X, \text{Hom}_A(f, g)) \cong \text{Hom}_{\text{Fun}(X, A)}(\text{Fun}(X, f), \text{Fun}(X, g)) & \xrightarrow{\phi} & \text{Fun}(X, A)^2 \\ \downarrow (p_1, p_0) & \lrcorner & \downarrow (p_1, p_0) \\ \text{Fun}(X, C) \times \text{Fun}(X, B) & \xrightarrow{\text{Fun}(X, g) \times \text{Fun}(X, f)} & \text{Fun}(X, A) \times \text{Fun}(X, A) \end{array}$$

of quasi-categories. Now Lemma 3.1.7 demonstrates that the canonical 2-cell (3.3.3) induces a natural map of hom-categories

$$\begin{array}{ccc} \text{hFun}(X, \text{Hom}_A(f, g)) & \xrightarrow{\quad} & \text{Hom}_{\text{hFun}(X, A)}(\text{hFun}(X, f), \text{hFun}(X, g)) \\ & \searrow ((p_1)_*, (p_0)_*) & \swarrow (ev_1, ev_0) \\ & \text{hFun}(X, C) \times \text{hFun}(X, B) & \end{array}$$

over $\text{hFun}(X, C \times B) \cong \text{hFun}(X, C) \times \text{hFun}(X, B)$ that is a smothering functor. The properties of 1-cell induction, 2-cell induction, and 2-cell conservativity follow from surjectivity on objects, fullness, and conservativity of this smothering functor respectively. \square

The 1-cells $X \rightarrow \text{Hom}_A(f, g)$ that are induced by a fixed 2-cell $\alpha: fb \Rightarrow gc$ are unique up to fibered isomorphism over $C \times B$.

3.3.7. PROPOSITION. Whiskering with the comma cone (3.3.3) induces a bijection between 2-cells as displayed below-left

$$\left\{ \begin{array}{ccc} & X & \\ c \swarrow & & \searrow b \\ C & \xleftarrow{\alpha} & B \\ g \searrow & & \swarrow f \\ & A & \end{array} \right\} \rightsquigarrow \left\{ \begin{array}{ccc} & X & \\ c \swarrow & & \searrow b \\ C & \xleftarrow{p_1} & \text{Hom}_A(f, g) & \xrightarrow{p_0} & B \\ & a \downarrow & & & \\ & \text{Hom}_A(f, g) & & & \end{array} \right\} / \cong$$

and fibered isomorphism classes of maps of spans from C to B as displayed above-right, where the fibered isomorphisms are given by invertible 2-cells

$$\begin{array}{ccc} & X & \\ c \swarrow & & \searrow b \\ C & \xleftarrow{a'} & \text{Hom}_A(f, g) & \xrightarrow{a} & B \\ p_1 \swarrow & \gamma \cong & \searrow p_0 & & \\ & \text{Hom}_A(f, g) & & & \end{array}$$

so that $p_0\gamma = \text{id}_b$ and $p_1\gamma = \text{id}_c$.

PROOF. Lemma 3.1.3 proves that the fibers of the smothering functor of Proposition 3.3.6 are connected groupoids. The objects of these fibers are functors $X \rightarrow \text{Hom}_A(f, g)$ and the morphisms are invertible 2-cells that whisker with

$$(p_1, p_0): \text{Hom}_A(f, g) \twoheadrightarrow C \times B$$

to an identity 2-cell. The action of the smothering functor defines a bijection between the objects of its codomain and their corresponding fibers. \square

The construction of the comma ∞ -category is also pseudo-functorial in lax maps defined in the homotopy 2-category:

3.3.8. OBSERVATION. By 1-cell induction a diagram

$$\begin{array}{ccccc} C & \xrightarrow{g} & A & \xleftarrow{f} & B \\ r \downarrow & \Leftarrow \gamma & \downarrow p & \Leftarrow \beta & \downarrow q \\ \bar{C} & \xrightarrow{\bar{g}} & \bar{A} & \xleftarrow{\bar{f}} & \bar{B} \end{array}$$

induces a map between comma ∞ -categories as displayed below-right:

$$\begin{array}{ccc} \text{Hom}_A(f, g) & & \text{Hom}_A(f, g) \\ \begin{array}{ccc} \swarrow p_1 & & \searrow p_0 \\ C & \xrightarrow{\phi} & B \\ \downarrow r & \searrow g & \swarrow f & \downarrow q \\ \bar{C} & \xleftarrow{\gamma} & A & \xleftarrow{\beta} & \bar{B} \\ & \searrow \bar{g} & \downarrow p & \swarrow \bar{f} & \\ & & \bar{A} & & \end{array} & = & \begin{array}{ccc} \text{Hom}_{\bar{A}}(\bar{f}, \bar{g}) \\ \begin{array}{ccc} \swarrow p_1 & & \searrow p_0 \\ \bar{C} & \xrightarrow{\phi} & \bar{B} \\ \downarrow \bar{g} & & \swarrow \bar{f} \\ & & \bar{A} \end{array} \end{array} \end{array}$$

that is well-defined and functorial up to fibered isomorphism.

One of many uses of comma ∞ -categories is to define the internal mapping spaces between two elements of an ∞ -category A . This is one motivation for our notation “ \mathbf{Hom}_A .”

3.3.9. DEFINITION. For any two elements $x, y: 1 \rightrightarrows A$ of an ∞ -category A , their **mapping space** is the comma ∞ -category $\mathbf{Hom}_A(x, y)$ defined by the pullback diagram

$$\begin{array}{ccc} \mathbf{Hom}_A(x, y) & \xrightarrow{\phi} & A^2 \\ (p_1, p_0) \downarrow & \lrcorner & \downarrow (p_1, p_0) \\ 1 & \xrightarrow{(y, x)} & A \times A \end{array}$$

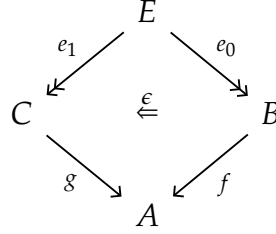
The mapping spaces in any ∞ -category are discrete in the sense of Definition 1.2.21.

3.3.10. PROPOSITION (internal mapping spaces are discrete). *For any pair of elements $x, y: 1 \rightrightarrows A$ of an ∞ -category A , the mapping space $\mathbf{Hom}_A(x, y)$ is discrete.*

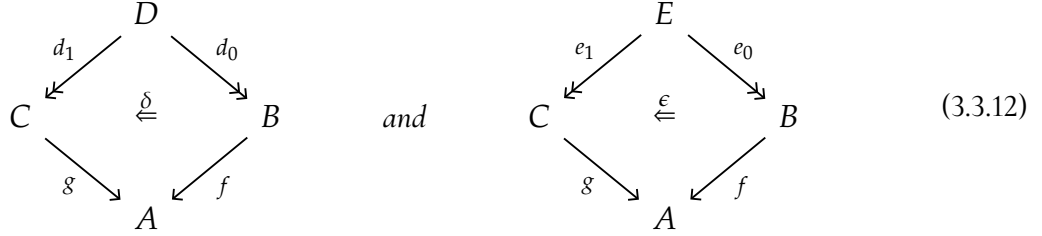
PROOF. Our task is to prove that for any ∞ -category X , the functor space $\mathbf{Fun}(X, \mathbf{Hom}_A(x, y))$ is a Kan complex. This is so just when $\mathbf{hFun}(X, \mathbf{Hom}_A(x, y))$ is a groupoid, i.e., when any 2-cell with codomain $\mathbf{Hom}_A(x, y)$ is invertible. By 2-cell conservativity, a 2-cell with codomain $\mathbf{Hom}_A(x, y)$ is invertible just when its whiskered composite with the isofibration $(p_1, p_0): \mathbf{Hom}_A(x, y) \twoheadrightarrow 1 \times 1$ is an invertible 2-cell, but in fact this whiskered composite is an identity since 1 is terminal. \square

As in our convention for ∞ -categories of arrows, it will be convenient to weaken the meaning of “comma ∞ -category” to extend this appellation to any object of $\mathcal{K}_{C \times B}$ that is fibered equivalent (see Definition 3.2.7) to the strict model $(p_1, p_0): \mathbf{Hom}_A(f, g) \rightarrow C \times B$ defined by 3.3.1. This is justified because such objects satisfy the weak universal property of Proposition 3.3.6 and conversely any two objects satisfying this weak universal property are equivalent over $C \times B$.

3.3.11. PROPOSITION (uniqueness of comma ∞ -categories). *For any isofibration $(e_1, e_0): E \rightarrow C \times B$ that is fibered equivalent to $\mathbf{Hom}_A(f, g) \rightarrow C \times B$ the 2-cell*



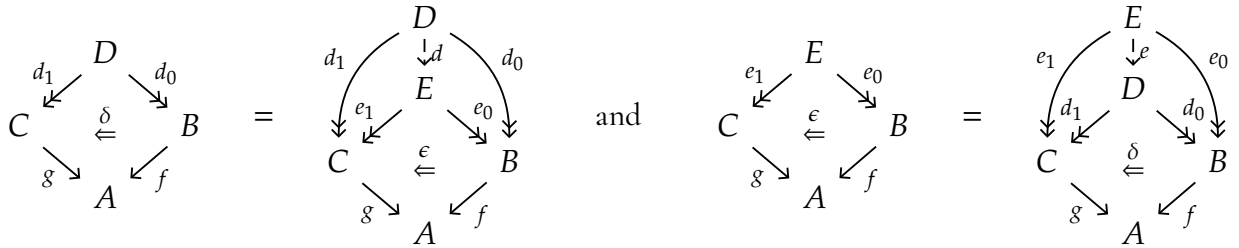
encoded by the equivalence $E \simeq \mathbf{Hom}_A(f, g)$ satisfies the weak universal property of Proposition 3.3.6. Conversely, if $(d_1, d_0): D \rightarrow C \times B$ and $(e_1, e_0): E \rightarrow C \times B$ are equipped with 2-cells



satisfying the weak universal property of Proposition 3.3.6, then D and E are fibered equivalent over $C \times B$.

PROOF. The proof of the first statement proceeds exactly as in the special case of Proposition 3.2.10. We prove the converse, solving Exercise 3.2.ii.

Consider a pair of 2-cells (3.3.12) satisfying the weak universal properties enumerated in Proposition 3.3.6. 1-cell induction supplies maps of spans



with the property that $\epsilon de = \epsilon$ and $\delta ed = \delta$. By Proposition 3.3.7 it follows that $de \cong \text{id}_E$ over $C \times B$ and $ed \cong \text{id}_D$ over $C \times B$. This defines the data of a fibered equivalence $D \simeq E$.³ \square

3.3.13. CONVENTION. On account of Proposition 3.3.11, we extend the appellation “comma ∞ -category” from the strict model constructed in Definition 3.3.1 to any ∞ -category that is fibered equivalent to it and refer to its accompanying 2-cell as the “comma cone.”

³For the reader uncomfortable with Remark 3.2.9, Proposition 3.5.3 and Lemma 3.5.4 provides a small boost to finish the proof.

For example, in §4.3 we define the ∞ -category of cones over a fixed diagram as a comma ∞ -category. Proposition 3.3.11 gives us the flexibility to use multiple models for this ∞ -category, which will be useful in characterizing the universal properties of limits and colimits.

Exercises.

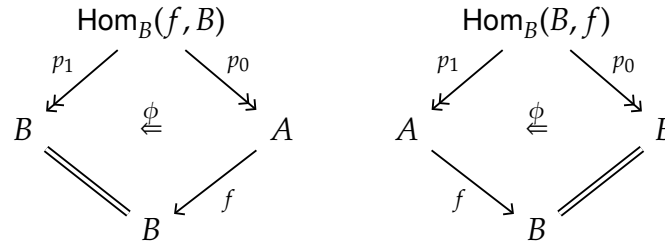
3.3.i. EXERCISE. Prove Proposition 3.3.5 by observing that the map $\mathbf{Hom}_p(q, r)$ factors as a pullback of the Leibniz cotensor of $\partial\Delta[1] \hookrightarrow \Delta[1]$ with p followed by a pullback of $r \times q$.

3.3.ii. EXERCISE. Use Proposition 3.3.7 to justify the pseudofunctoriality of the comma construction in lax morphisms described in Observation 3.3.8.

3.4. Representable comma ∞ -categories

Definition 3.3.1 constructs a comma ∞ -category for any cospan. Of particular importance, are the special cases of this construction where one of the legs of the cospan is an identity:

3.4.1. DEFINITION (left and right representations). Any functor $f: A \rightarrow B$ admits a **left representation** and a **right representation** as a comma ∞ -category, displayed below-left and below-right respectively:



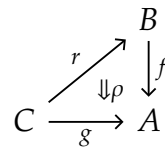
To save space, we typically depict the **left comma cone over p** displayed above-left and the **right comma cone over p** displayed above-right as inhabiting triangles rather than squares.

By Proposition 3.3.11, the weak universal property of the comma cone characterizes the comma span up to fibered equivalence over the product of the codomain objects. Thus:

3.4.2. DEFINITION. A comma ∞ -category $\mathbf{Hom}_A(f, g) \rightarrow C \times B$ is

- **left representable** if there exists a functor $\ell: B \rightarrow C$ so that $\mathbf{Hom}_A(f, g) \simeq \mathbf{Hom}_C(\ell, C)$ over $C \times B$ and
- **right representable** if there exists a functor $r: C \rightarrow B$ so that $\mathbf{Hom}_A(f, g) \simeq \mathbf{Hom}_B(B, r)$ over $C \times B$.

In this section, we prove the first of many representability theorems: demonstrating that a functor $g: C \rightarrow A$ admits an absolute right lifting along $f: B \rightarrow A$ if and only if the comma ∞ -category $\mathbf{Hom}_A(f, g)$ is right representable, the representing functor then defining the postulated lifting. We prove this over the course of three theorems, each strengthening the previous statement. The first theorem characterizes 2-cells



that define absolute right lifting diagrams via an induced equivalence $\mathbf{Hom}_B(B, r) \simeq_{C \times B} \mathbf{Hom}_A(f, g)$ between comma ∞ -categories. The second theorem proves that a functor r defines an absolute right lifting of g through f just when $\mathbf{Hom}_A(f, g)$ is right-represented by r ; the difference is that no 2-cell $\rho: fr \Rightarrow g$ need be postulated a priori to exist. The final theorem gives a general right-representability criterion that can be applied to construct a right representation to $\mathbf{Hom}_A(f, g)$ without a priori specifying the representing functor r .

3.4.3. THEOREM. *The triangle below-left defines an absolute right lifting diagram if and only if the induced 1-cell below-right*

$$\begin{array}{c}
 \begin{array}{ccc}
 & B & \\
 r \nearrow & & \downarrow f \\
 C & \xrightarrow{g} & A
 \end{array}
 \Downarrow \rho
 \end{array}
 \rightsquigarrow
 \begin{array}{ccc}
 & \mathbf{Hom}_B(B, r) & \\
 p_1 \swarrow & \phi & \searrow p_0 \\
 C & \xrightarrow{r} & B \\
 g \searrow & \rho & \swarrow f \\
 & A &
 \end{array}
 =
 \begin{array}{ccc}
 & \mathbf{Hom}_B(B, r) & \\
 p_0 \swarrow & & \searrow p_1 \\
 & \mathbf{Hom}_A(f, g) & \\
 p_1 \swarrow & \phi & \searrow p_0 \\
 C & \xrightarrow{r} & B \\
 g \searrow & & \swarrow f \\
 & A &
 \end{array}
 \quad (3.4.4)$$

defines a fibered equivalence $\mathbf{Hom}_B(B, r) \simeq \mathbf{Hom}_A(f, g)$ over $C \times B$.

PROOF. Suppose that (r, ρ) defines an absolute right lifting of g through f and consider the corresponding unique factorization of the comma cone under $\mathbf{Hom}_A(f, g)$ through ρ as displayed below-center

$$\begin{array}{ccc}
 \begin{array}{ccc}
 & \mathbf{Hom}_A(f, g) & \\
 p_1 \swarrow & \phi & \searrow p_0 \\
 C & \xrightarrow{r} & B \\
 g \searrow & & \swarrow f \\
 & A &
 \end{array}
 =
 \begin{array}{ccc}
 & \mathbf{Hom}_A(f, g) & \\
 p_1 \swarrow & \zeta & \searrow p_0 \\
 C & \xrightarrow{r} & B \\
 g \searrow & \rho & \swarrow f \\
 & A &
 \end{array}
 =
 \begin{array}{ccc}
 & \mathbf{Hom}_A(f, g) & \\
 p_1 \swarrow & & \searrow p_0 \\
 & \mathbf{Hom}_B(B, r) & \\
 p_1 \swarrow & \phi & \searrow p_0 \\
 C & \xrightarrow{r} & B \\
 g \searrow & \rho & \swarrow f \\
 & A &
 \end{array}
 \quad (3.4.5)
 \end{array}$$

By 1-cell induction, the 2-cell ζ factors through the right comma cone over r as displayed above-right. Substituting the right-hand side of (3.4.4) into the bottom portion of the above-right diagram, we see that $\eta z: \mathbf{Hom}_A(f, g) \rightarrow \mathbf{Hom}_A(f, g)$ is a 1-cell that factors the comma cone for $\mathbf{Hom}_A(f, g)$ through itself. Applying the universal property of Proposition 3.3.7, it follows that there is a fibered isomorphism $\eta z \cong \text{id}_{\mathbf{Hom}_A(f, g)}$ over $C \times B$.

To prove that $zy \cong \text{id}_{\mathbf{Hom}_B(B, r)}$ it suffices to argue similarly that the right comma cone over r restricts along zy to itself. Since ρ is absolute right lifting, it suffices to verify the equality $\phi zy = \phi$

after pasting below with ρ . But now reversing the order of the equalities in (3.4.5) and (3.4.4) we have

$$\begin{array}{c}
 \text{Hom}_B(B, r) \\
 \downarrow y \\
 \text{Hom}_A(f, g) \\
 \downarrow z \\
 \text{Hom}_B(B, r) \\
 \downarrow \phi \\
 C \xrightarrow{r} B \\
 \downarrow \rho \\
 A
 \end{array}
 \begin{array}{c}
 \text{Hom}_B(B, r) \\
 \downarrow y \\
 \text{Hom}_A(f, g) \\
 \downarrow \zeta \\
 C \xrightarrow{r} B \\
 \downarrow \rho \\
 A
 \end{array}
 =
 \begin{array}{c}
 \text{Hom}_B(B, r) \\
 \downarrow y \\
 \text{Hom}_A(f, g) \\
 \downarrow \phi \\
 C \xrightarrow{r} B \\
 \downarrow \rho \\
 A
 \end{array}
 =
 \begin{array}{c}
 \text{Hom}_B(B, r) \\
 \downarrow y \\
 \text{Hom}_A(f, g) \\
 \downarrow \phi \\
 C \xrightarrow{r} B \\
 \downarrow \rho \\
 A
 \end{array}
 =
 \begin{array}{c}
 \text{Hom}_B(B, r) \\
 \downarrow y \\
 \text{Hom}_A(f, g) \\
 \downarrow \phi \\
 C \xrightarrow{r} B \\
 \downarrow \rho \\
 A
 \end{array}$$

which is exactly what we wanted to show. Thus, we see that if (r, ρ) is an absolute right lifting of g through f , then the induced map (3.4.4) defines a fibered equivalence $\text{Hom}_B(B, r) \simeq \text{Hom}_A(f, g)$.

Now, conversely, suppose the 1-cell y defined by (3.4.4) is a fibered equivalence and let us argue that (r, ρ) is an absolute right lifting of g through f . By Proposition 3.3.11, via this fibered equivalence the 2-cell displayed on the left-hand side of (3.4.4) inherits the weak universal property of a comma cone from $\text{Hom}_A(f, g)$. So Proposition 3.3.7 supplies a bijection displayed below-left-center

$$\left\{ \begin{array}{ccc} & X & \\ c \swarrow & & \searrow b \\ C & \xrightarrow{\alpha} & B \\ g \searrow & & \swarrow f \\ & A & \end{array} \right\} \leftrightarrow \left\{ \begin{array}{ccc} & X & \\ c \swarrow & & \searrow b \\ C & \xrightarrow{a} & B \\ p_1 \swarrow & \text{Hom}_B(B, r) & \searrow p_0 \end{array} \right\} / \cong \leftrightarrow \left\{ \begin{array}{ccc} & X & \\ c \swarrow & & \searrow b \\ C & \xrightarrow{r} & B \end{array} \right\}$$

between 2-cells over the cospan and fibered isomorphism classes of maps of spans that is implemented, from center to left, by whiskering with the 2-cell $\rho p_1 \cdot f \phi: f p_0 \Rightarrow g p_1$ in the center of (3.4.4). Proposition 3.3.7 also applies to the right comma cone ϕ over $r: C \rightarrow B$ giving us a second bijection, displayed above center-right between the same fibered isomorphism classes of maps of spans and 2-cells over r . This second bijection is implemented, from center to right, by pasting with the right comma cone $\phi: p_0 \Rightarrow r p_1$. Combining these yields a bijection between the 2-cells displayed on the right and the 2-cells displayed on the left implemented by pasting with ρ , which is precisely the universal property that characterizes absolute right lifting diagrams. \square

As a special case of this result, we can now present several equivalent characterizations of fully faithful functors between ∞ -categories.

3.4.6. COROLLARY. *The following are equivalent, and define what it means for a functor $f: A \rightarrow B$ between ∞ -categories to be fully faithful:*

(i) The identity defines an absolute right lifting diagram:

$$\begin{array}{ccc} & A & \\ & \parallel & \downarrow f \\ A & \xrightarrow{f} & B \end{array}$$

(ii) The identity defines an absolute left lifting diagram:

$$\begin{array}{ccc} & A & \\ & \parallel & \downarrow f \\ A & \xrightarrow{f} & B \end{array}$$

(iii) For all $X \in \mathcal{K}$, the induced functor

$$f_*: \mathbf{hFun}(X, A) \rightarrow \mathbf{hFun}(X, B)$$

is a fully faithful functor of 1-categories.

(iv) The functor induced by the identity 2-cell id_f is an equivalence

$$\begin{array}{ccccc} & \mathcal{A}^2 & & & \\ p_1 \swarrow & \downarrow \wr & \searrow p_0 & & \\ A & & A & & \\ p_1 \swarrow & \downarrow & \searrow p_0 & & \\ & \mathrm{Hom}_B(f, f) & & & \end{array}$$

PROOF. The statement (iii) is an unpacking of the meaning of both (i) and (ii). Theorem 3.4.3 specializes to prove (i) \Leftrightarrow (iv) or dually (ii) \Leftrightarrow (iv). \square

It is not surprising that post-composition with a fully faithful functor of ∞ -categories should induce a fully-faithful functor of hom-categories in the homotopy 2-category. What is surprising is that this definition is strong enough. This result, together with the general case of Theorem 3.4.3 should be provide some retroactive justification for our use of absolute lifting diagrams in Chapter 2.

Having proven Theorem 3.4.3 our immediate aim is to strengthen it to show that a fibered equivalence $\mathrm{Hom}_B(B, r) \simeq \mathrm{Hom}_A(f, g)$ over $C \times B$ implies that $r: C \rightarrow B$ defines an absolute right lifting of g through f without a previously specified 2-cell $\rho: fr \Rightarrow g$.

3.4.7. THEOREM. Given a trio of functors $r: C \rightarrow B$, $f: B \rightarrow A$, and $g: C \rightarrow A$ there is a bijection between 2-cells as displayed below-left and fibered isomorphism classes of maps of spans as displayed below-right

$$\left\{ \begin{array}{ccc} & B & \\ r \nearrow & \downarrow f & \\ C & \xrightarrow{g} & A \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{ccccc} & \mathrm{Hom}_B(B, r) & & & \\ p_1 \swarrow & \downarrow y & \searrow p_0 & & \\ C & & B & & \\ p_1 \swarrow & \downarrow & \searrow p_0 & & \\ & \mathrm{Hom}_A(f, g) & & & \end{array} \right\} / \cong$$

that is constructed by pasting the right comma cone over r and then applying 1-cell induction to factor through the comma cone for $\text{Hom}_A(f, g)$.

$$\begin{array}{ccc}
 & \text{Hom}_B(B, r) & \\
 p_1 \swarrow & \phi \quad \Leftarrow & \searrow p_0 \\
 C & \xrightarrow{r} & B \\
 g \searrow & \rho \quad \Leftarrow & \swarrow f \\
 & A &
 \end{array}
 =
 \begin{array}{ccc}
 & \text{Hom}_B(B, r) & \\
 p_1 \swarrow & \downarrow y & \searrow p_0 \\
 & \text{Hom}_A(f, g) & \\
 p_1 \swarrow & \phi \quad \Leftarrow & \searrow p_0 \\
 C & \xrightarrow{r} & B \\
 g \searrow & & \swarrow f \\
 & A &
 \end{array}$$

Moreover, a 2-cell $\rho: fr \Rightarrow g$ displays r as an absolute right lifting of g through f if and only if the corresponding map of spans $y: \text{Hom}_B(B, r) \rightarrow \text{Hom}_A(f, g)$ is an equivalence.

The second clause is the statement of Theorem 3.4.3, so it remains only to prove the first. We show the claimed construction is a bijection by exhibiting its inverse, the construction of which involves a rather mysterious lemma the significance of which will gradually reveal itself. For instance, Lemma 3.4.8 figures prominently in the proof of the external Yoneda lemma in §5.5 and is also the main ingredient in a “cheap” version of the Yoneda lemma appearing as Corollary 3.4.10.

3.4.8. LEMMA. Let $f: A \rightarrow B$ be any functor and denote the right comma cone over f by

$$\begin{array}{ccc}
 & \text{Hom}_B(B, f) & \\
 p_1 \swarrow & \phi \quad \Leftarrow & \searrow p_0 \\
 A & \xrightarrow{f} & B
 \end{array}$$

Then the codomain-projection functor $p_1: \text{Hom}_B(B, f) \rightarrow A$ admits a right adjoint right inverse⁴ induced from the identity 2-cell id_f , defining an adjunction

$$\begin{array}{ccc}
 & p_1 & \\
 A & \xleftarrow{\quad} & \text{Hom}_B(B, f) \\
 & \dashv & \\
 & i & \\
 & A &
 \end{array}$$

over A whose counit is an identity and whose unit $\eta: \text{id} \Rightarrow ip_1$ satisfies the conditions $\eta i = \text{id}_i$, $p_1 \eta = \text{id}_{p_1}$ and $p_0 \eta = \phi$.

⁴A functor admits a **right adjoint right inverse** just when it admits a right adjoint in an adjunction whose counit is the identity. When the original functor is an isofibration, as is the case here, it suffices to merely assume that the counit is invertible; see Lemma 3.5.9 and Appendix B.

PROOF. This adjunction will be constructed using the weak universal properties of the right comma cone over f . The identity 2-cell id_f induces a 1-cell over the right comma cone over f :

$$\begin{array}{c}
 \begin{array}{ccc}
 & A & \\
 \text{---} \downarrow i & & \text{---} f \\
 \text{Hom}_B(B, f) & & \\
 \text{---} \swarrow p_1 & \phi & \searrow p_0 \\
 A & \xrightarrow{f} & B
 \end{array} \\
 = \\
 \begin{array}{ccc}
 & A & \\
 \text{---} \swarrow & & \searrow f \\
 A & \xrightarrow{f} & B
 \end{array}
 \end{array}$$

Note that $p_1 i = \text{id}_A$, so we may take the counit to be the identity 2-cell. Since $\phi i = \text{id}_f$, we have a pasting equality:

$$\begin{array}{ccc}
 \begin{array}{ccc}
 & \text{Hom}_B(B, f) & \\
 \text{---} \swarrow ip_1 & & \searrow \\
 \text{Hom}_B(B, f) & = & \text{Hom}_B(B, f) \\
 \text{---} \swarrow p_1 & & \searrow p_0 \\
 A & \xrightarrow{f} & B
 \end{array} \\
 = \\
 \begin{array}{ccc}
 & \text{Hom}_B(B, f) & \\
 \text{---} \swarrow p_1 & & \searrow p_0 \\
 A & \xrightarrow{f} & B
 \end{array}
 \end{array}$$

while allows us to induce a 2-cell $\eta: \text{id} \Rightarrow ip_1$ with defining equations $p_1 \eta = \text{id}_{p_1}$ and $p_0 \eta = \phi$. The first of these conditions ensures one triangle identity; for the other, we must verify that $\eta i = \text{id}_i$. By 2-cell conservativity, ηi is an isomorphism since $p_1 \eta i = \text{id}_A$ and $p_0 \eta i = \phi i = \text{id}_f$ are both invertible. By naturality of whiskering, we have

$$\begin{array}{ccc}
 i & \xrightarrow{\eta i} & i \\
 \eta i \downarrow & & \downarrow \eta i \\
 i & \xrightarrow{ip_1 \eta i} & i
 \end{array}$$

and since $p_1 \eta = \text{id}_{p_1}$ the bottom edge is an identity. So $\eta i \cdot \eta i = \eta i$ and since ηi is an isomorphism cancelation implies that $\eta i = \text{id}_i$ as required. \square

One interpretation of Lemma 3.4.8 is best revealed though a special case:

3.4.9. COROLLARY. *For any element $b: 1 \rightarrow B$, the identity at b defines a terminal element in $\text{Hom}_B(B, b)$.*

PROOF. By Lemma 3.4.8, the codomain-projection from the right representation of any functor admits a right adjoint right inverse induced from its identity 2-cell. In this case, the codomain-projection is the unique functor $!: \text{Hom}_B(B, b) \rightarrow 1$, so by Definition 2.2.1, this right adjoint identifies a terminal element of $\text{Hom}_B(B, b)$ corresponding to the identity morphism id_b in the homotopy category \mathbf{hB} . \square

The general version of Lemma 3.4.8 has a similar interpretation: in the sliced ∞ -cosmos \mathcal{K}_A , the identity functor at A defines the terminal object, and Lemma 3.4.8 asserts that id_f induces a terminal element of $\text{Hom}_B(B, f)$ “over A .”

PROOF OF THEOREM 3.4.7. The inverse to the function that takes a 2-cell $fr \Rightarrow g$ and produces an isomorphism class of maps $\mathbf{Hom}_B(B, r) \rightarrow \mathbf{Hom}_A(f, g)$ over $C \times B$ is constructed by applying Lemma 3.4.8 to the functor $r: C \rightarrow B$: given a map of spans, restrict along the right adjoint $i: C \rightarrow \mathbf{Hom}_B(B, r)$ and paste with the comma cone for $\mathbf{Hom}_A(f, g)$ to define a 2-cell $fr \Rightarrow g$.

Starting from a 2-cell $\rho: fr \Rightarrow g$, the composite of these two functions constructs the 2-cell displayed below-left

which equals the above-center pasted composite by the definition of y from ρ , and equals the above-right composite since $\phi i = \text{id}_r$. Thus, when a 2-cell $\rho: fr \Rightarrow g$ is encoded as a map $y: \mathbf{Hom}_B(B, r) \rightarrow \mathbf{Hom}_A(f, g)$ over $C \times B$, and then re-converted into a 2-cell, the original 2-cell ρ is recovered.

For the converse, starting with a map $z: \mathbf{Hom}_B(B, r) \rightarrow \mathbf{Hom}_A(f, g)$ over $C \times B$, the composite of these two functions constructs an isomorphism class of maps of spans w displayed below-left by applying 1-cell induction for the comma cone $\mathbf{Hom}_A(f, g)$ to the composite 2-cell pasted below-center-left:

Applying Lemma 3.4.8, there exists a 2-cell $\eta: \text{id} \Rightarrow ip_1$ so that $p_0\eta = \phi$ — this gives the pasting equality above center — and $p_1\eta = \text{id}$ — which gives the pasting equality above right. Proposition 3.3.7 now implies that $w \cong z$ over $C \times B$. \square

A dual version of Theorem 3.4.7 represents 2-cells $g \Rightarrow f\ell$ as fibered isomorphism classes of maps $\text{Hom}_B(\ell, B) \rightarrow \text{Hom}_A(g, f)$ over $B \times C$. Specializing these results to the case where one of f or g is the identity, we immediately recover a “cheap” form of the Yoneda lemma:

3.4.10. COROLLARY. *Given a parallel pair of functors, $f, g: A \rightrightarrows B$, there are bijections between 2-cells as displayed below-center and fibered isomorphism classes of maps between their left and right representations as comma ∞ -categories, as displayed below-left and below-right, respectively:*

$$\left\{ \begin{array}{c} \text{Hom}_B(g, B) \\ \begin{array}{ccc} p_1 \swarrow & & \searrow p_0 \\ B & & A \\ p_1 \swarrow & & \searrow p_0 \\ \text{Hom}_B(f, B) \end{array} \\ a \downarrow \\ \end{array} \right\} \Leftrightarrow \left\{ \begin{array}{c} A \xrightarrow{f} B \\ \Downarrow \alpha \\ A \xrightarrow{g} B \end{array} \right\} \Leftrightarrow \left\{ \begin{array}{c} \text{Hom}_B(B, f) \\ \begin{array}{ccc} p_1 \swarrow & & \searrow p_0 \\ A & & B \\ p_1 \swarrow & & \searrow p_0 \\ \text{Hom}_B(B, g) \end{array} \\ a \downarrow \\ \end{array} \right\} / \cong$$

that are constructed by pasting with the left comma cone over g and right comma cone over f , respectively:

$$\begin{array}{c} \text{Hom}_B(g, B) \\ \begin{array}{ccc} p_1 \swarrow & & \searrow p_0 \\ B & & A \\ p_1 \swarrow & & \searrow p_0 \\ \text{Hom}_B(f, B) \end{array} \\ a \downarrow \\ \end{array} = \begin{array}{c} \text{Hom}_B(g, B) \\ \begin{array}{ccc} p_1 \swarrow & & \searrow p_0 \\ B & & A \\ p_1 \swarrow & & \searrow p_0 \\ \text{Hom}_B(f, B) \end{array} \\ a \downarrow \\ \end{array} \begin{array}{c} \text{Hom}_B(B, f) \\ \begin{array}{ccc} p_1 \swarrow & & \searrow p_0 \\ A & & B \\ p_1 \swarrow & & \searrow p_0 \\ \text{Hom}_B(B, g) \end{array} \\ a \downarrow \\ \end{array}$$

and then applying 1-cell induction to factor through the left comma cone over f in the former case or the right comma cone over g in the latter. \square

Combining the results of this section, we prove one final representability theorem that allows us to recognize when a comma ∞ -category is right representable in the absence of a predetermined representing functor. This result specializes to give existence theorems for adjoint functors and limits and colimits in the next chapter.

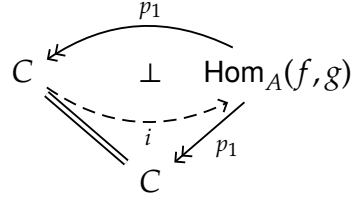
3.4.11. THEOREM. *The comma ∞ -category $\text{Hom}_A(f, g)$ associated to a cospan $C \xrightarrow{g} A \xleftarrow{f} B$ is right representable if and only if its codomain-projection functor admits a right adjoint right inverse*

$$\begin{array}{ccc} & \text{Hom}_A(f, g) & \\ p_1 \swarrow & \nearrow p_0 & \\ C & \xrightarrow{i} & B \end{array}$$

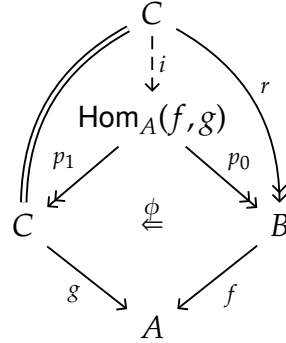
in which case the composite $p_0i: C \rightarrow B$ defines the representing functor and the 2-cell represented by the functor $i: C \rightarrow \text{Hom}_A(f, g)$ defines an absolute right lifting of g through f .

PROOF. If $\mathbf{Hom}_A(f, g)$ is represented on the right by a functor $r: C \rightarrow B$, then $\mathbf{Hom}_A(f, g) \simeq \mathbf{Hom}_B(B, r)$ over $C \times B$ and the codomain-projection functor is equivalent to $p_1: \mathbf{Hom}_B(B, r) \rightarrow C$, which admits a right adjoint right inverse i by Lemma 3.4.8. The proof of Theorem 3.4.3 then shows that i represents an absolute right lifting diagram. Thus, it remains only to prove the converse.

To that end, suppose we are given a right adjoint right inverse adjunction $p_1 \dashv i$. Unpacking the definition, this provides an adjunction

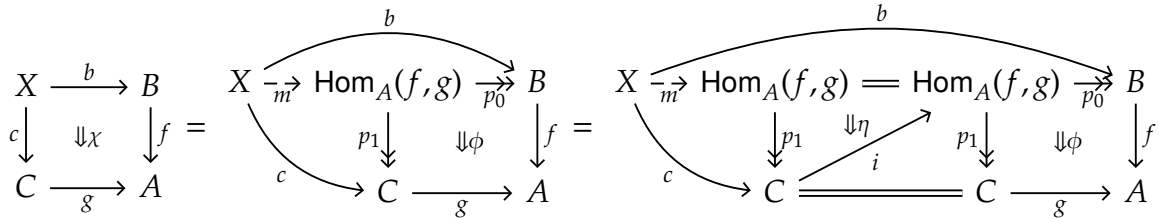


over C whose counit is an identity and whose unit $\eta: \text{id} \Rightarrow ip_1$ satisfies the conditions $\eta i = \text{id}_i$ and $p_1 \eta = \text{id}_{p_1}$. By Theorem 3.4.7, to construct the fibered equivalence $\mathbf{Hom}_B(B, r) \simeq_{C \times B} \mathbf{Hom}_A(f, g)$ with $r := p_0 i$, it suffices to demonstrate that the 2-cell defined by restricting the comma cone for $\mathbf{Hom}_A(f, g)$ along i



defines an absolute right lifting diagram.

By 1-cell induction any 2-cell as displayed below-left induces a 1-cell m as displayed below-center:



Inserting the triangle equality $p_1 \eta = \text{id}_{p_1}$ as displayed above-right constructs the desired factorization $p_0 \eta m: b \Rightarrow rc$ of χ through ϕi .

In fact, by 2-cell induction for the comma cone ϕ , any 2-cell $\tau_0: b \Rightarrow rc$ defining a factorization of $\chi: fb \Rightarrow gc$ through ϕi must have the form $\tau_0 = p_0 \tau$ for some 2-cell $\tau: m \Rightarrow ic$ so that $\pi_1 \tau = \text{id}_c$. The pair (τ_0, id_c) satisfies the compatibility condition of Proposition 3.3.6(ii) to induce a 2-cell $\tau: m \Rightarrow ic$. We'll argue that the 2-cell τ is unique, proving that the factorization $p_0 \tau: b \Rightarrow rc$ is also unique.

To see this, note that the adjunction $p_1 \dashv i$ over C exhibits the right adjoint as a terminal element of the object $p_1: \mathbf{Hom}_A(f, g) \rightarrow C$ in the slice 2-category $(\mathbf{hK})_C$. It follows, as in Lemma 2.2.4, that for any object $c: X \rightarrow C$ and any morphism $m: X \rightarrow \mathbf{Hom}_A(f, g)$ over C , there exists a unique 2-cell

$m \Rightarrow ic$ over C . Thus, there is a unique 2-cell $\tau: m \Rightarrow ic$ with the property that $p_1\tau = \text{id}_c$, and so the factorization $p_0\tau: b \Rightarrow rc$ of χ through ϕi must also be unique. \square

More concisely, Theorem 3.4.11 shows that a comma ∞ -category $\text{Hom}_A(f, g)$ is right representable just when its codomain-projection functor $p_1: \text{Hom}_A(f, g) \rightarrow C$ admits a terminal element as an object of the sliced ∞ -cosmos \mathcal{K}_C ; dually, $\text{Hom}_A(f, g)$ is left representable just when its domain-projection functor admits an initial element as an object of the sliced ∞ -cosmos \mathcal{K}_B ; see Corollary 3.5.10. There is a small gap between this statement and the version proven in Theorem 3.4.11 having to do with the discrepancy between the homotopy 2-category of \mathcal{K}_C and the slice of the homotopy 2-category $\mathfrak{h}\mathcal{K}$ over C . This is the subject to which we now turn.

Exercises.

3.4.i. EXERCISE. How might one encode the existence of an adjunction $f \dashv u$ between a given opposing pair of functors using comma ∞ -categories?

3.5. Sliced homotopy 2-categories and fibered equivalences

The ∞ -category A^2 of arrows in A together with its domain- and codomain-evaluation functors $(p_0, p_1): A^2 \rightarrow A \times A$ satisfies a weak universal property in the homotopy 2-category that characterizes the ∞ -category up to equivalence over $A \times A$; see Proposition 3.2.10. Similarly the comma ∞ -category is characterized up to fibered equivalence, as defined in Definition 3.2.7.

As commented upon in Remark 3.2.9 there is some ambiguity regarding the 2-categorical data required to specify a fibered equivalence, that we shall now address head-on. The issue is that, for an ∞ -category B in an ∞ -cosmos \mathcal{K} , the homotopy 2-category $\mathfrak{h}(\mathcal{K}_B)$ of the sliced ∞ -cosmos of Proposition 1.2.17 is not isomorphic to the 2-category $(\mathfrak{h}\mathcal{K})_B$ of isofibrations, functors, and 2-cells over B in the homotopy 2-category $\mathfrak{h}\mathcal{K}$ of \mathcal{K} ; see Exercise 1.4.iii.

However, there is a canonical comparison functor relating this pair of 2-categories that satisfies a property we now introduce:

3.5.1. DEFINITION (smothering 2-functor). A 2-functor $F: \mathcal{A} \rightarrow \mathcal{B}$ is **smothering** if it is

- surjective on 0-cells;
- full on 1-cells: for any pair of objects A, A' in \mathcal{A} and 1-cell $k: FA \rightarrow FA'$ in \mathcal{B} , there exists $f: A \rightarrow A'$ in \mathcal{A} with $Ff = k$;

- full on 2-cells: for any parallel pair $f, g: A \rightrightarrows A'$ in \mathcal{A} and 2-cell $FA \begin{array}{c} \xrightarrow{Ff} \\ \Downarrow \beta \\ \xrightarrow{Fg} \end{array} FA'$ in \mathcal{B} , there

exists a 2-cell $\alpha: f \Rightarrow g$ in \mathcal{A} with $F\alpha = \beta$; and

- conservative on 2-cells: for any 2-cell α in \mathcal{A} if $F\alpha$ is invertible in \mathcal{B} then α is invertible in \mathcal{A} .

3.5.2. REMARK. Note that smothering 2-functors are surjective on objects 2-functors that are “locally smothering”: meaning that the action on hom-categories is by a smothering functor, as defined in 3.1.2.

The prototypical example of a smothering 2-functor solves Exercise 1.4.iii.

3.5.3. PROPOSITION. Let B be an ∞ -category in an ∞ -cosmos \mathcal{K} . There is a canonical 2-functor

$$\mathfrak{h}(\mathcal{K}_B) \rightarrow (\mathfrak{h}\mathcal{K})_B$$

from the homotopy 2-category of the sliced ∞ -cosmos \mathcal{K}_B to the 2-category of isofibrations, functors, and 2-cells over B in $\mathfrak{h}\mathcal{K}$ and this 2-functor is smothering.

This follows more-or-less immediately from Lemma 3.1.5 but we spell out the details nonetheless.

PROOF. The 2-categories $\mathfrak{h}(\mathcal{K}_B)$ and $(\mathfrak{h}\mathcal{K})_B$ have the same objects — isofibrations with codomain B — and 1-cells — functors between the “total spaces” that commute with these isofibrations to B — so the canonical mapping may be defined to act as the identity on underlying 1-categories.

By the definition of the sliced ∞ -cosmos given in Proposition 1.2.17, a 2-cell between functors $f, g: E \rightrightarrows F$ from $p: E \twoheadrightarrow B$ to $q: F \twoheadrightarrow B$ is a homotopy class of 1-simplices in the quasi-category defined by the pullback of simplicial sets below-left

$$\begin{array}{ccc} \mathbf{Fun}_B(E, F) & \longrightarrow & \mathbf{Fun}(E, F) \\ \downarrow & \lrcorner & \downarrow q_* \\ \mathbb{1} & \xrightarrow{p} & \mathbf{Fun}(E, B) \end{array} \quad \begin{array}{ccc} (\mathbf{hFun})_B(E, F) & \longrightarrow & \mathbf{hFun}(E, F) \\ \downarrow & \lrcorner & \downarrow q_* \\ \mathbb{1} & \xrightarrow{p} & \mathbf{hFun}(E, B) \end{array}$$

Unpacking, a 2-cell $\alpha: f \Rightarrow g$ is represented by a 1-simplex $\alpha: f \rightarrow g$ in $\mathbf{Fun}(E, F)$ that whisks with q to the degenerate 1-simplex on the vertex $p \in \mathbf{Fun}(E, B)$, and two such 1-simplices represent the same 2-cell if and only if they bound a 2-simplex of the form displayed in (1.1.8) that also whisks with q to the degenerate 2-simplex on p .

By contrast, a 2-cell in $(\mathfrak{h}\mathcal{K})_B$ is a morphism in the category defined by the pullback of categories above-right. Such 2-cells are represented by 1-simplices $\alpha: f \rightarrow g$ in $\mathbf{Fun}(E, F)$ that whisker with q to 1-simplices in $\mathbf{Fun}(E, B)$ that are homotopic to the degenerate 1-simplex on p , and two such 1-simplices represent the same 2-cell if and only if they are homotopic in $\mathbf{Fun}(E, F)$.

Applying the homotopy category functor $\mathfrak{h}: \mathbf{QCat} \rightarrow \mathbf{Cat}$ to the above-left pullback produces a cone over the above-right pullback, inducing a canonical map

$$\mathfrak{h}(\mathbf{Fun}_B(E, F)) \rightarrow (\mathbf{hFun})_B(E, F),$$

which is the action on homs of the canonical 2-functor $\mathfrak{h}(\mathcal{K}_B) \rightarrow (\mathfrak{h}\mathcal{K})_B$.

The 2-functor just constructed is bijective on 0- and 1-cells. To see that it is full on 2-cells we must show that any 1-simplex $\alpha: f \rightarrow g$ in $\mathbf{Fun}(E, F)$, for which $q\alpha: p \rightarrow p$ is homotopic to $p \cdot \sigma^0: p \rightarrow p$ in $\mathbf{Fun}(E, B)$, is homotopic in $\mathbf{Fun}(E, F)$ to a 1-simplex from f to g over $p \cdot \sigma^0$. By Lemma 1.1.9, any such α defines a lifting problem

$$\begin{array}{ccc} \Lambda^1[2] & \longrightarrow & \mathbf{Fun}(E, F) \\ \downarrow & \nearrow & \downarrow q_* \\ \Delta[2] & \longrightarrow & \mathbf{Fun}(E, B) \end{array} \quad \ni \quad \begin{array}{ccc} & f & \\ f & \xrightarrow{\alpha} & g \\ & \downarrow & \\ & p & \xrightarrow{q\alpha} p \\ & \xlongequal{\sigma^0} & \end{array}$$

A solution exists since $q_*: \mathbf{Fun}(E, F) \twoheadrightarrow \mathbf{Fun}(E, B)$ is an isofibration, proving that $\mathfrak{h}(\mathcal{K}_B) \rightarrow (\mathfrak{h}\mathcal{K})_B$ is full on 2-cells.

Now suppose $\alpha: f \rightarrow g$ represents a 2-cell in $\mathbf{Fun}_B(E, F)$ whose image in $(\mathbf{hFun})_B(E, F)$ is an isomorphism. A map in a 1-category defined by a pullback is invertible if and only if its projections along the legs of the pullback cone are isomorphisms. Thus the image of α is invertible if and only if

$\alpha: f \rightarrow g$ defines an isomorphism in $\mathbf{hFun}(E, F)$, which by Definition 1.1.13 is the case if and only if $\alpha: f \rightarrow g$ represents an isomorphism in $\mathbf{Fun}(E, F)$. Since α is fibered over the degenerate 1-simplex at p , this presents us with a lifting problem

$$\begin{array}{ccccc} \mathbb{2} & \xrightarrow{\alpha} & \mathbf{Fun}_B(E, F) & \longrightarrow & \mathbf{Fun}(E, F) \\ \downarrow & \nearrow \text{dotted} & \downarrow & \nearrow \text{dashed} & \downarrow q_* \\ \mathbb{I} & \longrightarrow & \mathbb{1} & \xrightarrow{p} & \mathbf{Fun}(E, B) \end{array}$$

which Exercise 1.1.v tells us we can solve. This proves that $\mathbf{h}(\mathcal{K}_B) \rightarrow (\mathbf{h}\mathcal{K})_B$ reflects invertibility of 2-cells and hence defines a smothering 2-functor. \square

Smothering 2-functors are not strictly speaking invertible, but nevertheless 2-categorical structures from the codomain can be lifted to the domain:

3.5.4. LEMMA. *Smothering 2-functors reflect equivalences: for any smothering 2-functor $F: \mathcal{A} \rightarrow \mathcal{B}$ and 1-cell $f: A \rightarrow B$ in \mathcal{A} , if $Ff: FA \rightarrow FB$ is an equivalence in \mathcal{B} then f is an equivalence in \mathcal{A} .*

PROOF. By fullness on 1-cells, an equivalence inverse $g': FB \rightarrow FA$ to Ff lifts to a 1-cell $g: B \rightarrow A$ in \mathcal{A} . By fullness on 2-cells, the isomorphisms $\text{id}_{FA} \cong g' \circ Ff$ and $Ff \circ g' \cong \text{id}_{FB}$ also lift to \mathcal{A} and by conservativity on 2-cells these lifted 2-cells are also invertible. \square

Applying Lemma 3.5.4 to the smothering 2-functor

$$\mathbf{h}(\mathcal{K}_B) \rightarrow (\mathbf{h}\mathcal{K})_B$$

we resolve the ambiguity about the 2-categorical data of a fibered equivalence.

3.5.5. PROPOSITION.

- (i) *Any equivalence in $(\mathbf{h}\mathcal{K})_B$ lifts to an equivalence in $\mathbf{h}(\mathcal{K}_B)$. That is, fibered equivalences over B may be specified by defining an opposing pair of 1-cells $f: E \rightarrow F$ and $g: F \rightarrow E$ over B together with invertible 2-cells $\text{id}_E \cong gf$ and $fg \cong \text{id}_F$ that lie over B in $\mathbf{h}\mathcal{K}$.*
- (ii) *Moreover, if $f: E \rightarrow F$ is a map between isofibrations over B that admits an not-necessarily fibered equivalence inverse $g: F \rightarrow E$ with not-necessarily fibered 2-cells $\text{id}_E \cong gf$ and $fg \cong \text{id}_F$, then this data is isomorphic to a genuine fibered equivalence.*

PROOF. The first statement is proven by Lemma 3.5.4 and Proposition 3.5.3. The second statement asserts that the forgetful 2-functor $(\mathbf{h}\mathcal{K})_B \rightarrow \mathbf{h}\mathcal{K}$ reflects equivalences. Exercise 3.5.i shows that for any map between isofibrations over B that admits an equivalence inverse in the underlying 2-category, the inverse equivalence and invertible 2-cells can be lifted to also lie over B . \square

This gives a 2-categorical proof of Proposition 1.2.17(vii), that for any ∞ -category B in an ∞ -cosmos \mathcal{K} , the forgetful functor $\mathcal{K}_B \rightarrow \mathcal{K}$ preserves and reflects equivalences.

The smothering 2-functor $\mathbf{h}(\mathcal{K}_B) \rightarrow (\mathbf{h}\mathcal{K})_B$ can also be used to lift adjunctions that are fibered 2-categorically over B to adjunctions in the sliced ∞ -cosmos \mathcal{K}_B .

3.5.6. DEFINITION (fibered adjunction). A **fibered adjunction** over an ∞ -category B in an ∞ -cosmos \mathcal{K} is an adjunction

$$\begin{array}{ccc} & f & \\ E & \xrightarrow{\quad} & F \\ & \perp & \\ & u & \\ & \searrow & \swarrow \\ & B & \end{array}$$

in the sliced ∞ -cosmos \mathcal{K}_B . We write $f \dashv_B u$ to indicate that specified maps over B are **adjoint over B** .

3.5.7. LEMMA (pullback and pushforward of fibered adjunctions).

- (i) A fibered adjunction over B can be pulled back along any functor $k: A \rightarrow B$ to define a fibered adjunction over A .
- (ii) A fibered adjunction over A can be pushed forward along any isofibration $p: A \twoheadrightarrow B$ to define a fibered adjunction over B .

PROOF. By Proposition 1.3.3(v), pullback defines a cosmological functor $k^*: \mathcal{K}_B \rightarrow \mathcal{K}_A$, which descends to a 2-functor $k^*: \mathfrak{h}(\mathcal{K}_B) \rightarrow \mathfrak{h}(\mathcal{K}_A)$ that carries fibered adjunctions over B to fibered adjunctions over A . This proves (i).

Composition with an isofibration $p: A \twoheadrightarrow B$ also defines a 2-functor $p_*: \mathfrak{h}(\mathcal{K}_A) \rightarrow \mathfrak{h}(\mathcal{K}_B)$; the reason we ask p to be an isofibration is due to our convention that the objects in the sliced ∞ -cosmoi are isofibrations over a fixed base. Thus, composition with an isofibration carries a fibered adjunction over A to a fibered adjunction over B proving (ii). \square

In analogy with Lemma 3.5.4, we have:

3.5.8. LEMMA. If $F: \mathcal{A} \rightarrow \mathcal{B}$ is a smothering 2-functor, then any adjunction in \mathcal{B} may be lifted to an adjunction in \mathcal{A} .

PROOF. Exercise 3.5.ii. \square

Many of the examples of fibered adjunctions we will encounter are right adjoint right inverses or left adjoint right inverses to a given isofibration. The next result shows that whenever an isofibration $p: E \twoheadrightarrow B$ admits a left adjoint with unit an isomorphism, then this left adjoint may be modified so as to define a left adjoint right inverse, making the adjunction fibered over B . The dual also holds:

3.5.9. LEMMA. Let $p: E \twoheadrightarrow B$ be any isofibration that admits a right adjoint $r': B \rightarrow E$ with counit $\epsilon: pr' \cong \text{id}_B$ an isomorphism. Then r' is isomorphic to a functor r that lies strictly over B and defines a right adjoint right inverse to p . Thus any such p defines a fibered adjunction

$$\begin{array}{ccc} & p & \\ E & \xrightarrow{\quad} & B \\ & \perp & \\ & \text{---} r \text{---} & \\ & p \searrow & \swarrow \\ & B & \end{array}$$

in \mathcal{K}_B whose right adjoint r lies strictly over B , whose counit is the identity 2-cell, and in which the unit η lies over B in the sense that $p\eta = \text{id}_p$.

PROOF. Exercise 3.5.iii. \square

Since the identity on B defines the terminal object of the sliced ∞ -cosmos \mathcal{K}_B , Lemma 3.5.9 can be summarized more compactly as follows:

3.5.10. COROLLARY. *An isofibration $p: E \rightarrow B$ admits a right adjoint right inverse if and only if it admits a terminal element as an object of \mathcal{K}_B . Dually, $p: E \rightarrow B$ admits a left adjoint right inverse if and only if it admits an initial element as an object of \mathcal{K}_B .*

3.5.11. EXAMPLE. Lemma 3.4.8 constructs an adjunction in the sliced 2-category $\mathfrak{h}\mathcal{K}_A$. Lemma 3.5.8 now allows us to lift it to a genuine adjunction

$$\begin{array}{ccc} & p_1 & \\ A & \xleftarrow{\quad} & \text{Hom}_B(B, f) \\ & \xrightarrow{\quad} & \\ & i & \\ & A & \end{array}$$

(Note: The diagram shows a curved arrow p_1 from $\text{Hom}_B(B, f)$ to A , a curved arrow i from A to $\text{Hom}_B(B, f)$, and a straight arrow p_1 from $\text{Hom}_B(B, f)$ to A . A vertical arrow \perp is also shown between A and $\text{Hom}_B(B, f)$.)

in the sliced ∞ -cosmos \mathcal{K}_A . By Corollary 3.5.10 this situation may be summarized by saying that $p_1: \text{Hom}_B(B, f) \rightarrow A$ admits a terminal element over A .

By Lemma 3.5.7(i), we may pull back the fibred adjunction along any element $a: 1 \rightarrow A$ to obtain an adjunction

$$\begin{array}{ccc} & ! & \\ 1 & \xleftarrow{\quad} & \text{Hom}_B(B, fa) \\ & \xrightarrow{\quad} & \\ & i_a & \end{array}$$

(Note: The diagram shows a curved arrow $!$ from $\text{Hom}_B(B, fa)$ to 1 , a curved arrow i_a from 1 to $\text{Hom}_B(B, fa)$, and a straight arrow from $\text{Hom}_B(B, fa)$ to 1 . A vertical arrow \perp is also shown between 1 and $\text{Hom}_B(B, fa)$.)

that identifies a terminal element in the fiber $\text{Hom}_B(B, fa)$ of $p_1: \text{Hom}_B(B, f) \rightarrow A$ over a . This generalizes the result of Corollary 3.4.9.

3.5.12. EXAMPLE (the fibred adjoints to composition). For any ∞ -category A , the adjoints to the “composition” functor $\circ: A^2 \times A^2 \rightarrow A^2$ constructed in Lemma 2.1.13 may be constructed by composing a triple of adjoint functors that are fibred over the endpoint-evaluation functors

$$\begin{array}{ccc} & A^{s^0} & \\ A^3 & \xleftarrow{\quad} & A^2 \\ & \xrightarrow{\quad} & \\ & A^{s^1} & \\ & A \times A & \end{array}$$

(Note: The diagram shows a curved arrow A^{s^0} from A^2 to A^3 , a curved arrow A^{s^1} from A^3 to A^2 , and a straight arrow A^{s^1} from A^2 to A^3 . A vertical arrow \perp is also shown between A^3 and A^2 . Arrows (ev_2, ev_0) and (ev_1, ev_0) point from A^3 and A^2 respectively to $A \times A$.)

with an adjoint equivalence involving a functor $A^3 \xrightarrow{\sim} A^2 \times_A A^2$, which also lies over $A \times A$. Lemma 3.5.9 and its dual implies that these adjoint equivalences can be lifted to fibred adjoint equivalences over $A \times A$, and now both adjoint triples and hence also the composite adjunctions

$$\begin{array}{ccc} & (-, \text{id}_{\text{dom}(-)}) & \\ A^2 \times_A A^2 & \xleftarrow{\quad} & A^2 \\ & \xrightarrow{\quad} & \\ & (\text{id}_{\text{cod}(-)}, -) & \\ & A \times A & \end{array}$$

(Note: The diagram shows a curved arrow $(-, \text{id}_{\text{dom}(-)})$ from A^2 to $A^2 \times_A A^2$, a curved arrow $(\text{id}_{\text{cod}(-)}, -)$ from $A^2 \times_A A^2$ to A^2 , and a straight arrow $(\text{id}_{\text{cod}(-)}, -)$ from A^2 to $A^2 \times_A A^2$. A vertical arrow \perp is also shown between $A^2 \times_A A^2$ and A^2 . Arrows (ev_2, ev_0) and (ev_1, ev_0) point from $A^2 \times_A A^2$ and A^2 respectively to $A \times A$.)

lie in $\mathcal{K}_{/A \times A}$.

This fibered adjunction figures in the proof of a result that will allow us to convert limit and colimit diagrams into right and left Kan extension diagrams in the next chapter.

3.5.13. PROPOSITION. *A cospan as displayed below-left admits an absolute right lifting if and only if the cospan displayed below-right admits an absolute right lifting*

$$\begin{array}{ccc}
 & B & \\
 \nearrow r & \downarrow f & \\
 C & \xrightarrow{g} & A
 \end{array}
 \quad
 \begin{array}{ccc}
 & \mathrm{Hom}_A(f, A) & \\
 \nearrow i & \downarrow p_1 & \\
 C & \xrightarrow{g} & A
 \end{array}$$

in which case the 2-cell ϵ is necessarily an isomorphism and can be chosen to be an identity.

PROOF. By Theorem 3.4.11, a cospan admits an absolute right lifting if and only if the codomain-projection functor from the associated comma ∞ -category admits a right adjoint right inverse. Our task is thus to show that this right adjoint right inverse exists for $\mathrm{Hom}_A(f, g)$ if and only if this right adjoint right inverse exists for $\mathrm{Hom}_A(p_1, g)$.

From the defining pullback (3.3.2) that constructs the comma ∞ -category $\mathrm{Hom}_A(p_1, g)$ reproduced below-left, we have the below-right pullback square

$$\begin{array}{ccccc}
 \mathrm{Hom}_A(p_1, g) & \longrightarrow & \mathrm{Hom}_A(A, g) & \longrightarrow & A^2 \\
 (p_1, p_0) \downarrow & \lrcorner & (p_1, p_0) \downarrow & \lrcorner & \downarrow \\
 C \times \mathrm{Hom}_A(f, A) & \xrightarrow{C \times p_1} & C \times A & \xrightarrow{g \times A} & A \times A \\
 \pi \downarrow & & \downarrow \pi & & \\
 \mathrm{Hom}_A(f, A) & \xrightarrow{p_1} & A & &
 \end{array}
 \quad \rightsquigarrow \quad
 \begin{array}{ccc}
 \mathrm{Hom}_A(p_1, g) & \twoheadrightarrow & \mathrm{Hom}_A(A, g) \\
 \downarrow & \lrcorner & \downarrow p_0 \\
 \mathrm{Hom}_A(f, A) & \twoheadrightarrow & A
 \end{array}
 \tag{3.5.14}$$

By Lemma 3.5.7, the composition-identity fibered adjunction of Example 3.5.12 pulls back along $g \times f: C \times B \rightarrow A \times A$ to define a fibered adjunction

$$\begin{array}{ccc}
 & \begin{array}{c} \xleftarrow{\quad \perp \quad} \\ \mathrm{Hom}_A(p_1, g) \cong \mathrm{Hom}_A(A, g) \times_{\mathrm{Hom}_A(f, A)} \mathrm{Hom}_A(f, g) \xrightarrow{\quad \circ \quad} \\ \xrightarrow{\quad \perp \quad} \end{array} & \\
 (p_1, p_0) \swarrow & & \searrow (p_1, p_0) \\
 & C \times B &
 \end{array}$$

which then pushes forward along the projection $\pi: C \times B \rightarrow C$ to a fibered adjunction over C

$$\begin{array}{ccc}
 & \begin{array}{c} \xleftarrow{\quad \perp \quad} \\ \mathrm{Hom}_A(p_1, g) \xrightarrow{\quad \circ \quad} \mathrm{Hom}_A(f, g) \\ \xrightarrow{\quad \perp \quad} \end{array} & \\
 p_1 \swarrow & & \searrow p_1 \\
 & C &
 \end{array}$$

between the codomain-projection for $\mathbf{Hom}_A(p_1, g)$ and the codomain projection for $\mathbf{Hom}_A(f, g)$. Now by Corollary 3.5.10, $p_1: \mathbf{Hom}_A(f, g) \rightarrow C$ admits a right adjoint right inverse just when the object on the right admits a terminal element, while $p_1: \mathbf{Hom}_A(p_1, g) \rightarrow C$ similarly admits a right adjoint right inverse just when the object on the left admits a terminal element. By Theorem 2.4.2, a terminal element on either side is carried by the appropriate right adjoint to a terminal element on the other side. This proves the equivalence of these conditions.

It remains only to prove that the 2-cell for the absolute right lifting of g through p_1 is invertible. By Theorem 3.4.11, this 2-cell is constructed as by restricting the comma cone along the terminal element, so it is given by the composite

$$C \longrightarrow \mathbf{Hom}_A(p_1, g) \longrightarrow A^2 \begin{array}{c} \xrightarrow{p_0} \\ \Downarrow \kappa \\ \xrightarrow{p_1} \end{array} A$$

where the left-hand map is the terminal element just constructed and the middle one comes from the defining pullback diagram displayed on the left of (3.5.14). As just argued, that terminal element may be chosen to be in the image of the right adjoint $\mathbf{Hom}_A(f, g) \rightarrow \mathbf{Hom}_A(A, g) \times_A \mathbf{Hom}_A(f, A) \cong \mathbf{Hom}_A(p_1, g)$, whose component on the left factor is the identity. Simultaneously, the pullback defining the map $\mathbf{Hom}_A(p_1, g) \rightarrow A^2$ factors through the projection onto the left factor, so we see that the 2-cell in the absolute right lifting diagram is represented by the composite

$$C \xrightarrow{i} \mathbf{Hom}_A(f, g) \xrightarrow{(\mathrm{id}_{\mathrm{cod}(-)}, -)} \mathbf{Hom}_A(A, g) \times_A \mathbf{Hom}_A(f, A) \xrightarrow{\pi} \mathbf{Hom}_A(A, g) \longrightarrow A^2 \begin{array}{c} \xrightarrow{p_0} \\ \Downarrow \kappa \\ \xrightarrow{p_1} \end{array} A$$

and hence that this cell is invertible. \square

Exercises.

3.5.i. EXERCISE. Let B be an object in a 2-category \mathcal{C} and consider a map

$$\begin{array}{ccc} E & \xrightarrow{f} & F \\ & \searrow & \swarrow \\ & B & \end{array}$$

between isofibrations over B . Prove that if f is an equivalence in \mathcal{C} then f is also an equivalence in the slice 2-category \mathcal{C}_B of isofibrations over B , 1-cells that form commutative triangles over B , and 2-cells that lie over B in the sense that they whisker with the codomain isofibration to the identity 2-cell on the domain isofibration.

3.5.ii. EXERCISE. Let $F: \mathcal{A} \rightarrow \mathcal{B}$ be a smothering 2-functor. Show that any adjunction in \mathcal{B} can be lifted to an adjunction in \mathcal{A} . Demonstrate furthermore that if we have previously specified a lift of the objects, 1-cells, and either the unit or counit of the adjunction in \mathcal{B} , then there is a lift of the remaining 2-cell that combines with the previously specified data to define an adjunction in \mathcal{A} . This proves a more precise version of Lemma 3.5.8.

3.5.iii. EXERCISE. Prove Lemma 3.5.9.

Adjunctions, limits, and colimits II

Comma ∞ -categories provide a vehicle for encoding the universal properties of categorical constructions that restrict to define equivalences between the internal mapping spaces introduced in Definition 3.3.9 between suitable pairs of elements. Using the theory developed in Chapter 3, we quickly prove a variety of results of this type first for adjunctions in §4.1 and then for limits and colimits in §4.3. In an interlude in §4.2, we introduce the ∞ -categories of cones over or under a diagram as a comma ∞ -category and then give a second model for these ∞ -categories of cones in the case of diagrams indexed by simplicial sets built from Joyal’s join construction. Then we conclude in §4.4 with an application, constructing the loops \vdash suspension adjunction for *pointed* ∞ -categories, containing an element that is both initial and terminal.

4.1. The universal property of adjunctions

Our first result shows that an adjunction between an opposing pair of functors can equally be encoded by a “transposing equivalence” between their left and right representations as comma ∞ -categories.

4.1.1. PROPOSITION. *An opposing pair of functors $u: A \rightarrow B$ and $f: B \rightarrow A$ define an adjunction $f \dashv u$ if and only if $\mathrm{Hom}_A(f, A) \simeq \mathrm{Hom}_B(B, u)$ over $A \times B$.*

PROOF. This is a special case of Theorem 3.4.7. If $f \dashv u$, then Lemma 2.3.6 tells us that its counit $\epsilon: fu \Rightarrow \mathrm{id}_A$ defines an absolute right lifting diagram. Theorem 3.4.7 then tells us that the 1-cell induced by the left-hand pasted composite

$$\begin{array}{ccc}
 & \mathrm{Hom}_B(B, u) & \\
 p_1 \swarrow & \phi & \searrow p_0 \\
 A & \xrightarrow{u} & B \\
 \parallel & \epsilon & \swarrow f \\
 & A &
 \end{array}
 =
 \begin{array}{ccc}
 & \mathrm{Hom}_B(B, u) & \\
 p_1 \swarrow & \downarrow y & \searrow p_0 \\
 & \mathrm{Hom}_A(f, A) & \\
 p_1 \swarrow & \phi & \searrow p_0 \\
 A & \xrightarrow{u} & B \\
 \parallel & & \swarrow f \\
 & A &
 \end{array}$$

defines a fibered equivalence $\mathrm{Hom}_B(B, u) \xrightarrow{\sim} \mathrm{Hom}_A(f, A)$ over $A \times B$. We interpret this result as saying that in the presence of an adjunction $f \dashv u$, the right comma cone over u transposes to define the left comma cone over f .¹

¹If desired, an inverse equivalence can be constructed by applying the dual of Theorem 3.4.7 to the absolute left lifting diagram presented by the unit.

Conversely, Theorem 3.4.7 tells us that from a fibered equivalence $\text{Hom}_B(B, u) \simeq \text{Hom}_A(f, A)$ over $A \times B$ one can extract a 2-cell that defines an absolute right lifting diagram

$$\begin{array}{ccc} & B & \\ u \nearrow & \Downarrow \epsilon & \downarrow f \\ A & \xlongequal{\quad} & A \end{array}$$

Lemma 2.3.6 then tells us that this 2-cell defines the counit of an adjunction $f \dashv u$. □

4.1.2. OBSERVATION (the transposing equivalence). To justify referring to the induced functor

$$\text{Hom}_B(B, u) \simeq \text{Hom}_A(f, A)$$

as a **transposing equivalence**, recall that the transpose of a 2-cell $\chi: b \Rightarrow ua$ across the adjunction $f \dashv u$ is computed by the left-hand pasting diagram below:

$$\begin{array}{ccccc} & X & & X & \\ & \swarrow a & \searrow b & \swarrow a & \searrow b \\ A & \xrightarrow{u} & B & = & A & \xrightarrow{u} & B & = & A & \xrightarrow{u} & B \\ & \searrow \epsilon & \swarrow f & & \searrow \epsilon & \swarrow f & & \searrow \epsilon & \swarrow f & & \searrow \epsilon & \swarrow f \\ & A & & A & & A & & A & & A & & A \end{array}$$

(Note: The diagram shows three stages of a pasting equality. The first stage shows a triangle with vertices A, B, X and arrows a, b, u, and a 2-cell χ. The second stage shows the same triangle with a natural transformation φ and projections p1, p0. The third stage shows the same triangle with a natural transformation φ and projections p1, p0, but with a different arrangement of arrows and 2-cells.)

By the weak universal property of the right comma cone over u , the 2-cell χ is represented by the induced functor $X \rightarrow \text{Hom}_B(B, u)$, which then composes with the transposing equivalence to define a functor $X \rightarrow \text{Hom}_A(f, A)$ that represents the transpose of χ , by the pasting diagram equalities from right to left.

4.1.3. COROLLARY. An adjunction $B \overset{f}{\underset{u}{\rightleftarrows}} A$ induces an equivalence $\text{Hom}_A(fb, a) \simeq \text{Hom}_B(b, ua)$ over $X \times Y$ for any pair of generalized elements $a: X \rightarrow A$ and $b: Y \rightarrow B$.

PROOF. By the pullback construction of comma ∞ -categories given in (3.3.2), the equivalence $\text{Hom}_A(f, A) \simeq \text{Hom}_B(B, u)$ in $\mathcal{K}_{/A \times B}$ pulls back along $a \times b: X \times Y \rightarrow A \times B$ to define an equivalence $\text{Hom}_A(fb, a) \simeq \text{Hom}_B(b, ua)$ in $\mathcal{K}_{/X \times Y}$. □

In particular, the equivalence of Proposition 4.1.1 pulls back to define an equivalence of internal mapping spaces, introduced in 3.3.9.

4.1.4. PROPOSITION (the universal property of units and counits). Consider an adjunction

$$B \overset{f}{\underset{u}{\rightleftarrows}} A \quad \text{with unit } \eta: \text{id}_B \Rightarrow uf \text{ and counit } \epsilon: fu \Rightarrow \text{id}_A.$$

Then for each element $a: 1 \rightarrow A$, the component ϵa defines a terminal element of $\text{Hom}_A(f, a)$, and for each element $b: 1 \rightarrow B$, the component ηb defines an initial element of $\text{Hom}_B(b, u)$.

PROOF. By Corollary 4.1.3, the fibered equivalence $\mathbf{Hom}_A(f, A) \simeq_{A \times B} \mathbf{Hom}_B(B, u)$ of Proposition 4.1.1 pulls back to define equivalences

$$\mathbf{Hom}_A(f, a) \simeq_B \mathbf{Hom}_B(B, ua) \quad \text{and} \quad \mathbf{Hom}_A(fb, A) \simeq_A \mathbf{Hom}_B(b, u).$$

By Corollary 3.4.9, id_{ua} induces a terminal element of $\mathbf{Hom}_B(B, ua)$ and by Observation 4.1.2 its image across the equivalence $\mathbf{Hom}_B(B, ua) \simeq \mathbf{Hom}_A(f, a)$ is again a terminal element, which represents the transposed 2-cell: the component of the counit ϵ at the element a . The proof that the unit component defines a terminal element of $\mathbf{Hom}_B(b, u)$ is dual. \square

A more sophisticated formulation of the universal property of unit and counit components will appear in Proposition 8.3.2 where it will form a key step in the proof that any adjunction extends to a *homotopy coherent adjunction*.

The universal property of unit and counit components captured in Proposition 4.1.4 gives the main idea behind the adjoint functor theorems: a functor $f: B \rightarrow A$ admits a right adjoint just when for each element $a: 1 \rightarrow A$, the ∞ -category $\mathbf{Hom}_A(f, a)$ admits a terminal element. The image of this terminal element under the domain-projection functor $p_0: \mathbf{Hom}_A(f, a) \rightarrow B$ then defines the element $ua: 1 \rightarrow B$ and the comma cone defines the component of the counit at a . The universal property of these unit components is then used to extend the mapping on elements to a functor $u: A \rightarrow B$.

The result just stated is true in the ∞ -cosmos of quasi-categories and in other ∞ -cosmoi where universal properties are generated by the terminal ∞ -category 1 .² What is true in all ∞ -cosmoi is the version of the result just stated where the quantifier “for each element $a: 1 \rightarrow A$ ” is replaced with “for each generalized element $a: X \rightarrow A$,” in which case the meaning of “terminal element” should be enhanced to “terminal element over X ”; see the remark after Corollary 3.4.9. Since every generalized element factors through the universal generalized element, namely the identity functor at A , it suffices to prove:

4.1.5. PROPOSITION. *A functor $f: B \rightarrow A$ admits a right adjoint if and only if $\mathbf{Hom}_A(f, A)$ admits a terminal element over A . Dually, $f: B \rightarrow A$ admits a left adjoint if and only if $\mathbf{Hom}_A(A, f)$ admits an initial element over A .*

PROOF. By Proposition 4.1.1, $f: B \rightarrow A$ admits a right adjoint if and only if the comma ∞ -category $\mathbf{Hom}_A(f, A)$ is right representable. Theorem 3.4.11 specializes to tell us that this is the case if and only if the codomain-projection functor $p_1: \mathbf{Hom}_A(f, A) \rightarrow A$ admits a right adjoint right inverse, which by Corollary 3.5.10 is equivalent to postulating a terminal element over A . \square

The same suite of results from §3.4 specialize to theorems that encode the universal properties of limits and colimits. Before proving these, we first construct the ∞ -category of cones over a fixed diagram and also construct alternate models for the ∞ -categories of cones over varying J -indexed diagrams, in the case where J is a simplicial set.

Exercises.

4.1.i. EXERCISE. Prove that the transposing equivalence of Proposition 4.1.1, as elaborated upon in Observation 4.1.2, is natural with respect to pre-composing with a 2-cell $\beta: b' \Rightarrow b$ or post-composing with a 2-cell $\alpha: a \Rightarrow a'$.

²We delay the discussion of “analytically-proven” theorems about quasi-categories until we demonstrate in Part IV that such results apply also in biequivalent ∞ -cosmoi.

4.2. ∞ -categories of cones

4.2.1. DEFINITION (the ∞ -category of cones). Let $d: 1 \rightarrow A^J$ be a J -shaped diagram in an ∞ -category A . The ∞ -category of cones over d is the comma ∞ -category $\mathrm{Hom}_{A^J}(\Delta, d)$ with comma cone displayed below-left, while the ∞ -category of cones under d is the comma ∞ -category $\mathrm{Hom}_{A^J}(d, \Delta)$ with comma cone displayed below-right:

$$\begin{array}{ccc}
 & \mathrm{Hom}_{A^J}(\Delta, d) & \\
 p_1 \swarrow & & \searrow p_0 \\
 1 & \xleftarrow{\phi} & A \\
 d \searrow & & \swarrow \Delta \\
 & A^J &
 \end{array}
 \qquad
 \begin{array}{ccc}
 & \mathrm{Hom}_{A^J}(d, \Delta) & \\
 p_1 \swarrow & & \searrow p_0 \\
 A & \xleftarrow{\phi} & 1 \\
 \Delta \searrow & & \swarrow d \\
 & A^J &
 \end{array}$$

By replacing the “ d ” leg of the cospans, Definition 4.2.1 can be modified to allow $d: D \rightarrow A^J$ to be a family of diagrams or to define ∞ -categories of cones over any diagram of shape J : an element of $\mathrm{Hom}_{A^J}(\Delta, A^J)$ is a cone with any summit over any J -indexed diagram.

In the case where the indexing shape J is a simplicial set (and not an ∞ -category in a cartesian closed ∞ -cosmos), there is another model of the ∞ -categories of cones over or under a diagram that may be constructed using Joyal’s join construction. The reason for the equivalence is that joins of simplicial sets are known to be equivalent to so-called “fat joins” of simplicial sets, and a particular instance of the fat join construction gives the shape of the cones appearing in Definition 4.2.1. We now introduce these notions.

4.2.2. DEFINITION (fat join). The **fat join** of simplicial sets I and J is the simplicial set constructed by the following pushout:

$$\begin{array}{ccc}
 (I \times J) \sqcup (I \times J) & \xrightarrow{\pi_I \sqcup \pi_J} & I \sqcup J \\
 \downarrow & & \downarrow \\
 I \times \mathbb{2} \times J & \xrightarrow{\quad r \quad} & I \diamond J
 \end{array}$$

from which it follows that

$$(I \diamond J)_n := I_n \sqcup \left(\coprod_{[n] \twoheadrightarrow [1]} I_n \times J_n \right) \sqcup J_n.$$

Note there is a natural map $I \diamond J \rightarrow \mathbb{2}$ induced by the projection $\pi: I \times \mathbb{2} \times J \rightarrow \mathbb{2}$ so that I is the fiber over 0 and J is the fiber over 1:

$$\begin{array}{ccc}
 I \sqcup J & \hookrightarrow & I \diamond J \\
 \downarrow & \lrcorner & \downarrow \\
 \mathbb{1} + \mathbb{1} & \xrightarrow{(0,1)} & \mathbb{2}
 \end{array}$$

4.2.3. LEMMA. For any simplicial set J and ∞ -category A we have natural isomorphisms

$$\mathrm{Hom}_{A^J}(\Delta, A^J) \cong A^{\mathbb{1} \diamond J} \quad \text{and} \quad \mathrm{Hom}_{A^J}(A^J, \Delta) \cong A^{J \diamond \mathbb{1}}.$$

PROOF. The simplicial cotensor $A^{(-)}: \mathcal{SSet}^{\text{op}} \rightarrow \mathcal{K}$ carries the pushout of Definition 4.2.2 to the pullback squares that define the left and right representations of $\Delta: A \rightarrow A^I$ as a comma ∞ -category:

$$\begin{array}{ccc} A^{\mathbb{1} \circ J} & \longrightarrow & (A^J)^2 \\ \downarrow & \lrcorner & \downarrow (p_1, p_0) \\ A^J \times A & \xrightarrow{\text{id} \times \Delta} & A^J \times A^J \end{array} \quad \begin{array}{ccc} A^{J \circ \mathbb{1}} & \longrightarrow & (A^J)^2 \\ \downarrow & \lrcorner & \downarrow (p_1, p_0) \\ A \times A^J & \xrightarrow{\Delta \times \text{id}} & A^J \times A^J \end{array} \quad \square$$

4.2.4. DEFINITION (join). The **join** of simplicial sets I and J is the simplicial set $I \star J$

$$\begin{array}{ccc} I \sqcup J & \hookrightarrow & I \star J \\ \downarrow & \lrcorner & \downarrow \\ \mathbb{1} + \mathbb{1} & \xrightarrow{(0,1)} & \mathbb{2} \end{array}$$

with

$$(I \star J)_n := I_n \sqcup \left(\coprod_{0 \leq k < n} I_{n-k-1} \times J_k \right) \sqcup J_n$$

and with the vertices of these n -simplices oriented so that there is a canonical map $I \star J \rightarrow \mathbb{2}$ so that I is the fiber over 0 and J is the fiber over 1. See [24, §3] for more details.

The join functor $- \star J: \mathcal{SSet} \rightarrow \mathcal{SSet}$ preserves connected colimits but not the initial object or other coproducts, but this issue can be rectified by replacing the codomain by the slice category under J . Contextualized in this way, the join admits a right adjoint, defined by Joyal's **slice** construction:

4.2.5. PROPOSITION. *The join functors admit right adjoints*

$$\begin{array}{ccc} \mathcal{SSet} & \xrightarrow{I \star -} & I/\mathcal{SSet} \\ & \perp & \\ & \xleftarrow{-/-} & \end{array} \quad \begin{array}{ccc} \mathcal{SSet} & \xrightarrow{- \star J} & I/\mathcal{SSet} \\ & \perp & \\ & \xleftarrow{-/-} & \end{array}$$

defined by the natural bijections

$$\left\{ \begin{array}{c} \Delta[n] \xrightarrow{I} X \\ \swarrow \searrow^h \\ I \star \Delta[n] \longrightarrow X \end{array} \right\} \cong \left\{ \Delta[n] \rightarrow {}^h X \right\} \quad \text{and} \quad \left\{ \begin{array}{c} \Delta[n] \xrightarrow{J} X \\ \swarrow \searrow^k \\ \Delta[n] \star J \longrightarrow X \end{array} \right\} \cong \left\{ \Delta[n] \rightarrow X_{/k} \right\}.$$

PROOF. As in the statement, the simplicial set $X_{/k}$ is defined to have n -simplices corresponding to maps $\Delta[n] \star J \rightarrow X$ under J , with the right action by the simplicial operators $[m] \rightarrow [n]$ given by pre-composition with $\Delta[m] \rightarrow \Delta[n]$. Since the join functor $- \star J: \mathcal{SSet} \rightarrow I/\mathcal{SSet}$ preserves colimits, this extends to a bijection between maps $I \rightarrow X_{/k}$ and maps $I \star J \rightarrow X$ under J that is natural in I and in $k: J \rightarrow X$. \square

4.2.6. NOTATION. For any simplicial set J , we write

$$J^{\triangleleft} := \mathbb{1} \star J \quad \text{and} \quad J^{\triangleright} := J \star \mathbb{1}$$

and write \top for the **cone vertex** of J^{\triangleleft} and \perp for the **cone vertex** of J^{\triangleright} . These simplicial sets are equipped with canonical inclusions

$$J^{\triangleleft} \longleftarrow J \longrightarrow J^{\triangleright}$$

4.2.7. PROPOSITION (an alternate model). *For any simplicial sets I and J and any ∞ -category A , there is a natural equivalence*

$$\begin{array}{ccc} A^{I \star J} & \xrightarrow{\sim} & A^{I \circ J} \\ \text{res} \searrow & & \swarrow \text{res} \\ & A^{I \sqcup J} & \end{array}$$

In particular, there are comma squares

$$\begin{array}{ccccc} & & A^{I^{\triangleleft}} & & \\ \text{res} \swarrow & & \searrow \text{ev}_{\top} & & \\ A^J & & \phi \Leftarrow & & A \\ & \Downarrow & \Delta & & \\ & & A^J & & \end{array} \quad \begin{array}{ccccc} & & A^{J^{\triangleright}} & & \\ \text{ev}_{\perp} \swarrow & & \searrow \text{res} & & \\ A & & \phi \Leftarrow & & A^J \\ & \Delta & & \Downarrow & \\ & & A^J & & \end{array} \quad (4.2.8)$$

PROOF. There is a canonical map of simplicial sets

$$\begin{array}{ccccc} (I \times J) \sqcup (I \times J) & \xrightarrow{\pi_I \sqcup \pi_J} & I \sqcup J & & \\ \downarrow & & \downarrow & \searrow & \\ I \times 2 \times J & \xrightarrow{\quad} & I \diamond J & \dashrightarrow & I \star J \\ & \searrow & \downarrow & \swarrow & \\ & & 2 & & \end{array}$$

that commutes with the inclusions of the fibers $I \sqcup J$ over the endpoints of 2 . This dashed map displayed above is defined on those n -simplices over $I \diamond J$ that map surjectively onto 2 to send a triple $(\alpha: [n] \twoheadrightarrow [1], \sigma \in I_n, \tau \in J_n)$ representing an n -simplex of $I \diamond J$ to the pair $(\sigma|_{\{0, \dots, k\}} \in I_k, \tau|_{\{k+1, \dots, n\}} \in J_{n-k-1})$ representing an n -simplex of $I \star J$, where $k \in [n]$ is the maximal vertex in $\alpha^{-1}(0)$. Proposition ?? of Appendix C proves that this map induces a natural equivalence $Q^{I \star J} \simeq Q^{I \circ J}$ of quasi-categories over $Q^J \times Q^I$. Taking Q to be the functor space $\mathbf{Fun}(X, A)$ proves the claimed equivalence for general ∞ -categories.

Now Proposition 3.3.11 and Lemma 4.2.3 implies that this fibered equivalence equips $A^{I^{\triangleleft}}$ and $A^{J^{\triangleright}}$ with comma cone squares. The 2-cells in (4.2.8) are represented by the maps

$$\begin{array}{ccccc} J \sqcup J & \xrightarrow{\quad} & 1 \sqcup J & & \\ \downarrow & & \downarrow & \searrow & \\ J \times 2 & \xrightarrow{\quad} & 1 \diamond J & \dashrightarrow & J^{\triangleleft} \\ & \searrow & \downarrow & \swarrow & \\ & & 2 & & \end{array} \quad \begin{array}{ccccc} J \sqcup J & \xrightarrow{\quad} & J \sqcup 1 & & \\ \downarrow & & \downarrow & \searrow & \\ J \times 2 & \xrightarrow{\quad} & J \diamond 1 & \dashrightarrow & J^{\triangleright} \\ & \searrow & \downarrow & \swarrow & \\ & & 2 & & \end{array}$$

which yield 2-cells

$$\begin{array}{ccc}
 A^{J^{\triangleleft}} & \xrightarrow{\quad} & (A^J)^2 \\
 \Delta \text{ev}_{\top} \nearrow & & \searrow p_0 \\
 & \Downarrow \kappa & \\
 & p_1 \searrow & \\
 \text{res} \nwarrow & & A^J
 \end{array}
 \qquad
 \begin{array}{ccc}
 A^{J^{\triangleright}} & \xrightarrow{\quad} & (A^J)^2 \\
 \text{res} \nearrow & & \searrow p_0 \\
 & \Downarrow \kappa & \\
 & p_1 \searrow & \\
 \Delta \text{ev}_{\perp} \nwarrow & & A^J
 \end{array}$$

upon cotensoring into A . □

Exercises.

4.2.i. EXERCISE. Compute $\Delta[n] \star \Delta[m]$ and $\Delta[n] \diamond \Delta[m]$ and define a section

$$\Delta[n] \star \Delta[m] \rightarrow \Delta[n] \diamond \Delta[m]$$

to the map constructed in the proof of Proposition 4.2.7.

4.3. The universal property of limits and colimits

We now return to the general context of Definition 2.3.1, simultaneously considering diagrams valued in an ∞ -category A that are indexed either by a simplicial set or by another ∞ -category in the case where the ambient ∞ -cosmos is cartesian closed. As was the case for Proposition 4.1.1, Theorem 3.4.7 specializes immediately to prove:

4.3.1. PROPOSITION (co/limits represent cones). *A family of diagrams $d: D \rightarrow A^J$ admits a limit if and only if the ∞ -category of cones $\mathbf{Hom}_{A^J}(\Delta, d)$ over d is right representable*

$$\mathbf{Hom}_{A^J}(\Delta, d) \simeq_{D \times A} \mathbf{Hom}_A(A, \ell),$$

in which case the representing functor $\ell: D \rightarrow A$ defines the limit functor. Dually, $d: D \rightarrow A^J$ admits a colimit if and only if the ∞ -category of cones $\mathbf{Hom}_{A^J}(d, \Delta)$ under d is left representable

$$\mathbf{Hom}_{A^J}(d, \Delta) \simeq_{A \times D} \mathbf{Hom}_A(c, A),$$

in which case the representing functor $c: D \rightarrow A$ defines the colimit functor. □

Theorem 3.4.11 now specializes to tell us that such representations can be encoded by terminal or initial elements, a result which is easiest to interpret in the case of a single diagram rather than a family of diagrams.

4.3.2. PROPOSITION (limits as terminal elements). *Consider a diagram $d: 1 \rightarrow A^J$ of shape J in an ∞ -category A .*

- (i) *If d admits a limit, then the 1-cell $1 \rightarrow \mathbf{Hom}_{A^J}(\Delta, d)$ induced by the limit cone $\epsilon: \Delta \ell \Rightarrow d$ defines a terminal element of the ∞ -category of cones.*
- (ii) *Conversely, if the ∞ -category of cones $\mathbf{Hom}_{A^J}(\Delta, d)$ admits a terminal element, then the cone represented by this element defines a limit cone.*

Dually d admits a colimit if and only if the ∞ -category $\mathbf{Hom}_{A^J}(d, \Delta)$ of cones under d admits an initial element, in which case the initial element defines the colimit cone.

PROOF. By Definition 2.3.7, a limit cone defines an absolute right lifting diagram, which by Theorem 3.4.3, induces an equivalence $\mathbf{Hom}_A(A, \ell) \simeq \mathbf{Hom}_{A^I}(\Delta, d)$ over A . By Corollary 3.4.9, the identity at ℓ induces a terminal element of $\mathbf{Hom}_A(A, \ell)$ which the equivalence carries to a terminal element of the ∞ -category of cones, this being the element that represents the limit cone $\epsilon: \Delta \ell \Rightarrow d$.

Conversely, if $\mathbf{Hom}_{A^I}(\Delta, d)$ admits a terminal element, this defines a right adjoint right inverse to the codomain-projection functor $\mathbf{Hom}_{A^I}(\Delta, d)$. Theorem 3.4.11 then tells us that the cone represented by this element $1 \rightarrow \mathbf{Hom}_{A^I}(\Delta, d)$ defines an absolute right lifting of d through Δ . \square

4.3.3. REMARK. The proof of Proposition 4.3.2 extends without change to the case of a family of diagrams $d: D \rightarrow A^I$ in place of a single diagram since Theorem 3.4.11 applies at this level of generality. For a family of diagrams d parametrized by D , the ∞ -category of cones defines an object $p_1: \mathbf{Hom}_{A^I}(\Delta, d) \rightarrow D$ of the sliced ∞ -cosmos \mathcal{K}_D and the terminal elements referred to in both (i) and (ii) should be interpreted as terminal elements in \mathcal{K}_D .

4.3.4. PROPOSITION. *An ∞ -category A admits a limit of a family of diagrams $d: D \rightarrow A^I$ indexed by a simplicial set J if and only if there exists an absolute right lifting of d through the restriction functor*

$$\begin{array}{ccc} & & A^{J^\triangleleft} \\ & \nearrow \text{ran} & \downarrow \text{res} \\ D & \xrightarrow{d} & A^J \end{array} \quad \Downarrow \epsilon$$

When these equivalent conditions hold, ϵ is necessarily an isomorphism and may be chosen to be the identity.

PROOF. By Definition 2.3.7, the family of diagrams admits a limit if and only if d admits an absolute right lifting through $\Delta: A \rightarrow A^I$. By Proposition 3.5.13, such an absolute lifting diagram exists if and only if d admits an absolute right lifting through codomain-projection functor $p_1: \mathbf{Hom}_{A^I}(\Delta, A^I) \rightarrow A^I$, in which case the 2-cell of this latter absolute right lifting diagram is invertible. By Proposition 4.2.7, the restriction functor $\text{res}: A^{J^\triangleleft} \rightarrow A^J$ is equivalent to this codomain-projection functor, so absolute right liftings of d through p_1 are equivalent to absolute right liftings of d through res . If this absolute lifting diagram is inhabited by an invertible 2-cell, the isomorphism lifting property of the isofibration proven in Proposition 1.4.10 can be used to replace the functor $\text{ran}: D \rightarrow A^{J^\triangleleft}$ with an isomorphic functor making the triangle commute strictly. \square

Recall from Lemma 2.3.6 that absolute lifting diagrams can be used to encode the existence of adjoint functors. Combining this with Definition 2.3.2, Proposition 4.3.4 specializes to prove:

4.3.5. COROLLARY. *An ∞ -category A admits all limits indexed by a simplicial set J if and only if the restriction functor*

$$\begin{array}{ccc} & \xrightarrow{\text{res}} & \\ A^{J^\triangleleft} & \perp & A^J \\ & \xleftarrow{\text{ran}} & \end{array}$$

³We have stated this result for diagrams indexed by simplicial sets because its means is easiest to interpret, but we actually prove it with the codomain-projection functor $p_1: \mathbf{Hom}_{A^I}(\Delta, A^I) \rightarrow A^I$ in place of the equivalent isofibration $A^{J^\triangleleft} \rightarrow A^J$, and this proof applies equally in the case of diagrams indexed by ∞ -categories J in cartesian closed ∞ -cosmoi that may or may not have a join operation available.

admits a right adjoint. Dually, an ∞ -category A admits all colimits indexed by a simplicial set J if and only if the restriction functor

$$A^{J^{\triangleright}} \begin{array}{c} \xleftarrow{\text{lan}} \\ \perp \\ \xrightarrow{\text{res}} \end{array} A^J$$

admits a left adjoint. □

4.3.6. REMARK. Since the restriction functor is an isofibration, Lemma 3.5.9 applies and the adjunctions of Corollary 4.3.5 can be defined so as to be fibered over the ∞ -category of diagrams A^J .

The adjunctions of Corollary 4.3.5 are particularly useful in the case of pullbacks and pushouts.

4.3.7. DEFINITION (pushouts and pullbacks). A **pushout** in an ∞ -category A is a colimit indexed by the simplicial set

$$\ulcorner := \Lambda^0[2].$$

Dually, a **pullback** in an ∞ -category A is a limit indexed by the simplicial set

$$\lrcorner := \Lambda^2[2].$$

Cones over diagrams of shape \lrcorner or cones under diagrams of shape \ulcorner define **commutative squares**, diagrams of shape

$$\square := \Delta[1] \times \Delta[1] \cong \ulcorner^{\triangleright} \cong \lrcorner^{\triangleleft}.$$

A **pullback square** in an ∞ -category A is an element of A^{\square} in the essential image of the functor ran of Proposition 4.3.4 for some diagram of shape \lrcorner . When A admits all pullbacks, these are exactly those elements of A^{\square} at which the component of the unit of the adjunction $\text{res} \dashv \text{ran}$ of Corollary 4.3.5 is an isomorphism. Dually, a **pushout square** in A is an element in the essential image of the dual functor lan for some diagram of shape \ulcorner , i.e., those elements for which the component of the counit of the adjunction $\text{lan} \dashv \text{res}$ is an isomorphism.

An X -indexed commutative square in A is a diagram $X \rightarrow A^{\square}$, or equivalently, an element of $\text{Fun}(X, A)^{\square}$. We label the 0- and 1-simplex components as follows:

$$\begin{array}{ccc} d & \xrightarrow{u} & b \\ v \downarrow & \searrow w & \downarrow f \\ c & \xrightarrow{g} & a \end{array} \in \text{Fun}(X, A)$$

The diagram also determines a pair of 2-simplices that witness commutativity $fu = w = gv$ in $\mathbf{hFun}(X, A)$, but the names of these witnesses won't matter for this discussion.

4.3.8. LEMMA. An X -indexed commutative square valued in an ∞ -category A in \mathcal{K} as below-left is a pullback square if and only if the induced 2-cell below-right is an absolute right lifting diagram in \mathcal{K}_X :

$$\begin{array}{ccc} d & \xrightarrow{u} & b \\ v \downarrow & \searrow w & \downarrow f \\ c & \xrightarrow{g} & a \end{array} \quad \begin{array}{ccc} & & \text{Hom}_A(A, b) \\ & \nearrow \ulcorner u \urcorner & \downarrow \ulcorner f_* \urcorner \\ X & \xrightarrow{\ulcorner g \urcorner} & \text{Hom}_A(A, a) \\ & \searrow \ulcorner \ulcorner & \nearrow \ulcorner \ulcorner \\ & X & \end{array}$$

The statement requires some explanation. The 1-simplex $g: c \rightarrow a$ represents a 2-cell $X \begin{smallmatrix} \xrightarrow{c} \\ \Downarrow g \\ \xrightarrow{a} \end{smallmatrix} A$, inducing the map $\ulcorner g \urcorner: 1 \rightarrow \text{Hom}_A(A, a)$. The map $\ulcorner u \urcorner: X \rightarrow \text{Hom}_A(A, b)$ is defined similarly. The map $\ulcorner f_* \urcorner: \text{Hom}_A(A, b) \rightarrow \text{Hom}_A(A, a)$ is characterized by the pasting diagram

$$\begin{array}{ccc} & \text{Hom}_A(A, b) & \\ p_1 \swarrow & \phi \Leftarrow & \searrow p_0 \\ X & \Downarrow f & A \\ & a & \end{array} \quad = \quad \begin{array}{ccc} & \text{Hom}_A(A, b) & \\ p_1 \swarrow & \ulcorner f_* \urcorner \downarrow & \searrow p_0 \\ & \text{Hom}_A(A, a) & \\ p_1 \swarrow & \phi \Leftarrow & \searrow p_0 \\ X & \xrightarrow{a} & A \end{array}$$

By Proposition 3.3.7, the composite $\ulcorner f_* \urcorner \ulcorner u \urcorner$ is isomorphic to $\ulcorner fu \urcorner$. By 2-cell induction, the 2-cell may be constructed by specifying its domain and codomain components, the former of which we take to

be $X \begin{smallmatrix} \xrightarrow{d} \\ \Downarrow v \\ \xrightarrow{c} \end{smallmatrix} A$ and the latter of which we take to be id_a . Note that the 2-cell just constructed lies in $\mathfrak{h}\mathcal{K}_X$ and so can be lifted to $\mathfrak{h}(\mathcal{K}_X)$ by Proposition 3.5.3.

PROOF. We prove the result in the case $X = 1$ and then deduce the result for families of pullback diagrams from this case. By Proposition 4.2.7, the pullback

$$\begin{array}{ccc} A_{g \vee f}^\square & \longrightarrow & A^\square \\ \downarrow & \lrcorner & \downarrow \text{res} \\ 1 & \xrightarrow{g \vee f} & A^\natural \end{array}$$

is equivalent to the ∞ -category of cones over the cospan diagram $g \vee f$. By Proposition 4.3.2, to show that the commutative square defines a pullback diagram is to show that $(u, v, f, g): 1 \rightarrow A_{g \vee f}^\square$ defines a terminal element in the pullback. We will show that this pullback $A_{g \vee f}^\square$ is also equivalent to the comma ∞ -category $\text{Hom}_{\text{Hom}_A(A, a)}(\ulcorner f_* \urcorner, \ulcorner g \urcorner)$. By Theorem 3.4.11, the pair $(\ulcorner u \urcorner, (\text{id}_a, v))$ defines an absolute right lifting if and only if it represents a terminal element in this comma ∞ -category, which will prove the claimed equivalence.

To see this first consider the diagram, which induces a map between the two pullbacks

$$\begin{array}{ccccccc} & & A/f & \xrightarrow{\quad} & A^3 & \xrightarrow{p_{01}} & A^2 \\ & \swarrow p_f & \downarrow & \lrcorner & \swarrow p_{02} & \downarrow p_{12} & \downarrow p_1 \\ \text{Hom}_A(A, a) & \xrightarrow{\quad} & A^2 & & A^2 & \xrightarrow{p_0} & A \\ \downarrow & \lrcorner & \downarrow & & \downarrow p_1 & & \\ X & \xrightarrow{\quad} & X & \xrightarrow{f} & A^2 & \xrightarrow{p_0} & A \\ & \searrow & \downarrow & & \swarrow p_1 & & \\ & & X & \xrightarrow{a} & A & & \end{array}$$

Since $A^3 \simeq A^{\wedge^1[2]}$, the right-hand back square is equivalent to a pullback. Composing the pullback squares in the back face of the diagram, we obtain an equivalence $A_{/f} \simeq \mathbf{Hom}_A(A, b)$ and by inspection see that the map $p_f: A_{/f} \twoheadrightarrow \mathbf{Hom}_A(A, a)$ is equivalent to the map $\ulcorner f_* \urcorner: \mathbf{Hom}_A(A, b) \rightarrow \mathbf{Hom}_A(A, a)$ over $\mathbf{Hom}_A(A, a)$.

By applying $(-)^2$ to the pullback diagram that defines $\mathbf{Hom}_A(A, a)$ we obtain a pullback square that factors as:

$$\begin{array}{ccccc} \mathbf{Hom}_A(A, a)^2 & \longrightarrow & A^{2 \circ 1} & \longrightarrow & A^{2 \times 2} \\ \downarrow & \lrcorner & \downarrow & \lrcorner & \downarrow p_1^2 \\ 1 & \xrightarrow{a} & A & \xrightarrow{\Delta} & A^2 \end{array}$$

By the equivalence $A^{2 \circ 1} \simeq A^{2 \star 1}$ of Proposition 4.2.7, the left-hand pullback square shows that $\mathbf{Hom}_A(A, a)^2$ is equivalent to the pullback of $p_2: A^3 \twoheadrightarrow A$ along $a: 1 \rightarrow A$. Modulo this equivalence, the map $p_0: \mathbf{Hom}_A(A, a)^2 \twoheadrightarrow \mathbf{Hom}_A(A, a)$ is the pullback of the fibered map

$$\begin{array}{ccc} A^3 & \xrightarrow{p_{02}} & A^2 \\ & \searrow p_2 \quad \swarrow p_1 & \\ & A & \end{array}$$

along $a: 1 \rightarrow A$ and the codomain projection is similarly the pullback of the fibered map $p_{12}: A^3 \twoheadrightarrow A^2$.

Putting this together, it follows that the pullback

$$\begin{array}{ccc} \mathbf{Hom}_{\mathbf{Hom}_A(A, a)}(\ulcorner f_* \urcorner, \mathbf{Hom}_A(A, a)) & \longrightarrow & \mathbf{Hom}_A(A, a)^2 \\ \downarrow & \lrcorner & \downarrow p_0 \\ \mathbf{Hom}_A(A, b) & \xrightarrow{\ulcorner f_* \urcorner} & \mathbf{Hom}_A(A, a) \end{array}$$

is equivalently computed by forming the limit

$$\begin{array}{ccccccc} \bullet & \longrightarrow & A^\square & \longrightarrow & A^3 & \xrightarrow{p_{12}} & A^2 \\ \downarrow & \lrcorner & \downarrow & \lrcorner & \downarrow p_{02} & & \\ & & A^3 & \xrightarrow{p_{02}} & A^2 & & \\ \downarrow & & \downarrow p_{12} & & & & \\ 1 & \xrightarrow{f} & A^2 & & & & \end{array}$$

The codomain projection $p_1: \mathbf{Hom}_{\mathbf{Hom}_A(A, a)}(\ulcorner f_* \urcorner, \mathbf{Hom}_A(A, a)) \twoheadrightarrow \mathbf{Hom}_A(A, a)$ is the pullback of the top-horizontal composite in the above diagram along $\mathbf{Hom}_A(A, a) \rightarrow A^2$. So we see that the comma ∞ -category $\mathbf{Hom}_{\mathbf{Hom}_A(A, a)}(\ulcorner f_* \urcorner, \ulcorner g \urcorner)$ is equivalently computed by the limit below-left, or equivalently

by the limit below right, exactly as we claimed:

$$\begin{array}{ccccc}
 \bullet & \longrightarrow & \bullet & \longrightarrow & 1 \\
 \downarrow & \lrcorner & \downarrow & \lrcorner & \downarrow g \\
 \bullet & \longrightarrow & A^\square & \twoheadrightarrow & A^2 \\
 \downarrow & \lrcorner & \downarrow & \lrcorner & \downarrow p_{02} \\
 & & A^3 & \twoheadrightarrow & A^2 \\
 & & \downarrow p_{02} & & \\
 & & A^3 & \twoheadrightarrow & A^2 \\
 & & \downarrow p_{12} & & \\
 1 & \xrightarrow{f} & A^2 & &
 \end{array}
 \quad
 \begin{array}{ccc}
 A^\square_{g \vee f} & \longrightarrow & A^\square \\
 \downarrow & \lrcorner & \downarrow \text{res} \\
 1 & \xrightarrow{g \vee f} & A^\square
 \end{array}$$

The same computation proves the general case for $X \neq 1$ when the comma ∞ -category is constructed in \mathcal{K}_X ; see Proposition 1.2.17 for a description of the simplicial limits in sliced ∞ -cosmoi. Alternatively, a diagram $s: X \rightarrow A^\square$ in \mathcal{K} also defines a X -indexed diagram in the ∞ -cosmos \mathcal{K}_X valued in the ∞ -category $\pi: A \times X \rightarrow X$. This takes the form of a functor $(d, \text{id}_X): X \rightarrow A^\square \times X$ over X . It's easy to verify that a diagram valued in $\pi: A \times X \rightarrow X$ whose component at X is the identity has a limit in \mathcal{K}_X if and only if the A -component of the diagram has a limit in \mathcal{K} . Since id_X is the terminal object of \mathcal{K}_X , this object is the ∞ -category $1 \in \mathcal{K}_X$, so the proof just give applies to prove the general case of X -indexed families of commutative squares. \square

There is an automorphism of the simplicial set 2×2 that swaps the “intermediate” vertices $(0, 1)$ and $(1, 0)$, which induces a “transposition” automorphism of A^\square . By symmetry, a commutative square in A is a pullback if and only if its transposed square is a pullback. This gives a dual form of Lemma 4.3.8 with the roles of f and g and of u and v interchanged. As a corollary, we can easily prove that pullback squares compose both “vertically” and “horizontally” and can be cancelled from the “right” and “bottom”:

4.3.9. PROPOSITION (composition and cancelation of pullback squares). *Given a composable pair of X -indexed commutative squares in A and their composite rectangle defined via the equivalence $A^{3 \times 2} \simeq A^\square \times_{A^2} A^\square$*

$$\begin{array}{ccccc}
 p & \xrightarrow{x} & d & \xrightarrow{u} & b \\
 y \downarrow & \searrow z & \downarrow v & \searrow w & \downarrow f \\
 e & \xrightarrow{h} & c & \xrightarrow{g} & a
 \end{array}$$

if the right-hand square is a pullback, then the left-hand square is a pullback if and only if the composite rectangle is a pullback.

PROOF. By Lemma 4.3.8, we are given an absolute right lifting diagram in \mathcal{K}_X

$$\begin{array}{ccc}
 & \text{Hom}_A(A, c) & \\
 \nearrow \ulcorner v \urcorner & \downarrow \ulcorner g_* \urcorner & \\
 X & \xrightarrow{\ulcorner f \urcorner} & \text{Hom}_A(A, a)
 \end{array}$$

By Lemma 2.4.1, the composite diagram

$$\begin{array}{ccc}
 & \text{Hom}_A(A, e) & \\
 \nearrow \ulcorner y \urcorner & \Downarrow (\text{id}_c, x) & \downarrow \ulcorner h_* \urcorner \\
 & \text{Hom}_A(A, c) & \\
 \nearrow \ulcorner v \urcorner & \Downarrow (\text{id}_a, u) & \downarrow \ulcorner g_* \urcorner \\
 X & \xrightarrow{\ulcorner f \urcorner} & \text{Hom}_A(A, a)
 \end{array}$$

is an absolute right lifting diagram in \mathcal{K}_X if and only if the top triangle is an absolute right lifting diagram in \mathcal{K}_X . By Lemma 4.3.8, this is exactly what we wanted to show. \square

Terminal elements are special cases of limits where the diagram shape is empty. For any ∞ -category A , the ∞ -category of diagrams $A^\emptyset \cong 1$, which tells us that there is a unique \emptyset -indexed diagram in A . In this context, the ∞ -categories of cones over or under the unique diagram constructed in Definition 4.2.1 are isomorphic to A . In the case of cones over an empty diagram, the domain-evaluation functor, carrying a cone to its summit, is the identity on A , while in the case of cones under the empty diagram, the codomain-evaluation functor, carrying a cone to its nadir, is the identity on A . The following characterization of terminal elements can be deduced as a special case of Proposition 4.3.1, though we find it easier to argue from Proposition 4.1.1.

4.3.10. PROPOSITION. *For an element $t: 1 \rightarrow A$ of an ∞ -category A ,*

- (i) *t defines a terminal element of A if and only if the domain-projection functor $p_0: \text{Hom}_A(A, t) \rightarrow A$ is a trivial fibration.*
- (ii) *t defines an initial element of A if and only if the codomain-projection functor $p_1: \text{Hom}_A(t, A) \rightarrow A$ is a trivial fibration.*

PROOF. Recall from Definition 2.2.1, that an element is terminal if and only if it is right adjoint to the unique functor

$$\begin{array}{ccc}
 & ! & \\
 1 & \xleftarrow{\quad} & A \\
 & \xrightarrow{t} &
 \end{array}$$

By Proposition 4.1.1, $! \dashv t$ if and only if there is an equivalence $\text{Hom}_1(!, 1) \simeq_A \text{Hom}_A(A, t)$. By the defining pullback (3.3.2) for the comma ∞ -category, the left representation of $!: A \rightarrow 1$ is A itself, with domain-projection functor the identity. So the component of the equivalence $\text{Hom}_A(A, t) \simeq A$ over A must be the domain projection functor $p_0: \text{Hom}_A(A, t) \rightarrow A$, and we conclude that t is a terminal element if and only if this isofibration is a trivial fibration. \square

4.3.11. DIGRESSION (terminal elements of a quasi-category). In the ∞ -cosmos of quasi-categories the isofibration $p_0: \text{Hom}_A(A, t) \rightarrow A$ is equivalent over A to the *slice quasi-category* A_t , defined as a right adjoint to the join construction of Definition 4.2.4. Proposition 4.3.10 proves that t is terminal if and only if the projection $A_t \rightarrow A$ is a trivial fibration in the sense of Definition 1.1.23, which transposes to Joyal's original definition of a terminal element of a quasi-category. See Appendix F for a full proof.

We conclude with two results that could have been proven in Chapter 2, were it not for one small step of the argument, as we explain. A functor $f: A \rightarrow B$ *preserves* limits if the image of a limit cone in A also defines a limit cone in B . In the other direction, a functor $f: A \rightarrow B$ *reflects* limits if a cone in A that defines a limit cone in B is also a limit cone in A .

4.3.12. PROPOSITION. A fully faithful functor $f: A \rightarrow B$ reflects any limits or colimits that exist in A .

PROOF. The statement for limits asserts that given any family of diagrams $d: D \rightarrow A^J$ of shape J in A , any functor $\ell: D \rightarrow A$ and cone $\rho: \Delta \ell \Rightarrow d$ as below-left so that the whiskered composite with $f^J: A^J \rightarrow B^J$ displayed below is an absolute right lifting diagram

$$\begin{array}{ccccc} & & A & \xrightarrow{f} & B \\ & \nearrow \ell & \downarrow \Delta & & \downarrow \Delta \\ D & \xrightarrow{d} & A^J & \xrightarrow{f^J} & B^J \end{array}$$

then (ℓ, ρ) defines an absolute right lifting of $d: D \rightarrow A^J$ through $\Delta: A \rightarrow A^J$. Our proof strategy mirrors the results of §2.4. By Corollary 3.4.6(i), to say that f is fully faithful is to say that $\text{id}_A: A \rightarrow A$ defines an absolute right lifting of f through itself. So by Lemma 2.4.1 and the hypothesis just stated, the composite diagram below-left is an absolute right lifting diagram, and by 2-functoriality of the simplicial cotensor with J , the diagram below-left coincides with the diagram below-right:

$$\begin{array}{ccccc} & & A & \xrightarrow{f} & B \\ & \nearrow \ell & \downarrow \Delta & & \downarrow \Delta \\ D & \xrightarrow{d} & A^J & \xrightarrow{f^J} & B^J \end{array} = \begin{array}{ccccc} & & A & \xrightarrow{f} & B \\ & \nearrow \ell & \downarrow \Delta & & \downarrow \Delta \\ D & \xrightarrow{d} & A^J & \xrightarrow{f^J} & B^J \end{array}$$

By Corollary 3.4.6(iv) to say that f is fully faithful is to say that $\lceil \text{id}_f \rceil: A^2 \simeq \text{Hom}_B(f, f)$ is a fibered equivalence over $A \times A$. Applying $(-)^J: \mathcal{K} \rightarrow \mathcal{K}$, this maps to a fibered equivalence $\lceil \text{id}_{f^J} \rceil: (A^J)^2 \simeq \text{Hom}_{B^J}(f^J, f^J)$ over $A^J \times A^J$, proving that if $f: A \rightarrow B$ is fully faithful, then $f^J: A^J \rightarrow B^J$ is also.⁴ Hence by Corollary 3.4.6(i), $\text{id}_{A^J}: A^J \rightarrow A^J$ defines an absolute right lifting of f^J through itself. Applying Lemma 2.4.1 again, we now conclude that (ℓ, ρ) is an absolute right lifting of d through Δ as required. \square

An alternate approach to proving this result is suggested as Exercise 4.3.iii.

Our final result, proves that, for I and J simplicial sets, whenever we are given a J -indexed diagram valued in the ∞ -category A^I of I -indexed diagrams in A , its limit may be computed pointwise in the vertices of I as the limit of the corresponding J -indexed diagram in A . Our argument requires the following representable characterization of absolute lifting diagrams whose proof again makes use of the fact that they are preserved by cosmological functors.

4.3.13. PROPOSITION. A natural transformation defined in an ∞ -cosmos \mathcal{K} as below-left is an absolute right lifting diagram if and only if its “externalization” displayed below-right defines a right lifting diagram in \mathbf{QCat}

$$\begin{array}{ccc} & B & \\ r \nearrow & \downarrow f & \\ C & \xrightarrow{g} & A \end{array} \quad \Leftrightarrow \quad \begin{array}{ccc} & \text{Fun}(C, B) & \\ r \nearrow & \downarrow f_* & \\ \mathbb{1} & \xrightarrow{g} & \text{Fun}(C, A) \end{array}$$

⁴This is the statement that we could not yet prove in Chapter 2.

that is preserved by precomposition with any functor $c: X \rightarrow C$ in \mathcal{K} in the sense that the diagram below is also right lifting:

$$\begin{array}{ccc} \text{Fun}(C, B) & \xrightarrow{c^*} & \text{Fun}(X, B) \\ \nearrow r & \Downarrow \rho & \downarrow f_* \\ \mathbb{1} & \xrightarrow{g} & \text{Fun}(C, A) \xrightarrow{c^*} \text{Fun}(X, A) \end{array} = \begin{array}{ccc} & & \text{Fun}(X, B) \\ \nearrow rc & \Downarrow \rho c & \downarrow f_* \\ \mathbb{1} & \xrightarrow{gc} & \text{Fun}(X, C) \end{array}$$

Moreover the externalized right lifting diagrams in \mathcal{QCat} are in fact absolute.

PROOF. Since $\text{Fun}(\mathbb{1}, -): \mathcal{QCat} \rightarrow \mathcal{QCat}$ is naturally isomorphic to the identity functor, for any ∞ -categories $X, A \in \mathcal{K}$ we have $\text{Fun}(X, A) \cong \text{Fun}(\mathbb{1}, \text{Fun}(X, A))$ and hence

$$\text{hFun}(X, A) \cong \text{hFun}(\mathbb{1}, \text{Fun}(X, A)). \quad (4.3.14)$$

This justifies our use of the same name ρ for the 2-cell in $\mathfrak{h}\mathcal{K}$ and the 2-cell in $\mathfrak{h}\mathcal{QCat}$ in the statement.

To say that (r, ρ) defines a right lifting of g through f in $\mathfrak{h}\mathcal{K}$ asserts a bijection between 2-cells in $\text{hFun}(C, B)$ with codomain r and 2-cells in $\text{hFun}(C, A)$ with codomain g and domain factoring through f implemented by pasting with ρ . Under the correspondence of (4.3.14), this asserts equally that r defines a right lifting of g through f_* in $\mathfrak{h}\mathcal{QCat}$. To say that (r, ρ) defines an *absolute* right lifting of g through f is to assert the analogous right lifting property for the pair $(rc, \rho c)$ defined by restricting along any $c: X \rightarrow C$. This is exactly the first claim of the statement.

It remains only to argue that if (r, ρ) is an absolute right lifting diagram in \mathcal{K} , then its externalized right lifting diagram of quasi-categories is also absolute. To see this, first note that the cosmological functor $\text{Fun}(C, -): \mathcal{K} \rightarrow \mathcal{QCat}$ preserves this absolute right lifting diagram, yielding an absolute right lifting diagram of quasi-categories as below left:

$$\begin{array}{ccc} \text{Fun}(C, B) & & \text{Fun}(C, B) \\ \nearrow r_* & \Downarrow \text{Fun}(C, \rho) & \downarrow f_* \\ \text{Fun}(C, C) & \xrightarrow{g_*} & \text{Fun}(C, A) \end{array} \quad \begin{array}{ccc} \text{Fun}(C, B) & & \text{Fun}(C, B) \\ \nearrow r & \Downarrow \rho & \downarrow f_* \\ \mathbb{1} & \xrightarrow{g} & \text{Fun}(C, A) \end{array} = \begin{array}{ccc} & & \text{Fun}(C, B) \\ \nearrow r_* & \Downarrow \text{Fun}(C, \rho) & \downarrow f_* \\ \mathbb{1} \xrightarrow{\text{id}_C} \text{Fun}(C, C) & \xrightarrow{g_*} & \text{Fun}(C, A) \end{array}$$

We obtain the desired absolute right lifting diagram by evaluating at the identity. \square

4.3.15. PROPOSITION. Let I and J be simplicial sets and let A be an ∞ -category. Then a diagram as below-left is an absolute right lifting diagram

$$\begin{array}{ccc} & A^I & \\ \lim \nearrow & \Downarrow \rho & \downarrow \Delta^I \\ D & \xrightarrow{d} & A^{I \times J} \end{array} \quad \begin{array}{ccc} & A^I & \xrightarrow{\text{ev}_i} A \\ \lim \nearrow & \Downarrow \rho & \downarrow \Delta^I \\ D & \xrightarrow{d} & A^{I \times J} \xrightarrow{\text{ev}_i} A^J \end{array}$$

if for each vertex $i \in I$, the diagram above right is an absolute right lifting diagram.

Note this statement is not a biconditional. Even in the case of strict 1-categories, there may exist coincidental limits of diagram valued in functor categories that are not defined pointwise [9, 2.17.10].

PROOF. By Proposition 4.3.13, we may externalize and instead show that the diagram of quasi-categories displayed below left

$$\begin{array}{ccc}
& \text{Fun}(D, A)^I & \\
\lim \nearrow & \Downarrow \rho & \downarrow \Delta^I \\
\mathbb{1} & \xrightarrow{d} \text{Fun}(D, A)^{I \times J} &
\end{array}
\qquad
\begin{array}{ccc}
& \text{Fun}(D, A)^I & \xrightarrow{\text{ev}_i} \text{Fun}(D, A) \\
\lim \nearrow & \Downarrow \rho & \downarrow \Delta^I \\
\mathbb{1} & \xrightarrow{d} \text{Fun}(D, A)^{I \times J} & \xrightarrow{\text{ev}_i} \text{Fun}(D, A)^I
\end{array}$$

is absolute right lifting if the diagrams above-right are for each vertex $i \in I$. By naturality of our methods, our proof will show that the absolute right lifting diagrams on the left are preserved by postcomposition with the restriction functors induced by $d: X \rightarrow D$ if the same is true on the right.

We simplify our notation and write Q for the quasi-category $\text{Fun}(D, A)$ and assume that for each $i \in I$ the diagram

$$\begin{array}{ccc}
& Q^I & \xrightarrow{\text{ev}_i} Q \\
\lim \nearrow & \Downarrow \rho & \downarrow \Delta^I \\
\mathbb{1} & \xrightarrow{d} Q^{I \times J} & \xrightarrow{\text{ev}_i} Q^I
\end{array}$$

is absolute right lifting. By 2-adjunction $(- \times I) \dashv (-)^I$, a diagram as below-left is absolute right lifting if and only if the transposed diagram below-right is a right lifting diagram and this remains the case upon restricting along functors of the form $\pi: X \times I \rightarrow I$.⁵

$$\begin{array}{ccc}
& Q^I & \\
\lim \nearrow & \Downarrow \rho & \downarrow \Delta^I \\
\mathbb{1} & \xrightarrow{d} Q^{I \times J} &
\end{array}
\quad \Leftrightarrow \quad
\begin{array}{ccc}
& Q & \\
\lim \nearrow & \Downarrow \rho & \downarrow \Delta \\
I & \xrightarrow{d} Q^I &
\end{array}
\tag{4.3.16}$$

We'll argue that this right-hand diagram is in fact absolute right lifting, which implies that the left-hand diagram is absolute right lifting as well, as desired.

To see this we appeal to Corollary ??, a consequence of a general theorem proven in Appendix F that universal properties in \mathbf{QCat} are detected pointwise. Specifically, this tells us that the triangle above right is an absolute right lifting diagram if and only if the restricted diagram is absolute right lifting for each vertex $i \in I$

$$\begin{array}{ccc}
& Q & \\
\lim \nearrow & \Downarrow \rho & \downarrow \Delta \\
\mathbb{1} \xrightarrow{i} I & \xrightarrow{d} & Q^I
\end{array}$$

and this is exactly what we have assumed in (4.3.16). \square

⁵If the reader is concerned that I is not a quasi-category, there are two ways to proceed. One is to replace I by a quasi-category I' by inductively attaching fillers for inner horns; note that I and I' will have the same sets of vertices. By Proposition 1.1.27, the diagram quasi-categories $Q^{I'}$ and Q^I are equivalent. The other option is to observe that it doesn't matter if I is a quasi-category or not, because we may define $\mathbf{hFun}(I, Q) := \mathbf{h}(Q^I)$ and by Corollary 1.1.21 Q^I is a quasi-category regardless of whether I is.

Exercises.

4.3.i. EXERCISE. Prove that if A has a terminal element t then for any element a the mapping space $\mathrm{Hom}_A(a, t)$ is **contractible**, i.e., is equivalent to the terminal ∞ -category 1 .

4.3.ii. EXERCISE. Prove that a square in A is a pullback if and only if its “transposed” square, defined by composing with the involution $A^\square \cong A^\square$ induced from the automorphism of 2×2 that swaps the “off-diagonal” elements, is a pullback square.

4.3.iii. EXERCISE ([60, 3.7]). Use Theorem 3.4.3 and Corollary 3.4.6(iv) to prove that a fully faithful functor $f: A \rightarrow B$ reflects all limits or colimits that exist in A . Why does this argument not also show that $f: A \rightarrow B$ preserves them?

4.4. Loops and suspension in pointed ∞ -categories

4.4.1. DEFINITION (pointed ∞ -categories). An ∞ -category A is **pointed** if it admits a **zero element**: an element $*$: $1 \rightarrow A$ that is both initial and terminal.

The counit of the adjunction $*$ \dashv $!$ that witnesses the initiality of the zero element defines a natural transformation $\rho: *! \Rightarrow \mathrm{id}_A$ that we refer to as the **family of points** of A . Dually, the unit of the adjunction $! \dashv *$ that witnesses the terminality of the zero element defines a natural transformation $\xi: \mathrm{id}_A \Rightarrow *!$ that we refer to as the **family of copoints**.

Cospans and spans in an ∞ -category A may be defined by gluing together a pair of arrows along their codomains or domains respectively:

$$\begin{array}{ccc} A^\natural & \longrightarrow & A^2 \\ \downarrow & \lrcorner & \downarrow p_1 \\ A^2 & \xrightarrow{p_1} & A \end{array} \qquad \begin{array}{ccc} A^\Gamma & \longrightarrow & A^2 \\ \downarrow & \lrcorner & \downarrow p_0 \\ A^2 & \xrightarrow{p_0} & A \end{array}$$

For instance, the family of points in a pointed ∞ -category A is represented by a functor $\rho: A \rightarrow A^2$ whose domain-component is constant at $*$ and whose codomain component is id_A . Gluing two copies of this map along their codomain defines a diagram $\check{\rho}: A \rightarrow A^\natural$. Dually, there is a diagram $\hat{\xi}: A \rightarrow A^\Gamma$ defined by gluing the functor $\xi: A \rightarrow A^2$ that represents the family of copoints to itself along their domains.

4.4.2. DEFINITION (loops and suspension). A pointed ∞ -category A **admits loops** if it admits a limit of the family of diagrams

$$\begin{array}{ccc} & & A \\ & \nearrow \Omega & \downarrow \Delta \\ A & \xrightarrow{\check{\rho}} & A^\natural \end{array}$$

in which case the limit functor $\Omega: A \rightarrow A$ is called the **loops functor**. Dually, a pointed ∞ -category A **admits suspensions** if it admits a colimit of the family of diagrams

$$\begin{array}{ccc} & & A \\ & \nwarrow \Sigma & \downarrow \Delta \\ A & \xrightarrow{\hat{\xi}} & A^\Gamma \end{array}$$

in which case the colimit functor $\Sigma: A \rightarrow A$ is called the **suspension functor**.

Importantly, if A admits loops and suspensions, then the loops and suspension functors are adjoint:

4.4.3. PROPOSITION (the loops-suspension adjunction). *If A is a pointed ∞ -category that admits loops and suspensions, then the loops functor is right adjoint to the suspension functor*

$$\begin{array}{ccc} & \Sigma & \\ A & \overset{\perp}{\curvearrowright} & A \\ & \Omega & \end{array}$$

The main idea of the proof is easy to describe. If A admits all pullbacks and all pushouts, then Corollary 4.3.5 supplies adjunctions

$$\begin{array}{ccccc} & \text{res} & & \text{lan} & \\ A^{\sqcup} & \overset{\perp}{\curvearrowright} & A^{\square} & \overset{\perp}{\curvearrowright} & A^{\sqcap} \\ & \text{ran} & & \text{res} & \end{array}$$

that are fibered over $A \times A$ upon evaluating at the intermediate vertices of the commutative square. By pulling back along $(*, *): 1 \rightarrow A \times A$, we can pin these vertices at the zero element. Since the zero element is initial and terminal, the ∞ -categories of pullback and pushout diagrams of this form are both equivalent to A and the pulled-back adjoints now coincide with the loops and suspension functors.

The only subtlety in the proof that follows is that we have assumed weaker hypotheses: that A admits only loops and suspensions, but perhaps not all pullbacks and pushouts.

PROOF. The diagram $\check{\rho}$ lands in a subobject A_*^{\sqcup} of A^{\sqcup} defined below-left that is comprised of those pullback diagrams whose source elements are pinned at the zero element $*$ of A .

$$\begin{array}{ccc} \begin{array}{c} A \\ \downarrow \check{\rho}_* \\ A_*^{\sqcup} \\ \downarrow \\ 1 \end{array} & \xrightarrow{\rho \vee \rho} & \begin{array}{c} A \\ \downarrow \check{\rho}_* \\ A_*^{\sqcup} \\ \downarrow \\ A \times A \end{array} \\ & & \downarrow \scriptstyle{(\ast, \ast)} \\ & & A \times A \end{array} \qquad \begin{array}{ccc} \begin{array}{c} A \\ \downarrow \check{\rho}_* \\ A_*^{\sqcup} \\ \downarrow \\ \text{Hom}_A(\ast, A) \end{array} & \xrightarrow{\rho} & \begin{array}{c} A \\ \downarrow \check{\rho}_* \\ A_*^{\sqcup} \\ \downarrow \\ \text{Hom}_A(\ast, A) \end{array} \\ & & \downarrow \scriptstyle{p_1} \\ & & A \end{array}$$

From a second construction of A_*^{\sqcup} displayed above-right and the characterization of initiality given in Proposition 4.3.10, we may apply the 2-of-3 property of equivalences to conclude first that $\rho: A \simeq \text{Hom}_A(\ast, A)$ and then that the induced diagram $\check{\rho}_*: A \simeq A_*^{\sqcup}$ are equivalences. Dually, the diagram $\check{\xi}: A \rightarrow A^{\sqcap}$ defines an equivalence $\check{\xi}_*: A \simeq A_*^{\sqcap}$ when its codomain is restricted to the subobject of pushout diagrams whose target elements are pinned at the zero element $*$.

By Proposition 4.3.4, a pointed ∞ -category A admits loops or admits suspensions if and only if there exist absolute lifting diagrams as below-left and below-right respectively:

$$\begin{array}{ccc} & A^{\square} & \\ \text{ran} \nearrow & \downarrow \text{res} & \\ A & \xrightarrow{\check{\rho}} & A^{\sqcup} \end{array} \qquad \begin{array}{ccc} & A^{\square} & \\ \text{lan} \nearrow & \downarrow \text{res} & \\ A & \xrightarrow{\check{\xi}} & A^{\sqcap} \end{array}$$

By Theorem 3.4.3 the absolute right lifting diagram defines a right representation $\mathbf{Hom}_{A^\square}(A^\square, \text{ran}) \simeq \mathbf{Hom}_{A^\natural}(\text{res}, \check{\rho})$, this being a fibered equivalence over $A \times A^\square$. The represented comma ∞ -category may be pulled back along the inclusion of the subobject $A_*^\square \hookrightarrow A^\square$ of commutative squares in A whose intermediate vertices are pinned at the zero object:

$$\begin{array}{ccccc}
 & & \mathbf{Hom}_{A^\natural}(\text{res}, \check{\rho}) & \xrightarrow{\quad} & (A^\natural)^2 \\
 & \swarrow & \downarrow & \searrow & \downarrow \\
 \mathbf{Hom}_{A_*^\natural}(\text{res}, \check{\rho}_*) & \xrightarrow{\quad} & (A_*^\natural)^2 & \xrightarrow{\quad} & A^\natural \times A^\natural \\
 \downarrow & \swarrow & \downarrow & \searrow & \downarrow \\
 A_*^\square \times A & \xrightarrow{\quad} & A^\square \times A & \xrightarrow{\text{res} \times \check{\rho}} & A^\natural \times A^\natural \\
 & \searrow & \downarrow & \swarrow & \downarrow \\
 & & A_*^\natural \times A_*^\natural & &
 \end{array}$$

$\text{res} \times \check{\rho}_*$

The right-hand face of this commutative cube is not strictly a pullback but the universal property of the zero element implies that the induced map from $(A_*^\natural)^2$ to the pullback is an equivalence. It follows that $\mathbf{Hom}_{A_*^\natural}(\text{res}, \check{\rho}_*)$ is equivalent over $A_*^\square \times A$ to the pullback of $\mathbf{Hom}_{A^\natural}(\text{res}, \check{\rho})$ along this inclusion and so the fibered equivalence pulls back to define a right representation for $\mathbf{Hom}_{A_*^\natural}(\text{res}, \check{\rho}_*)$. Dually, the left representation for $\mathbf{Hom}_{A^\Gamma}(\xi, \text{res})$ pulls back to a left representation for $\mathbf{Hom}_{A_*^\Gamma}(\xi_*, \text{res})$. By Theorem 3.4.7 these unpack to define absolute lifting diagrams:

$$\begin{array}{ccc}
 \begin{array}{ccc} & A_*^\square & \\ \text{ran} \nearrow & \downarrow \text{res} & \\ A & \xrightarrow{\check{\rho}_*} & A_*^\natural \end{array} & \rightsquigarrow & \begin{array}{ccc} & A_*^\square & \\ \text{ran} \nearrow & \downarrow \text{res} & \\ A_*^\natural & \xrightarrow{\quad} & A_*^\natural \end{array} \\
 \end{array}
 \quad
 \begin{array}{ccc}
 \begin{array}{ccc} & A_*^\square & \\ \text{lan} \nearrow & \downarrow \text{res} & \\ A & \xrightarrow{\xi_*} & A_*^\Gamma \end{array} & \rightsquigarrow & \begin{array}{ccc} & A_*^\square & \\ \text{lan} \nearrow & \downarrow \text{res} & \\ A_*^\Gamma & \xrightarrow{\quad} & A_*^\Gamma \end{array}
 \end{array}$$

Restricting along the inverse equivalences $A_*^\natural \simeq A$ and $A_*^\Gamma \simeq A$ and pasting with the invertible 2-cell we obtain absolute lifting diagrams whose bottom edge is the identity.

By Lemma 2.3.6, these lifting diagrams define adjunctions:

$$\begin{array}{ccccc}
 & \text{res} & & \text{lan} & \\
 A \simeq A_*^\natural & \xleftarrow{\quad} & A_*^\square & \xleftarrow{\quad} & A_*^\Gamma \simeq A \\
 & \text{ran} & & \text{res} & \\
 & \perp & & \perp &
 \end{array}$$

which compose to the desired adjunction $\Sigma \dashv \Omega$. □

4.4.4. DEFINITION. An arrow $f: 1 \rightarrow A^2$ from x to y in a pointed ∞ -category A **admits a fiber** if A admits a pullback of the diagram defined by gluing f to the component ρy of the family of points. By Proposition 4.3.4 such pullbacks give rise to a pullback square

$$\begin{array}{ccc}
 & A^\square & \\
 \text{ran} \nearrow & \downarrow \text{res} & \\
 1 & \xrightarrow{\rho y \vee f} & A^\natural
 \end{array}$$

that is referred to as the **fiber sequence** for f . Dually, f **admits a cofiber** if A admits a pushout of the diagram defined by gluing f to the component ξx of the family of copoints, in which case the pushout

square

$$\begin{array}{ccc} & & A^{\square} \\ \text{lan} \nearrow & \cong \Uparrow & \downarrow \text{res} \\ 1 & \xrightarrow{\xi x \vee f} & A^{\Gamma} \end{array}$$

defines the **cofiber sequence** for f .

Fiber and cofiber sequences define commutative squares in A whose lower-left vertex is the zero element $*$. The data of such squares is given by a commutative triangle in A — an element of A^3 — together with a **nullhomotopy** of the diagonal edge, a witness that this edge factors through the zero element in $\mathbf{h}A$. Borrowing a classical term from homological algebra, a commutative square in A whose lower-left vertex is the zero element is referred to as a **triangle** in A .

4.4.5. DEFINITION (stable ∞ -category). A **stable ∞ -category** is a pointed ∞ -category A in which

- (i) every morphism admits a fiber and a cofiber: that is, there exist absolute lifting diagrams

$$\begin{array}{ccc} & & A^{\square} \\ \text{ran} \nearrow & \cong \Downarrow & \downarrow \text{res} \\ A^2 & \xrightarrow{\rho \vee \text{id}} & A^{\downarrow} \end{array} \quad \begin{array}{ccc} & & A^{\square} \\ \text{lan} \nearrow & \cong \Uparrow & \downarrow \text{res} \\ A^2 & \xrightarrow{\xi \vee \text{id}} & A^{\Gamma} \end{array}$$

- (ii) and a triangle in A defines a fiber sequence if and only if it also defines a cofiber sequence. Such triangles are called **exact**.

A stable ∞ -category admits loops and admits suspensions, formed by taking fibers of the arrows in the family of points and cofibers of arrows in the family of copoints respectively.

4.4.6. PROPOSITION. If A is a stable ∞ -category, then $\Sigma \dashv \Omega$ are inverse equivalences.

PROOF. In the proof of Proposition 4.4.3, the adjunction $\Sigma \dashv \Omega$ is constructed as a composite of adjunctions

$$\begin{array}{ccccc} & & \text{res} & & \text{lan} \\ & \swarrow & & \nwarrow & \\ A \simeq A_*^{\downarrow} & \perp & A_*^{\square} & \perp & A_*^{\Gamma} \simeq A \\ & \searrow & & \swarrow & \\ & \text{ran} & & \text{res} & \end{array}$$

that construct fiber and cofiber sequences. By Proposition 2.1.9, the unit and counit of this composite adjunction are given by

$$\begin{array}{ccc} A \xrightarrow{\quad} A \\ \text{lan} \searrow \quad \swarrow \text{res} \\ A_*^{\square} \xrightarrow{\quad} A_*^{\square} \\ \text{res} \searrow \quad \swarrow \text{ran} \\ A \xrightarrow{\quad} A \end{array} \quad \begin{array}{ccc} A \xrightarrow{\quad} A \\ \text{res} \searrow \quad \swarrow \text{lan} \\ A_*^{\square} \xrightarrow{\quad} A_*^{\square} \\ \text{ran} \searrow \quad \swarrow \text{res} \\ A \xrightarrow{\quad} A \end{array}$$

By Definition 4.3.7, the unit of $\text{res} \dashv \text{ran}$ restricts to an isomorphism on the subobject of pushout squares. In a stable ∞ -category, the cofiber sequences in the image of $\text{lan}: A \rightarrow A_*^{\square}$ are pullback squares, so this tells us that ηlan is an isomorphism. Dually, the fiber sequences in the image of

$\text{ran}: A \rightarrow A_*^\square$ are pushout squares, which tells us that ϵran is an isomorphism. Hence, the unit and counit of $\Sigma \dashv \Omega$ are invertible, so these functors define an adjoint equivalence. \square

4.4.7. PROPOSITION (finite limits and colimits in stable ∞ -categories). *A stable ∞ -category admits all pushouts and all pullbacks, and moreover, a square is pushout if and only if it is a pullback.*

PROOF. Given a cospan $g \vee f: X \rightarrow A^\natural$ in A , form the cofiber of f followed by the fiber of the composite map $c \rightarrow a \rightarrow \text{coker } f$:

$$\begin{array}{ccccc} \ker(qg) & \xrightarrow{-u-} & b & \longrightarrow & * \\ \downarrow v & \lrcorner & \downarrow f & \lrcorner & \downarrow \\ c & \xrightarrow{g} & a & \xrightarrow{-q-} & \text{coker}(f) \end{array}$$

By Definition 4.4.5(ii), the cofiber sequence $b \rightarrow a \rightarrow \ker f$ is also a fiber sequence. By the pullback cancellation result of Proposition 4.3.9, we conclude that $\ker(qg)$ computes the pullback of the cospan $g \vee f$.

To see that this pullback square is also a pushout, form the fiber of the map v :

$$\begin{array}{ccccc} \ker(v) & \xrightarrow{- - -} & \ker(qg) & \xrightarrow{u} & b \\ \downarrow & \lrcorner & \downarrow v & \lrcorner & \downarrow f \\ * & \longrightarrow & c & \xrightarrow{g} & a \end{array}$$

By the pullback composition result of Proposition 4.3.9, $\ker(v)$ is also the fiber of the map f . By Definition 4.4.5(ii), the fiber sequences $\ker(v) \rightarrow \ker(qg) \rightarrow c$ and $\ker(v) \rightarrow b \rightarrow a$ are also cofiber sequences. Now by the pushout cancellation result of Proposition 4.3.9, we see that the right-hand pullback square is also a pushout square. A dual argument proves that pushouts coincide with pullbacks. \square

Exercises.

4.4.i. EXERCISE. Arguing in the homotopy category, show that if an ∞ -category A

- admits an initial element i ,
- admits a terminal element t , and
- there exists an arrow $t \rightarrow i$

then A is a pointed ∞ -category.

Fibrations and Yoneda's lemma

The fibers E_b of an isofibration $p: E \twoheadrightarrow B$ over an element $b: 1 \rightarrow B$ are necessarily ∞ -categories, so it is natural to ask where the isofibration also encodes the data of functors between the fibers in this family of ∞ -categories. Roughly speaking, an isofibration defines a *cartesian fibration* just when the arrows of B act contravariantly functorially on the fibers and a *cocartesian fibration* when the arrows of B act covariantly functorially on the fibers. This action is not strict but rather *pseudofunctorial* or homotopy coherent in a sense that will be made precise when we study the comprehension construction.

One of the properties that characterizes cocartesian fibrations is an axiom that says that for any 2-cell with codomain B and specified lift of its source 1-cell, there is a lifted 2-cell with codomain E with that one cell as its source. In particular, this lifting property can be applied in the case where the 2-cell in question is a whiskered composite of an arrow in the homotopy category of B as below-left and the lift of the source 1-cell is the canonical inclusion of its fiber:

$$\begin{array}{ccc}
 \begin{array}{ccc}
 E_a & \xrightarrow{\ell_a} & E \\
 \downarrow & \lrcorner & \downarrow p \\
 1 & \xrightarrow{a} & B \\
 & \Downarrow \beta & \\
 & b &
 \end{array}
 & = &
 \begin{array}{ccc}
 E_a & \xrightarrow{\ell_a} & E \\
 \downarrow \beta_* & \Downarrow \chi_\beta & \downarrow p \\
 E_b & \xrightarrow{\beta_*(\ell_a)} & E \\
 & \lrcorner & \\
 & \ell_b & \\
 & \downarrow & \\
 & B &
 \end{array}
 \end{array}
 \tag{5.0.1}$$

In this case the codomain $\beta_*(\ell_a)$ of the lifted cell χ_β displayed above right lies strictly above the codomain of the original 2-cell, and thus factors through the pullback defining its fiber. This defines a functor $\beta_*: E_a \rightarrow E$, the “action” of the arrow β on the fibers of p . The pseudofunctoriality of these action maps arises from a universal property required of the specified lifted 2-cells, namely that they are *cartesian* in a sense we now define.

5.1. The 2-category theory of cartesian fibrations

There is a standard notion of cartesian fibration in a 2-category developed by Street [55] that recovers the Grothendieck fibrations when specialized to the 2-category \mathbf{Cat} . This is *not* the correct notion of cartesian fibration between ∞ -categories as the universal property the usual notion demands of lifted 2-cells is too strict. Instead of referring to the notions defined here as “weak,” we would prefer to refer to the classical notion of cartesian fibration in a 2-category as “strict” were we to refer to it again, which we largely will not.

To remind the reader of the interpretation of the data in the homotopy 2-category of an ∞ -cosmos, we refer to 1- and 2-cells as “functors” and “natural transformations.” Before defining the notion of

cartesian fibration we describe the weak universal property enjoyed by a certain class of “upstairs” natural transformations.

5.1.1. DEFINITION (p -cartesian transformations). Let $p: E \rightarrow B$ be an isofibration. A natural transformation $X \begin{smallmatrix} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{smallmatrix} E$ with codomain E is p -**cartesian** if

(i) **induction**: Given any natural transformations $X \begin{smallmatrix} \xrightarrow{e''} \\ \Downarrow \tau \\ \xrightarrow{e} \end{smallmatrix} E$ and $X \begin{smallmatrix} \xrightarrow{pe''} \\ \Downarrow \gamma \\ \xrightarrow{pe'} \end{smallmatrix} B$ so that $p\tau =$

$p\chi \cdot \gamma$, there exists a lift $X \begin{smallmatrix} \xrightarrow{e''} \\ \Downarrow \bar{\gamma} \\ \xrightarrow{e'} \end{smallmatrix} E$ of γ so that $\tau = \chi \cdot \bar{\gamma}$.

$$\begin{array}{ccc} \begin{array}{c} e'' \xrightarrow{\tau} e \\ \gamma \Downarrow \Delta e' \nearrow \chi \end{array} & \in & \text{hFun}(X, E) \\ \Downarrow & & \downarrow p_* \\ \begin{array}{c} pe'' \xrightarrow{p\tau} pe \\ \gamma \Downarrow \Delta pe' \nearrow p\chi \end{array} & \in & \text{hFun}(X, B) \end{array}$$

(ii) **conservativity**: Any fibered endomorphism of χ is invertible: if $X \begin{smallmatrix} \xrightarrow{e'} \\ \Downarrow \zeta \\ \xrightarrow{e'} \end{smallmatrix} E$ is any natural transformation so that $\chi \cdot \zeta = \chi$ and $p\zeta = \text{id}_{pe'}$, then ζ is invertible.

5.1.2. REMARK (why “cartesian”). The induction property for a p -cartesian natural transformation $\chi: e' \Rightarrow e$ says that for any $e'': X \rightarrow E$, there is a surjective function from the set $\text{hFun}(X, E)(e'', e')$ of natural transformations from e'' to e' to the pullback induced in the commutative square

$$\begin{array}{ccc} \text{hFun}(X, E)(e'', e') & \xrightarrow{\chi \circ -} & \text{hFun}(X, E)(e'', e) \\ p \downarrow & & \downarrow p \\ \text{hFun}(X, B)(pe'', pe') & \xrightarrow{p\chi \circ -} & \text{hFun}(X, B)(pe'', pe) \end{array}$$

Were the induction property strict and not weak, this square would be a pullback, i.e., a “cartesian” square.

It follows that p -cartesian lifts of a given 2-cell with specified codomain are unique up to fibered isomorphism:

5.1.3. LEMMA (uniqueness of cartesian lifts). If $X \begin{smallmatrix} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{smallmatrix} E$ and $X \begin{smallmatrix} \xrightarrow{e''} \\ \Downarrow \chi' \\ \xrightarrow{e} \end{smallmatrix} E$ are p -cartesian lifts of a common 2-cell $p\chi$, then there exists an invertible 2-cell $X \begin{smallmatrix} \xrightarrow{e''} \\ \Downarrow \zeta \\ \xrightarrow{e'} \end{smallmatrix} E$ so that $\chi' = \chi \cdot \zeta$ and $p\zeta = \text{id}$. \square

PROOF. By induction, there exists 2-cells $\zeta: e'' \Rightarrow e'$ and $\zeta': e' \Rightarrow e''$ so that $\chi' = \chi \cdot \zeta$ and $\chi = \chi' \cdot \zeta'$ with $p\zeta = p\zeta' = \text{id}$. The composites $\zeta \cdot \zeta'$ and $\zeta' \cdot \zeta$ are then fibered automorphisms of χ and χ' and thus invertible by conservativity. Now the 2-of-6 property for isomorphisms implies that ζ and ζ' are also isomorphisms (though perhaps not inverses). \square

We frequently make use of the isomorphism stability of the p -cartesian transformations given by the following suite of observations:

5.1.4. LEMMA. *Let $p: E \rightarrow B$ be an isofibration.*

- (i) *Isomorphisms define p -cartesian transformations.*
- (ii) *Any p -cartesian lift of an identity is a natural isomorphism.*
- (iii) *The class of p -cartesian transformations is closed under pre- and post-composition with natural isomorphisms.*

PROOF. Exercise 5.1.i. \square

Furthermore:

5.1.5. LEMMA (more conservativity). *If $X \xrightarrow[e]{\Downarrow \chi} E$, $X \xrightarrow[e]{\Downarrow \chi'} E$, and $X \xrightarrow[e']{\Downarrow \zeta} E$ are 2-cells so that χ and χ' are p -cartesian, $\chi' = \chi \cdot \zeta$, and $p\zeta$ is invertible, then ζ is invertible.*

PROOF. Given the data in the statement we can use the induction property for χ' applied to the pair $(\chi, p\zeta^{-1})$ to induce a candidate inverse $\hat{\zeta}$ for ζ and then apply the conservativity property to conclude that $\zeta \cdot \hat{\zeta}$ and $\hat{\zeta} \cdot \zeta$ are both isomorphisms. By the 2-of-6 property, ζ is an isomorphism, as desired. \square

We now introduce the class of cartesian fibrations.

5.1.6. DEFINITION (cartesian fibration). An isofibration $p: E \rightarrow B$ is a **cartesian fibration** if

- (i) Any natural transformation $\beta: b \Rightarrow pe$ as below-left admits a p -cartesian lift¹ $\chi_\beta: \beta^*e \Rightarrow e$ as below-right:

$$\begin{array}{ccc} X & \xrightarrow{e} & E \\ & \Downarrow \beta & \downarrow p \\ & b & B \end{array} = \begin{array}{ccc} X & \xrightarrow[\beta^*e]{\Uparrow \chi_\beta} & E \\ & \downarrow p & \\ & B & \end{array}$$

- (ii) The class of p -cartesian transformations is closed under restriction: that is, if $X \xrightarrow[e]{\Downarrow \chi} E$ is

p -cartesian and $f: Y \rightarrow X$ is any functor then $Y \xrightarrow[ef]{e'f} E$ is p -cartesian.

The lifting property (i) implies that a p -cartesian transformation $\chi: e' \Rightarrow e$ is the “universal natural transformation over $p\chi$ with codomain e ” in the following weak sense: any transformation

¹To ask that $\chi_\beta: \beta^*e \Rightarrow e$ is a **lift** of $\beta: b \Rightarrow pe$ asserts that $p\chi_\beta = \beta$ and hence $p\beta^*e = b$.

$\psi: e' \Rightarrow e$ factors through a p -cartesian lift $\chi_\psi: (p\psi)^*e \Rightarrow e$ of $p\psi$ via a 2-cell $\gamma: e' \Rightarrow (p\psi)^*e$ over an identity, and moreover ψ is p -cartesian if and only if this factorization γ is invertible.

The reason for condition (ii) will become clearer in §5.3. For now, note that since all p -cartesian lifts of a given 2-cell β are isomorphic and the class of p -cartesian cells is stable under isomorphism, to verify the condition (ii) it suffices to show that for any functor $f: Y \rightarrow X$ there is *some* p -cartesian lift of β that restricts along f to another p -cartesian transformation.

5.1.7. LEMMA (composites of cartesian fibrations). *If $p: E \twoheadrightarrow B$ and $q: B \twoheadrightarrow A$ are cartesian fibrations, then so is $qp: E \twoheadrightarrow A$. Moreover, a natural transformation $X \begin{smallmatrix} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{smallmatrix} E$ is qp -cartesian if and only if χ is p -cartesian and $p\chi$ is q -cartesian.*

PROOF. The first claim follows immediately from the second, for the lifts required by Definition 5.1.6(i) can be constructed by first taking a q -cartesian lift χ_β and then taking a p -cartesian lift χ_{χ_β} of this lifted cell.

$$\begin{array}{ccccc} X & \xrightarrow{e} & E & & X & \xrightarrow{e} & E & & X & \xrightarrow{e} & E \\ & \Uparrow \beta & \downarrow p & & & \Uparrow \chi_\beta & \downarrow p & & & \Uparrow \chi_{\chi_\beta} & \downarrow p \\ & & B & = & & B & = & & & B \\ & \searrow a & \downarrow q & & \searrow b & \downarrow q & & & & \downarrow q & A \\ & & A & & & A & & & & A \end{array}$$

and the stability condition 5.1.6(ii) is then inherited from the stability of p - and q -cartesian transformations.

To prove the second claim, first consider a natural transformation $X \begin{smallmatrix} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{smallmatrix} E$ that is p -cartesian and so that $p\chi$ is q -cartesian. Given any natural transformations $X \begin{smallmatrix} \xrightarrow{e''} \\ \Downarrow \tau \\ \xrightarrow{e} \end{smallmatrix} E$ and $X \begin{smallmatrix} \xrightarrow{qpe''} \\ \Downarrow \gamma \\ \xrightarrow{qpe'} \end{smallmatrix} A$ so that $qp\tau = qp\chi \cdot \gamma$, q -cartesianness of $p\chi$ induces a lift $X \begin{smallmatrix} \xrightarrow{e''} \\ \Downarrow \hat{\gamma} \\ \xrightarrow{e'} \end{smallmatrix} B$ of γ so that $p\tau = p\chi \cdot \hat{\gamma}$.

Now p -cartesianness of χ induces a further lift $X \begin{smallmatrix} \xrightarrow{e''} \\ \Downarrow \bar{\gamma} \\ \xrightarrow{e'} \end{smallmatrix} E$ of $\hat{\gamma}$ so that $\tau = \chi \cdot \bar{\gamma}$. Moreover, if

$X \begin{smallmatrix} \xrightarrow{e'} \\ \Downarrow \zeta \\ \xrightarrow{e'} \end{smallmatrix} E$ is any natural transformation so that $\chi \cdot \zeta = \chi$ and $qp\zeta = \text{id}$ then $p\chi \cdot p\zeta = p\chi$ and by conservativity for $p\chi$, $p\zeta$ is invertible. Applying Lemma 5.1.5, we conclude that ζ is invertible. This proves that χ is qp -cartesian.

Conversely, if χ is qp -cartesian, then Lemma 5.1.3 implies it is isomorphic to all other qp -cartesian lifts of $qp\chi$. The construction given above produces a qp -cartesian lift of any 2-cell that is p -cartesian

and whose image under p is q -cartesian. By the isomorphism stability of p - and q -cartesian transformations of Lemma 5.1.4, χ must also have these properties. \square

The following lemma proves that cartesian fibrations come equipped with a “generic p -cartesian transformation.”

5.1.8. LEMMA. *An isofibration $p: E \twoheadrightarrow B$ is a cartesian fibration if and only if the right comma cone over p displayed below-left admits a lift χ as displayed below-right:*

$$\begin{array}{ccc} \text{Hom}_B(B, p) & \xrightarrow{p_1} & E \\ & \uparrow \phi & \downarrow p \\ & & B \end{array} \quad \begin{array}{ccc} \text{Hom}_B(B, p) & \xrightarrow{p_1} & E \\ & \uparrow \chi & \downarrow p \\ & & B \end{array} \quad (5.1.9)$$

with the property that the restriction of χ along any $X \rightarrow \text{Hom}_B(B, p)$ is a p -cartesian transformation.

PROOF. If $p: E \twoheadrightarrow B$ is cartesian, then the right comma cone ϕ admits a p -cartesian lift $\chi: r \Rightarrow p_1$ by 5.1.6(i), which by 5.1.6(ii) has the property that the restriction of this p -cartesian transformation along any $X \rightarrow \text{Hom}_B(B, p)$ is also p -cartesian.

For the converse, suppose we are given the generic p -cartesian transformation $\chi: r \Rightarrow p_1$ of the statement and consider a 2-cell $\beta: b \Rightarrow pe$ as below-left.

$$\begin{array}{ccc} X & \xrightarrow{e} & E \\ & \Downarrow \beta & \downarrow p \\ & & B \end{array} \quad = \quad \begin{array}{ccc} X & \xrightarrow{e} & E \\ & \searrow \beta & \downarrow p \\ & & B \end{array} \quad = \quad \begin{array}{ccc} X & \xrightarrow{e} & E \\ & \searrow \beta & \downarrow p \\ & & B \end{array}$$

By 1-cell induction $\beta = \phi \circ \beta'$ for some functor $\beta': X \rightarrow \text{Hom}_B(B, p)$ as above-center. By substituting the equation (5.1.9) as above-right, we see that $\chi \circ \beta'$ is a lift of β whose codomain is $p_1 \circ \beta' = e$, as required. The hypothesis that restrictions of χ are p -cartesian implies that this lift is a p -cartesian transformation.

Now Lemma 5.1.3 implies that any p -cartesian natural transformation is isomorphic to a restriction of χ . Thus restrictions of p -cartesian transformations are isomorphic to restrictions of χ , and it follows from Lemma 5.1.4 that the class of p -cartesian transformation is closed under restriction. \square

The first major result of this section is an internal characterization of cartesian fibrations inspired by a similar result of Street [55, 58, 59]; see also [63]. Before stating this result, recall from Lemma 3.4.8 that from a functor $p: E \twoheadrightarrow B$, we can build a fibered adjunction $p_1 \dashv_E i$, where the right adjoint is induced from the identity 2-cell id_p :

$$\begin{array}{ccc} \begin{array}{ccc} E & & \\ \downarrow i & & \downarrow p \\ \text{Hom}_B(B, p) & & \\ \uparrow p_1 & \phi & \uparrow p_0 \\ E & \xrightarrow{p} & B \end{array} & = & \begin{array}{ccc} E & & \\ & \searrow p & \\ E & \xrightarrow{p} & B \end{array} \quad \rightsquigarrow \quad \begin{array}{ccc} & p_1 & \\ & \swarrow & \searrow \\ E & \perp & \text{Hom}_B(B, p) \\ & \swarrow i & \searrow p_1 \\ & E & \end{array} \end{array}$$

$$\begin{array}{ccc}
\begin{array}{c} E^2 \\ \downarrow p_1 \quad \downarrow p_0 \\ E \\ \downarrow p \\ B \end{array} & = & \begin{array}{c} \begin{array}{ccc} E^2 & & E^2 \\ \downarrow p_1 & \searrow k & \downarrow p_0 \\ & \text{Hom}_B(B, p) & \\ \downarrow p_1 & \swarrow \phi & \downarrow p_0 \\ E & \xrightarrow{p} & B \end{array} \end{array} \quad (5.1.10)
\end{array}$$

- (i) $p: E \twoheadrightarrow B$ defines a cartesian fibration.
- (ii) The functor $i: E \rightarrow \mathbf{Hom}_B(B, p)$ admits a right adjoint over B :

(iii) The functor $k: E^2 \rightarrow \text{Hom}_B(B, p)$ admits a right adjoint with invertible counit:

When these equivalent conditions hold, then for a natural transformation $X \begin{matrix} \xrightarrow{e'} \\ \Downarrow \psi \\ \xrightarrow{e} \end{matrix} E$ the following are equivalent:

- $$\begin{array}{c}
\begin{array}{ccc}
X & \begin{array}{c} \xrightarrow{e} \\ \uparrow \psi \\ \xrightarrow{e'} \end{array} & E
\end{array} \\
= & \begin{array}{ccccc}
X & \xrightarrow{-r p \psi} & \text{Hom}_B(B, p) & \begin{array}{c} \xrightarrow{\uparrow \epsilon} \\ \text{---} \end{array} & \text{Hom}_B(B, p) \xrightarrow{-p_1} E \\
& \begin{array}{c} \text{---} \\ \text{---} \end{array} & \xrightarrow{\cong \uparrow \gamma} & E & \begin{array}{c} \xrightarrow{i} \\ \text{---} \end{array} \\
& \text{---} & \text{---} & \text{---} & \text{---} \\
& \text{---} & \text{---} & \text{---} & \text{---}
\end{array}
\end{array}$$

- $$X \xrightarrow{[\psi]} E^2 \begin{array}{c} \xrightarrow{\quad} \\ \Downarrow \bar{\eta} \\ \xrightarrow{\quad} \end{array} E^2$$

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The right adjoint of (ii) is the domain-component of the generic cartesian lift of (5.1.9); that cartesian transformation is then recovered as $p_1\epsilon$, where ϵ is the counit of the fibered adjunction $i \dashv r$. This explains the statement of (v). By 1-cell induction, the generic cartesian lift χ can be represented by a functor $\bar{r}: \mathbf{Hom}_B(B, p) \rightarrow E^2$ and this defines the right adjoint of (iii) and explains the statement of (vi).

Before proving Theorem 5.1.11 we make two further remarks on these postulated adjunctions.

5.1.12. REMARK. By Lemma 3.4.8, the functor $i: E \rightarrow \mathbf{Hom}_B(B, p)$ is itself a right adjoint over B to the codomain-projection functor. Since the counit of the adjunction $p_1 \dashv i$ is an isomorphism, it follows formally that the unit of the adjunction $i \dashv r$ must also be an isomorphism, whenever the adjunction postulated in (ii) exists; see Lemma B.3.2.

5.1.13. REMARK. In the case where the ∞ -categories E^2 and $\mathbf{Hom}_B(B, p)$ are defined by the strict simplicial limits of Definitions 3.2.1 and 3.3.1, the 1-cell k induced in (5.1.10) can be modeled by an isofibration:

$$\begin{array}{ccccc}
 E^2 & & \xrightarrow{p^2} & & B^2 \\
 \downarrow k & & & & \downarrow p_1 \\
 \mathbf{Hom}_B(B, p) & \xrightarrow{\quad} & & & B \\
 \downarrow p_1 & \lrcorner & & & \downarrow p_1 \\
 E & \xrightarrow{\quad p \quad} & & & B
 \end{array}$$

namely the Leibniz cotensor of the codomain inclusion $1: \mathbb{1} \hookrightarrow \mathbb{2}$ and the isofibration $p: E \twoheadrightarrow B$. Now Lemma 3.5.9 can be used to rectify the adjunction $k \dashv r$ of (iii) to a right adjoint right inverse adjunction, that is then fibered over $\mathbf{Hom}_B(B, p)$. So when Theorem 5.1.11(iii) holds, we may model the postulated adjunction by a right adjoint right inverse to the isofibration k .

PROOF. We'll prove (i) \Rightarrow (iii) \Rightarrow (ii) \Rightarrow (i) and demonstrate the equivalences (iv) \Leftrightarrow (vi) and (iv) \Leftrightarrow (v) in parallel.

(i) \Rightarrow (iii): If $p: E \twoheadrightarrow B$ is cartesian, then the right comma cone over p admits a cartesian lift along p ,

$$\begin{array}{ccc}
 \mathbf{Hom}_B(B, p) & \xrightarrow{p_1} & E \\
 \downarrow p_0 & \Uparrow \phi & \downarrow p \\
 & & B
 \end{array}
 =
 \begin{array}{ccc}
 \mathbf{Hom}_B(B, p) & \xrightarrow{p_1} & E \\
 \downarrow p_0 & \Uparrow \chi & \downarrow p \\
 & & B
 \end{array}$$

defining a functor $r: \mathbf{Hom}_B(B, p) \rightarrow E$ over B together with a p -cartesian transformation $\chi: r \Rightarrow p_1$. By 1-cell induction, this generic cartesian transformation is represented by a functor

$$\begin{array}{ccc}
 \mathbf{Hom}_B(B, p) & \xrightarrow{r} & E \\
 \downarrow p_0 & \Downarrow \chi & \downarrow p_1
 \end{array}
 =
 \mathbf{Hom}_B(B, p) \xrightarrow{\bar{r}} E^2 \begin{array}{c} \xrightarrow{p_0} \\ \Downarrow \kappa \\ \xrightarrow{p_1} \end{array} E$$

which we take as our definition of the putative right adjoint \bar{r} . By the definition (5.1.10) of k , $\phi k \bar{r} = p \kappa \bar{r} = p \chi = \phi$, so Proposition 3.3.7 supplies a fibered isomorphism $\bar{\epsilon}: k \bar{r} \cong \text{id}$ with $p_0 \bar{\epsilon} = \text{id}_{p_0}$ and $p_1 \bar{\epsilon} = \text{id}_{p_1}$.

To prove that $k \dashv \bar{r}$, it remains to define the unit 2-cell $\bar{\eta}$, which we do by 2-cell induction from a pair given by an identity 2-cell $p_1 \bar{\eta} = \text{id}_{p_1}$ and a 2-cell $p_0 \bar{\eta}$ that remains to be specified. The required compatibility condition of Proposition 3.3.6(ii) asserts that this $p_0 \bar{\eta}$ must define a factorization of the generic arrow

$$\begin{array}{ccc} p_0 & \xrightarrow{\kappa} & p_1 \\ p_0 \bar{\eta} \Downarrow & & \parallel_{p_1 \bar{\eta} = \text{id}} \\ p_0 \bar{r} k = r k & \xRightarrow{\chi k} & p_1 k \end{array} \quad (5.1.14)$$

through $\kappa \bar{r} k = \chi k$. Note $p\kappa = \phi k$ has χk as its p -cartesian lift, so we define $p_0 \bar{\eta}$ by the induction property for the cartesian transformation χk applied to the generic arrow $\kappa: p_0 \Rightarrow p_1$. By construction $pp_0 \bar{\eta} = \text{id}$.

By Lemma B.4.1, once we verify that $k \bar{\eta}$ and $\bar{\eta} \bar{r}$ are invertible, then this data together with $\bar{e}: k \bar{r} \cong \text{id}$ defines an adjunction with invertible counit. We prove $k \bar{\eta}$ is invertible by 2-cell conservativity: $p_1 k \bar{\eta} = p_1 \bar{\eta} = \text{id}$ and $p_0 k \bar{\eta} = pp_0 \bar{\eta} = \text{id}$.

Similarly, by 2-cell conservativity, to conclude that $\bar{\eta} \bar{r}$ is invertible, it suffices to prove that $p_0 \bar{\eta} \bar{r}$ is an isomorphism. Restricting (5.1.14) along \bar{r} , we see that $p_0 \bar{\eta} \bar{r}$ defines a fibered isomorphism of p -cartesian transformations

$$\begin{array}{ccc} r & \xrightarrow{\chi} & p_1 \\ p_0 \bar{\eta} \bar{r} \searrow & & \nearrow \chi k \bar{r} \\ & p_0 \bar{r} k = r k & \end{array}$$

so this follows from Lemma 5.1.5.

Finally note that a transformation $\psi: e' \Rightarrow e$ is p -cartesian if and only if its factorization through the generic p -cartesian lift of $p\psi$ is invertible. This factorization may be constructed by restricting the 2-cells of (5.1.14) along $\ulcorner \psi \urcorner: X \rightarrow E^2$ since $\kappa \ulcorner \psi \urcorner = \psi$, so we see that ψ is p -cartesian if and only if $p_0 \bar{\eta} \ulcorner \psi \urcorner$ is invertible. By 2-cell conservativity, $\bar{\eta} \ulcorner \psi \urcorner$ is invertible if and only if its domain component is invertible. This proves that (iv) \Leftrightarrow (vi).

(iii) \Rightarrow (ii): By Remark 5.1.13, we can model the left adjoint of (iii) by an isofibration $k: E^2 \twoheadrightarrow \text{Hom}_B(B, p)$ and use Lemma 3.5.9 to rectify the adjunction $k \dashv \bar{r}$ with invertible counit into a right adjoint right inverse adjunction, that is then fibered over $\text{Hom}_B(B, p)$. Composing with the projection $p_0: \text{Hom}_B(B, p) \twoheadrightarrow B$, Lemma 3.5.7(ii) then gives us a fibered adjunction over B

$$\begin{array}{ccc} E^2 & \xrightleftharpoons[k]{k} & \text{Hom}_B(B, p) \\ & \perp & \\ pp_0 \swarrow & \bar{r} & \nwarrow p_0 \\ & B & \end{array}$$

By the dual of Lemma 3.4.8, the 1-cell $j: E \rightarrow E^2$ induced by the identity defines a left adjoint right inverse to the domain projection

$$\begin{array}{ccc} E & \xrightleftharpoons[p_0]{j} & E^2 \\ & \perp & \\ & p_1 & \end{array} \quad (5.1.15)$$

supplying a fibered adjunction $j \dashv p_0$ over E that we push forward along $p: E \twoheadrightarrow B$ to a fibered adjunction over B :

$$\begin{array}{ccc}
 E & \xrightleftharpoons[j]{j} & E^2 \\
 & \perp & \\
 & \swarrow p \quad \searrow p_0 & \\
 & B & \swarrow pp_0
 \end{array}$$

This pair of fibered adjunctions composes to define a fibered adjunction over B with left adjoint kj and right adjoint $r := p_0 \bar{r}$. Proposition 3.3.7 supplies a fibered isomorphism $i \cong kj$ since both i and kj define functors $E \rightrightarrows \mathbf{Hom}_B(B, p)$ induced by the identity id_p over the right comma cone over p . Composing with this fibered isomorphism, we can replace the left adjoint of the composite adjunction by i

$$\begin{array}{ccc}
 \begin{array}{ccc}
 E & \xrightleftharpoons[j]{i} & E^2 \\
 & \perp & \\
 & \swarrow p_0 \quad \searrow pp_0 & \\
 & B & \swarrow p_0
 \end{array}
 & = &
 \begin{array}{ccc}
 E & \xrightleftharpoons[r]{i} & \mathbf{Hom}_B(B, p) \\
 & \perp & \\
 & \swarrow p \quad \searrow p_0 & \\
 & B &
 \end{array}
 \end{array}$$

proving (ii).

(ii) \Rightarrow (i): Now suppose given a fibered adjunction

$$\begin{array}{ccc}
 E & \xrightleftharpoons[r]{i} & \mathbf{Hom}_B(B, p) \\
 & \perp & \\
 & \swarrow p \quad \searrow p_0 & \\
 & B &
 \end{array}$$

We will show that the codomain component of the counit

$$\begin{array}{ccccc}
 \mathbf{Hom}_B(B, p) & \xrightleftharpoons[\uparrow \epsilon]{\uparrow \epsilon} & \mathbf{Hom}_B(B, p) & \xrightarrow{p_1} & E \\
 & \searrow r & \nearrow i & \searrow & \\
 & E & & &
 \end{array}$$

satisfies the conditions of the generic p -cartesian transformation described in Lemma 5.1.8. This will then also demonstrate the equivalence (iv) \Leftrightarrow (v).

The first thing to check is that $p_1 \epsilon$ defines a lift of the right comma cone along p . To see this, consider the horizontal composite:

$$\begin{array}{ccccc}
 \mathbf{Hom}_B(B, p) & \xrightleftharpoons[\uparrow \epsilon]{\uparrow \epsilon} & \mathbf{Hom}_B(B, p) & \xrightarrow{p_1} & E \\
 & \searrow r & \nearrow i & \searrow & \downarrow p \\
 & E & & & B \\
 & & & & \swarrow p_0
 \end{array}$$

Naturality of whiskering provides a commutative square

$$\begin{array}{ccc} p_0 i r & \xrightarrow{p_0 \epsilon} & p_0 \\ \phi i r \parallel & & \parallel \phi \\ p p_1 i r & \xrightarrow{p p_1 \epsilon} & p p_1 \end{array}$$

in which $p_0 \epsilon = \text{id}$, as a fibered counit, and $\phi i r = \text{id}$, since $\phi i = \text{id}_p$. Thus $p p_1 \epsilon = \phi$ and we see that $p_1 \epsilon$ is a lift of ϕ along p .

It remains only to verify that the restriction of $p_1 \epsilon$ along any functor defines a p -cartesian transformation. To that end, consider $\ulcorner \beta \urcorner: X \rightarrow \text{Hom}_B(B, p)$ representing a 2-cell $\beta: b \Rightarrow pe$; our task is to verify that $p_1 \epsilon \ulcorner \beta \urcorner$ is p -cartesian. Note that $p p_1 \epsilon \ulcorner \beta \urcorner = \phi \ulcorner \beta \urcorner = \beta$, so to prove the induction property, consider a 2-cell $\tau: e'' \Rightarrow e$ and a factorization $p\tau = \beta \cdot \gamma$ for some $\gamma: pe'' \Rightarrow b$. Our task is to define a 2-cell $\hat{\gamma}: e'' \Rightarrow r \ulcorner \beta \urcorner$ so that the pasted composite

$$\begin{array}{ccccc} X & \xrightarrow{\ulcorner \beta \urcorner} & \text{Hom}_B(B, p) & \xrightarrow{\ulcorner \epsilon \urcorner} & \text{Hom}_B(B, p) \xrightarrow{p_1} E \\ & \searrow e'' & \uparrow \hat{\gamma} & \searrow r & \nearrow i \\ & & E & & \end{array}$$

is τ . Transposing across the adjunction $i \dashv r$, it suffices instead to define a 2-cell $\hat{\gamma}: ie'' \Rightarrow \ulcorner \beta \urcorner$ so that $p_1 \hat{\gamma} = \tau$. We define $\hat{\gamma}$ by 2-cell induction from this condition and $p_0 \hat{\gamma} = \gamma$, a pair which satisfies the 2-cell induction compatibility condition

$$\begin{array}{ccc} p e'' & = & p e'' \\ \gamma = p_0 \hat{\gamma} \Downarrow & & \Downarrow p p_1 \hat{\gamma} = p \tau \\ b & \xRightarrow{\beta} & p e \end{array}$$

precisely on account of the postulated factorization $p\tau = \beta \cdot \gamma$. This verifies the induction condition of Definition 5.1.1(i).

Now consider an endomorphism $\zeta: r\hat{\beta} \Rightarrow r\beta$ so that $p_1 \epsilon \ulcorner \beta \urcorner \cdot \zeta = p_1 \epsilon \ulcorner \beta \urcorner$ and $p\zeta = \text{id}_b$. Write $\bar{r} := \ulcorner p_1 \epsilon \urcorner: \text{Hom}_B(B, p) \rightarrow E^2$ for the functor induced by 1-cell induction from the generic p -cartesian transformation. Now the conditions defining ζ allow us to induce a 2-cell $\bar{\zeta}: \bar{r} \ulcorner \beta \urcorner \Rightarrow \bar{r} \ulcorner \beta \urcorner$ satisfying $p_0 \bar{\zeta} = \zeta$ and $p_1 \bar{\zeta} = \text{id}$. To prove that ζ is invertible, will make use of the naturality of whiskering square for the horizontal composite

$$\begin{array}{ccccc} X & \xrightarrow{\ulcorner \beta \urcorner} & \text{Hom}_B(B, p) & \xrightarrow{\bar{r}} & E^2 \xrightarrow{p_0} E \\ & \searrow \ulcorner \beta \urcorner & \Downarrow \bar{\zeta} & \searrow \bar{r} & \Downarrow \bar{\gamma} \\ & & \text{Hom}_B(B, p) & \xrightarrow{k} & \text{Hom}_B(B, p) \xrightarrow{r} E \end{array} \rightsquigarrow \begin{array}{ccc} p_0 r \ulcorner \beta \urcorner & \xrightarrow{\bar{\gamma} \ulcorner \beta \urcorner} & r k \ulcorner \beta \urcorner \\ \zeta = p_0 \bar{\zeta} \Downarrow & & \Downarrow r k \bar{\zeta} \\ p_0 \bar{r} \ulcorner \beta \urcorner & \xrightarrow{\bar{\gamma} \ulcorner \beta \urcorner} & r k \ulcorner \beta \urcorner \end{array}$$

where $\bar{\gamma}$ is a special case of the 2-cell just given this name to be described momentarily for which we will demonstrate that $\bar{\gamma} \bar{r}$ is an isomorphism. The composite $k \bar{\zeta}$ is a 2-cell induced from $p_0 k \bar{\zeta} = p p_0 \bar{\zeta} = p \zeta = \text{id}$ and $p_1 k \bar{\zeta} = p_1 \bar{\zeta} = \text{id}$, so by 2-cell conservativity, this is an isomorphism. Now ζ is a composite of three isomorphisms and hence is invertible.

To complete the proof, we must define $\bar{\gamma}$ and prove that $\bar{\gamma}\bar{r}$ is invertible. Specializing the construction just given, we define $\bar{\gamma}$ to be the induced 2-cell satisfying $p\bar{\gamma} = \text{id}$ and $\kappa = p_1\epsilon k \cdot \bar{\gamma}$. Transposing across the fibered adjunction $i \dashv r$, it suffices to define the transposed 2-cell $\hat{\gamma}: ip_0 \Rightarrow k$ so that $p_1\hat{\gamma} = \kappa$ and $p_0\hat{\gamma} = \text{id}$. And we may transpose once more along an adjunction $j \dashv p_0$ of (5.1.15) constructed by the dual of Lemma 3.4.8. The counit $v: jp_0 \Rightarrow \text{id}$ of this adjunction satisfied the defining conditions that $p_0v = \text{id}$ and $p_1v = \kappa$, so to construct $\hat{\gamma}$ satisfying the conditions just described, it suffices to define instead a 2-cell $\xi: i \Rightarrow kj$ satisfying the conditions $p_1\xi = \text{id}$ and $p_0\xi = \text{id}$. These conditions are satisfied by the fibered isomorphism $\xi: i \cong kj$ that arises by Proposition 3.3.7 since both 1-cells $E \rightrightarrows \text{Hom}_B(B, p)$ are induced by the identity id_p . Unpacking these transpositions, $\bar{\gamma}$ is defined to be the composite

$$\bar{\gamma} := p_0 \xrightarrow[\cong]{\eta} rip_0 \xrightarrow[\cong]{\xi} rkjp_0 \xrightarrow{rkv} rk$$

To verify that $\bar{\gamma}\bar{r}$ is invertible, it thus suffices to demonstrate that $rkv\bar{r}$ is invertible. To see this, we consider another pasting diagram

$$\begin{array}{c} \begin{array}{ccc} & E & \\ r \nearrow & & \searrow i \\ \text{Hom}_B(B, p) & \xlongequal{\quad} & \text{Hom}_B(B, p) \end{array} \\ \Downarrow \epsilon \\ \text{Hom}_B(B, p) \xlongequal{\quad} \text{Hom}_B(B, p) \xrightarrow{\bar{r}} E^2 \xlongequal[\cong]{\bar{v}} E^2 \xrightarrow{k} \text{Hom}_B(B, p) \xrightarrow{r} E \end{array}$$

By the definition (5.1.10) of k , $\phi k\bar{r} = p\kappa\bar{r} = p\chi = \phi$, so Proposition 3.3.7 supplies a fibered isomorphism $\bar{\epsilon}: k\bar{r} \cong \text{id}$ with $p_0\bar{\epsilon} = \text{id}_{p_0}$ and $p_1\bar{\epsilon} = \text{id}_{p_1}$.

Now naturality of whiskering supplies a commutative diagram of 2-cells

$$\begin{array}{ccccc} rkjp_0\bar{r}ir & \xrightarrow{rkv\bar{r}ir} & rk\bar{r}ir & \xrightarrow[r\bar{\epsilon}ir]{\cong} & rir \\ rkjre \Downarrow \parallel & & \Downarrow rk\bar{r}\epsilon & & \Downarrow r\epsilon \\ rkjp_0\bar{r} & \xrightarrow[rkv\bar{r}]{\quad} & rk\bar{r} & \xrightarrow[r\bar{\epsilon}]{\cong} & r \end{array}$$

Since ϵ is the counit of an adjunction $i \dashv r$ with invertible unit, $r\epsilon$ is an isomorphism, so we see that $rkv\bar{r}$ is an isomorphism if and only if $rkv\bar{r}ir$ is. And this is the case since $kv\bar{r}i$ is an isomorphism by 2-cell conservativity: $p_0kv\bar{r}i = \text{id}_p$, while $p_1kv\bar{r}i = p_1\epsilon i$, which is an isomorphism again because ϵ is the counit of an adjunction $i \dashv r$ with invertible unit. \square

One of the myriad applications of Theorem 5.1.11 is:

5.1.16. COROLLARY. *Cosmological functors preserve cartesian fibrations and cartesian natural transformations.*

PROOF. By Theorem 5.1.11(i) \Leftrightarrow (iii), an isofibration $p: E \twoheadrightarrow B$ in an ∞ -cosmos \mathcal{K} is cartesian if and only if the isofibration $k: E^2 \twoheadrightarrow \text{Hom}_B(B, p)$ defined in Remark 5.1.13 admits a right adjoint right inverse. A cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ preserves the class of isofibrations and the simplicial limits that define the domain and codomain of this k . Moreover, cosmological functors preserve adjunctions and natural isomorphisms, so if this adjoint exists in \mathcal{K} it also does in \mathcal{L} . Similarly, the internal characterization of p -cartesian natural transformations given by Theorem 5.1.11(iv) \Leftrightarrow (vi) is also preserved by cosmological functors. \square

Another application of Theorem 5.1.11 is that it allows us to conclude that cartesianness is an equivalence-invariant property of isofibrations.

5.1.17. COROLLARY. *Consider a commutative square between isofibrations whose horizontals are equivalences*

$$\begin{array}{ccc} F & \xrightarrow[\sim]{g} & E \\ q \downarrow & & \downarrow p \\ A & \xrightarrow[\sim]{f} & B \end{array}$$

Then p is a cartesian fibration if and only if q is a cartesian fibration in which case g preserves and reflects cartesian transformations: χ is q -cartesian if and only if $g\chi$ is p -cartesian.

PROOF. The commutative square of the statement induces a commutative square up to isomorphism whose horizontals are equivalences

$$\begin{array}{ccc} F^2 & \xrightarrow[\sim]{g^2} & E^2 \\ k \downarrow & \cong & \downarrow k \\ \text{Hom}_A(A, q) & \xrightarrow[\text{Hom}_f(f, g)]{\sim} & \text{Hom}_B(B, p) \end{array}$$

By the equivalence-invariance of adjunctions, the left-hand vertical admits a right adjoint with invertible counit if and only if the right-hand vertical does, these adjunctions being defined in such a way that the mate of the given square is an isomorphism built by composing with the natural isomorphisms of the horizontal equivalences (see Proposition B.3.1). By Theorem 5.1.11(i) \Leftrightarrow (iii), it follows that p is cartesian if and only if q is cartesian.

Supposing the postulated adjoints exist, via their construction, the whiskered composites $g^2\eta$ and ηg^2 of the units of the respective adjunctions are isomorphic. Hence the component at an element $[\chi]: X \rightarrow F^2$ of $g^2\eta$ is invertible if and only if the component of ηg^2 is invertible; since g^2 is an equivalence, the former is the case if and only if the component of η is invertible. By Theorem 5.1.11(iv) \Leftrightarrow (vi), this proves that χ is p -cartesian if and only if $g\chi$ is q -cartesian. \square

In terminology we now introduce, the square defined by the equivalences and also the square defined by their inverses², defines a *cartesian functor* from q to p .

5.1.18. DEFINITION (cartesian functor). Let $p: E \twoheadrightarrow B$ and $q: F \twoheadrightarrow A$ be cartesian fibrations. A commutative square

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ q \downarrow & & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

defines a **cartesian functor** if g preserves cartesian transformations: if χ is q -cartesian then $g\chi$ is p -cartesian.

²For any inverse equivalences g' and f' to g and f , there is a natural isomorphism $qg' \cong f'fgg' = f'pgg' \cong f'p$. Using the isofibration property of q of Proposition 1.4.10, g' may be replaced by an isomorphic functor g'' , which also defines an inverse equivalence to g and for which the square $qg'' = f'p$ commutes strictly.

Lemma 5.1.8 for the cartesian fibration $q: F \rightarrow A$, whiskering with $\bar{g} := \text{Hom}_f(f, g): \text{Hom}_A(A, q) \rightarrow \text{Hom}_B(B, p)$ carries this to a 2-cell whose projection with p_0 is an identity, since $p_0\epsilon = \text{id}$, and whose projection along p_1 is $gp_1\epsilon$, by the commutativity of the left-hand portion of the diagram below.

$$\begin{array}{ccccc}
 & F & \xrightarrow{g} & E & \\
 r \nearrow & & & & \nwarrow i \\
 & \Downarrow \epsilon & & & \\
 \text{Hom}_A(A, q) & \xrightarrow{\quad} & \text{Hom}_A(A, q) & \xrightarrow{\bar{g}} & \text{Hom}_B(B, p) & \xrightarrow{\quad} & \text{Hom}_B(B, p) \\
 & & \downarrow p_1 & & \downarrow p_1 & & \downarrow p_1 \\
 & & F & \xrightarrow{g} & E & \xrightarrow{\quad} & E
 \end{array}$$

Now naturality of whiskering provides a commutative square of natural transformations:

$$\begin{array}{ccc}
 p_1 i r i g r & \xrightarrow{r \bar{g} \epsilon} & r \bar{g} \\
 p_1 \epsilon i g r \Downarrow \text{III} & & \Downarrow p_1 \epsilon \bar{g} \\
 p_1 \bar{g} i r & \xrightarrow{p_1 \bar{g} \epsilon} & p_1 \bar{g}
 \end{array}$$

where we've simplified some of the names since $p_1 i = \text{id}$. Since ϵ is the counit of an adjunction $i \dashv r$ with invertible unit, ϵi is an isomorphism. Note $pr\bar{g}\epsilon = p_0\bar{g}\epsilon = \text{id}$ and the right-hand vertical $p_1\epsilon\bar{g}$ is a p -cartesian lift of the restriction of $\phi\bar{g}$, this ϕ being the right comma cone over p , which equals the whiskered right comma cone $f\phi$, this ϕ being the right comma cone over q , by the definition of \bar{g} . The bottom horizontal $p_1\bar{g}\epsilon$ is similarly a lift of $f\phi = \phi\bar{g}$. So if g is a cartesian functor, the right-hand vertical and bottom horizontal are both p -cartesian lifts of a common 2-cell and the conservativity property implies that $r\bar{g}\epsilon$ is invertible. Conversely, if $r\bar{g}\epsilon$ is invertible, the $p_1\bar{g}\epsilon = gp_1\epsilon$ is isomorphic to a p -cartesian transformation and is consequently p -cartesian. Since Lemma 5.1.8 constructs the other canonical q -cartesian lifts as restrictions of $p_1\epsilon$, this is the case if and only if g is a cartesian functor. \square

5.1.20. PROPOSITION (pullback stability). *If*

$$\begin{array}{ccc}
 F & \xrightarrow{g} & E \\
 q \downarrow & \lrcorner & \downarrow p \\
 A & \xrightarrow{f} & B
 \end{array}$$

is a pullback square and p is a cartesian fibration then q is a cartesian fibration. Moreover, a natural transformation χ with codomain F is q -cartesian if and only if $g\chi$ is p -cartesian, and in particular the pullback square defines a cartesian functor.

PROOF. We apply Theorem 5.1.11(i) \Rightarrow (iii) in the form described in Remark 5.1.13 to the cartesian fibration p , which yields a fibered adjunction

$$\begin{array}{ccc}
 & k & \\
 E^2 & \xrightarrow{\quad} & \text{Hom}_B(B, p) \\
 & \dashleftarrow \bar{r} & \\
 & k & \\
 & \text{Hom}_B(B, p) &
 \end{array}
 \quad (5.1.21)$$

We will now argue that this functor k pulls back to the corresponding functor for q . To that end, first note that the top face of the following cube is a pullback since the front, back, and bottom faces are.

$$\begin{array}{ccccc}
 & & F^2 & \xrightarrow{q^2} & A^2 \\
 & g^2 \nearrow & \downarrow k & \searrow p^2 & \\
 E^2 & \xrightarrow{\quad} & \text{Hom}_A(A, q) & \xrightarrow{\quad} & A^2 \\
 \downarrow k & \searrow \text{Hom}_f(f, g) & \downarrow p_1 & \searrow f^2 & \downarrow p_1 \\
 \text{Hom}_B(B, p) & \xrightarrow{\quad} & B^2 & \xrightarrow{\quad} & A \\
 \downarrow p_1 & \searrow g & \downarrow q & \searrow f & \\
 E & \xrightarrow{\quad} & F & \xrightarrow{\quad} & B \\
 & p & & &
 \end{array}$$

The right adjoint $(-)^2$ preserves pullbacks, so F^2 is the pullback of p^2 along f^2 , and since this pullback square factors through the top face of the cube along the square inducing the maps k , we conclude that this last square is a pullback, as claimed.

Now pullback defines a cosmological functor $\text{Hom}_f(f, g)^*: \mathcal{K}_{/\text{Hom}_B(B, p)} \rightarrow \mathcal{K}_{/\text{Hom}_A(A, q)}$ that carries the fibered adjunction (5.1.21) to a fibered adjunction

$$\begin{array}{ccc}
 & k & \\
 F^2 & \xrightarrow{\quad} & \text{Hom}_A(A, q) \\
 & \dashleftarrow \bar{r} & \\
 & k & \\
 & \text{Hom}_A(A, q) &
 \end{array}$$

which by Theorem 5.1.11(iii) \Rightarrow (i) proves that q is a cartesian fibration. Moreover, by construction of the adjunction $k \dashv \bar{r}$ as a pullback of the adjunction $k \dashv \bar{r}$, both of the mates in Theorem 5.1.19(iii) are identities, proving that (g, f) defines a cartesian functor.

To see that (g, f) creates cartesian natural transformations, note that a natural transformation χ with codomain F is represented by an element $\ulcorner \chi \urcorner: X \rightarrow F^2$ and $g\chi$ is represented by the image of this element under the functor $g^2: F^2 \rightarrow E^2$. By Theorem 5.1.11(iv) \Leftrightarrow (vi), χ is q -cartesian just when the component $\bar{\eta} \ulcorner \chi \urcorner$ of the unit of $k \dashv \bar{r}$. This unit component $\bar{\eta} \ulcorner \chi \urcorner$ is the pullback of the corresponding

unit component $\eta g^2 \lceil \chi \rceil$ indexed by $g\chi$, and by conservativity of the smothering functor

$$\mathbf{hFun}(X, F^2) \rightarrow \mathbf{hFun}(X, \mathbf{Hom}_A(A, q)) \times_{\mathbf{hFun}(X, \mathbf{Hom}_B(B, p))} \mathbf{hFun}(X, E^2)$$

if $\eta g^2 \lceil \chi \rceil$ is invertible, then so is $\eta \lceil \chi \rceil$. \square

Pullback squares provide a key instance of cartesian functors. Another is given by the following lemma, which can be proven using Theorem 5.1.19.

5.1.22. LEMMA. *If*

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ & \searrow q \quad \swarrow p & \\ & B & \end{array}$$

is a functor between cartesian fibrations that admits a left adjoint over B , then g defines a cartesian functor.

PROOF. If $\ell \dashv_B g$, then the cosmological functor $p_1^*: \mathcal{K}_B \rightarrow \mathcal{K}_{B^2}$ carries this fibered adjunction to a fibered adjunction

$$\begin{array}{ccc} & \xleftarrow{\mathbf{Hom}_{\mathbf{id}_B}(\mathbf{id}_B, \ell)} & \\ \mathbf{Hom}_B(B, q) & \perp & \mathbf{Hom}_B(B, p) \\ & \xrightarrow{\mathbf{Hom}_{\mathbf{id}_B}(\mathbf{id}_B, g)} & \end{array}$$

Now both horizontal functors in the commutative square

$$\begin{array}{ccc} F^2 & \xrightarrow{g^2} & E^2 \\ k \downarrow & \cong \swarrow & \downarrow k \\ \mathbf{Hom}_A(A, q) & \xrightarrow{\mathbf{Hom}_f(f, g)} & \mathbf{Hom}_B(B, p) \end{array}$$

admit left adjoints and a standard result from the calculus of mates tells us that the mate with respect to the vertical adjunctions $k \dashv \bar{k}$ is an isomorphism if and only if the mate with respect to the horizontal adjunctions is an isomorphism, the latter natural transformation between left adjoints being the transpose of the former natural transformation between their right adjoints. This is the case because the mate with respect to the left adjoints lies in the fiber of the smothering functor of Proposition 3.2.5 for F^2 . \square

Examples of cartesian fibrations are overdue.

5.1.23. PROPOSITION (domain projection). *For any ∞ -category A , the domain-projection functor $p_0: A^2 \rightarrow A$ defines a cartesian fibration. Moreover, a natural transformation χ with codomain A^2 is p_0 -cartesian if and only if $p_1\chi$ is invertible.*

Before giving the proof, we explain the idea. A 2-cell

$$\begin{array}{ccc} X & \xrightarrow{\lceil \beta \rceil} & A^2 \\ & \uparrow \alpha \quad \downarrow p_0 & \\ & a & A \end{array}$$

defines a composable pair of 2-cells $\alpha: a \Rightarrow x$ and $\beta: x \Rightarrow y$ in $\mathbf{hFun}(X, A)$. Composing these we

induce a 2-cell $X \xrightarrow[\beta]{\beta \circ \alpha} A^2$ representing the commutative square

$$\begin{array}{ccc} a & \xrightarrow{\alpha} & x \\ \beta \circ \alpha \downarrow & & \downarrow \beta \\ y & \xrightarrow{\quad} & y \end{array}$$

so that $p_0\chi = \alpha$, as required, and $p_1\chi = \text{id}$.³

PROOF. We use Theorem 5.1.11(i) \Leftrightarrow (iii) and prove that p_0 is cartesian by constructing an appropriate adjoint to the functor

$$\begin{array}{ccc} (A^2)^2 & \xrightarrow{p_0^2} & A^2 \\ \text{---} k \text{---} & \searrow & \downarrow p_1 \\ & \text{Hom}_A(A, p_0) & \longrightarrow A^2 \\ p_1 \downarrow & \downarrow p_1 & \downarrow p_1 \\ A^2 & \xrightarrow{p_0} & A \end{array} \quad \begin{array}{ccc} 2 \times 2 & \xleftarrow{0 \times 2} & 2 \\ \text{---} \text{---} & \nwarrow & \downarrow 1 \\ & 3 & \downarrow 1 \\ 2 \times 1 & \uparrow & 2 \\ & \downarrow 0 & 1 \end{array}$$

defined by cotensoring with the 1-categories displayed above right.⁴

To construct a right adjoint with invertible counit to the map k , it suffices to construct a left adjoint left inverse to the inclusion of 1-categories $3 \hookrightarrow 2 \times 2$ with image $(0, 0) \rightarrow (0, 1) \rightarrow (1, 1)$. The left adjoint $\ell: 2 \times 2 \rightarrow 3$ is a left inverse on the image of 3 and sends $(1, 0)$ to the terminal element of 3 :

$$2 \times 2 \ni \left\{ \begin{array}{ccc} (0, 0) & \longrightarrow & (0, 1) \\ \downarrow & & \downarrow \\ (1, 0) & \longrightarrow & (1, 1) \end{array} \right\} \mapsto \left\{ \begin{array}{ccc} 0 & \longrightarrow & 1 \\ \downarrow & & \downarrow \\ 2 & \xlongequal{\quad} & 2 \end{array} \right\} \in 3$$

Now

$$\begin{array}{ccc} & \xrightarrow{k} & \\ (A^2)^2 & \perp & A^3 \simeq \text{Hom}_A(A, p_0) \\ & \xleftarrow{A^\ell} & \end{array}$$

defines the desired right adjoint with invertible counit.

³While the weak universal property of the arrow ∞ -category can be used to induce 2-cells with codomain A^2 , it cannot be used to prove equations between the induced 2-cells, as required to demonstrate that induction condition of Definition 5.1.1. Thus, some sort of ∞ -cosmos-level argument is necessary to establish this result.

⁴The cotensor $A^{(-)}$ carries pushouts of simplicial sets to pullbacks of ∞ -categories, and the pushout of $2 \cup_1 2$ of simplicial sets is $\Delta^1[2]$, not $3 = \Delta[2]$. However, on account of the equivalence of ∞ -categories $A^3 \simeq A^{\Delta^1[2]}$, no harm comes from making the indicated substitution.

The characterization of p_0 -cartesian transformations now follows from Theorem 5.1.11(iv) \Leftrightarrow (vi). A cell χ with codomain A^2 is p_0 -cartesian if and only if it is the representing element of $(A^2)^2$ is in the essential image of the right adjoint $A^\ell: A^3 \rightarrow A^{2 \times 2}$. Clearly if χ is in the essential image then its codomain component must be invertible.

Conversely, suppose the codomain component

$$X \xrightarrow{\ulcorner \chi \urcorner} A^{2 \times 2} \xrightarrow{\text{cv}(1, -)} A^2$$

represents a natural isomorphism. Applying Lemma 1.1.12 to $\text{Fun}(X, A)$ one can build a diagram in $\text{Fun}(X, A)^{2 \times 2} \cong \text{Fun}(X, A^{2 \times 2})$ whose top edge is the given isomorphism, whose vertical edges are isomorphisms, and whose bottom edge is an identity. This glues onto χ to define a diagram $X \rightarrow A^{\Lambda^1[2] \times 2}$ and now the composite

$$X \longrightarrow A^{\Lambda^1[2] \times 2} \xrightarrow{\sim} A^{3 \times 2} \xrightarrow{A^c} A^{2 \times 2 \times 2}$$

where $c: 2 \times 2 \rightarrow 3$ is the surjective functor that sends $(0, 0)$ and $(0, 1)$ to 0, witnesses an isomorphism between $\ulcorner \chi \urcorner$ and a diagram in the image of A^ℓ , whose codomain component is the identity. \square

The same argument proves that for any $g: C \rightarrow A$, the domain-projection $p_0: \text{Hom}_A(A, g) \twoheadrightarrow A$ is a cartesian fibration. For $f: B \rightarrow A$, the domain-projections $p_0: \text{Hom}_A(f, A) \twoheadrightarrow B$ and $p_0: \text{Hom}_A(f, g) \twoheadrightarrow B$ are obtained by pullback via Proposition 5.1.20. These cartesian fibrations figures in a final important lemma about the class of p -cartesian transformations.

5.1.24. LEMMA. Let $p: E \twoheadrightarrow B$ be a cartesian fibration and consider a composable pair of natural transformations

$$X \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \psi \\ \xrightarrow{e} \end{array} E \quad \text{and} \quad X \begin{array}{c} \xrightarrow{e''} \\ \Downarrow \psi' \\ \xrightarrow{e'} \end{array} E \quad \text{with codomain } E.$$

- (i) If ψ and ψ' are p -cartesian, then so is $\psi \cdot \psi'$.
- (ii) If ψ and $\psi \cdot \psi'$ are p -cartesian, then so is ψ' .

PROOF. For (i), recall from the proof of Lemma 5.1.8 that a p -cartesian lift of $p\psi$ is given by the composite

$$X \xrightarrow{\ulcorner p\psi \urcorner} \text{Hom}_B(B, p) \begin{array}{c} \xrightarrow{r} \\ \Downarrow \chi \\ \xrightarrow{p_1} \end{array} E$$

with the natural transformation $\chi: r \Rightarrow p_1$ of (5.1.9) whose domain r is the right adjoint of Theorem 5.1.11(ii). Since we are assuming that ψ is p -cartesian, ψ is isomorphic to this whiskered natural transformation so we may redefine ψ to equal it and redefine ψ' to absorb the isomorphism. By Lemma 5.1.4, this new ψ' is still p -cartesian since we've assumed ψ' is. This modification does not change the composition transformation $\psi \cdot \psi'$ that we desire to show is p -cartesian.

Now by 2-cell induction, the diagram as below-left defines a 2-cell as below-right:

$$\begin{array}{ccc} pe'' & \xrightarrow{p\psi'} & pe' \\ p(\psi \cdot \psi') \Downarrow & & \Downarrow p\psi \\ pe & \xlongequal{\quad} & pe \end{array} \quad \begin{array}{ccc} & \xrightarrow{\ulcorner p(\psi \cdot \psi') \urcorner} & \\ X & \Downarrow \gamma & \text{Hom}_B(B, p) \\ & \xrightarrow{\ulcorner p\psi \urcorner} & \end{array}$$

By the generalization of Proposition 5.1.23, γ is a p_0 -cartesian cell. By Lemma 5.1.22, the fibered right adjoint r

$$\begin{array}{ccc} & i & \\ \text{Hom}_B(B, p) & \xleftarrow{\quad} & E \\ & \searrow p_0 \quad \swarrow p & \\ & B & \end{array} \quad \perp$$

carries γ to a p -cartesian transformation $r\gamma$.

Now the horizontal composite

$$\begin{array}{ccccc} X & \xrightarrow{\lceil p(\psi \cdot \psi') \rceil} & \text{Hom}_B(B, p) & \xrightarrow{r} & E \\ & \Downarrow \gamma & & \Downarrow \chi & \\ X & \xrightarrow{\lceil p\psi \rceil} & \text{Hom}_B(B, p) & \xrightarrow{p_1} & E \end{array}$$

provides a commutative diagram of natural transformations

$$\begin{array}{ccc} \bar{e} & \xrightarrow{r\gamma} & e' \\ \chi_{p(\psi \cdot \psi')} \Downarrow & & \Downarrow \psi \\ e & \xlongequal{\quad} & e \end{array}$$

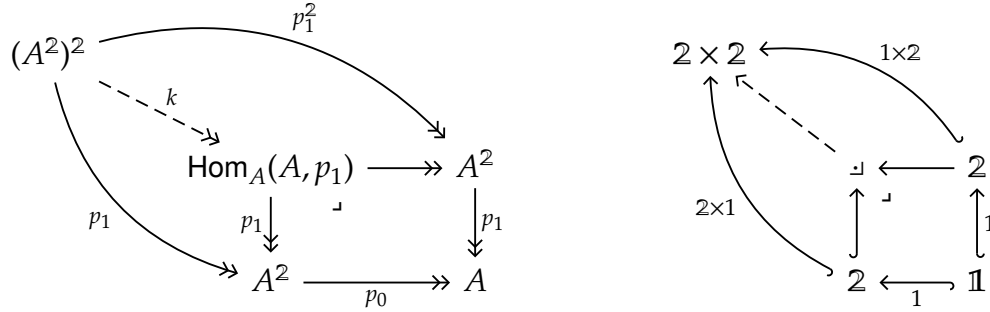
In particular, the composite $\psi \cdot r\gamma$ is a p -cartesian natural transformation. Since $pr\gamma = p_0\gamma = p\psi'$, $r\gamma$ is a p -cartesian lift of the cartesian transformation ψ' , so ψ' and $r\gamma$ are isomorphic. But now $\psi \cdot \psi'$ is isomorphic to the p -cartesian transformation $\chi_{p(\psi \cdot \psi')}$, and Lemma 5.1.4 proves that $\psi \cdot \psi'$ is p -cartesian.

Now for (ii) suppose ψ and $\psi \cdot \psi'$ are p -cartesian and let $\chi': \bar{e} \Rightarrow e'$ denote a p -cartesian lift of $p\psi'$. Consider the factorization $\psi' = \chi' \cdot \theta$ of ψ' through its p -cartesian lift with $p\theta = \text{id}$. Now part (i) implies that $\psi \cdot \chi'$ is p -cartesian and $\psi \cdot \psi' = \psi \cdot \chi' \cdot \theta$, so Lemma 5.1.5 implies that θ is an isomorphism. Now ψ' is isomorphic to a p -cartesian cell so Lemma 5.1.4 implies that ψ' must be p -cartesian. \square

For ∞ -categories admitting pullbacks, the codomain-projection functor also defines a cartesian fibration:

5.1.25. PROPOSITION (codomain projection). *Let A be an ∞ -category that admits pullbacks in the sense of Definition 4.3.7. Then the codomain-projection functor $p_1: A^2 \rightarrow A$ is a cartesian fibration and the p_1 -cartesian arrows are just those 2-cells that represent pullback squares.*

PROOF. Via Theorem 5.1.11(i) \Leftrightarrow (iii), we desire a right adjoint right inverse to the functor k defined below-left applying A^- to the diagram of simplicial sets appearing below-right:



This is done in Corollary 4.3.5:

$$(A^2)^2 \cong A^\square \begin{array}{c} \xrightarrow{\text{res}} \\ \perp \\ \xleftarrow{\text{ran}} \end{array} A^\natural \cong \text{Hom}_A(A, p_1)$$

□

Exercises.

5.1.i. EXERCISE. Prove Lemma 5.1.4.

5.1.ii. EXERCISE. Attempt to prove directly from Definition 5.1.6 that cosmological functors preserve cartesian fibrations and explain what goes wrong.

5.1.iii. EXERCISE. Categorify the intuition that cartesian fibrations $p: E \rightarrow B$ and $q: F \rightarrow B$ define “contravariant B -indexed functors valued in ∞ -categories” by proving that a cartesian functor

$$\begin{array}{ccc} E & \xrightarrow{g} & F \\ p \searrow & & \swarrow p \\ & B & \end{array}$$

defines a “natural transformation”: show that there exists a natural isomorphism in the square of fibers

$$\begin{array}{ccc} E_b & \xrightarrow{g} & F_b \\ \beta^* \downarrow & \exists \cong & \downarrow \beta^* \\ E_a & \xrightarrow{g} & F_a \end{array}$$

where the action of an arrow β in the homotopy category of B on the fibers is defined by factoring the domain of a p - or q -cartesian lift of β :

$$\begin{array}{ccc} E_b & \xrightarrow{\ell_b} & E \\ \downarrow & \lrcorner & \downarrow p \\ 1 & \xrightarrow{b} & B \\ & \Uparrow \beta & \\ & a & \end{array} = \begin{array}{ccc} E_b & \xrightarrow{\ell_b} & E \\ \downarrow \beta^* & \Uparrow \chi_\beta & \downarrow p \\ E_a & \xrightarrow{\ell_a} & B \\ & \lrcorner & \\ & a & \end{array}$$

5.1.iv. EXERCISE. Use Proposition 5.1.20 to prove that cartesian functors pull back.

5.2. Cocartesian fibrations and bifibrations

By the dual of Proposition 5.1.23, the codomain-projection functor is also a cocartesian fibration, a notion we now introduce.

5.2.1. DEFINITION (p -cocartesian transformations). Let $p: E \twoheadrightarrow B$ be an isofibration. A natural transformation

formation $X \begin{array}{c} \xrightarrow{e} \\ \Downarrow \chi \\ \xrightarrow{e'} \end{array} E$ with codomain E is p -cocartesian if

(i) **induction**: Given any natural transformations $X \begin{array}{c} \xrightarrow{e} \\ \Downarrow \tau \\ \xrightarrow{e''} \end{array} E$ and $X \begin{array}{c} \xrightarrow{pe'} \\ \Downarrow \gamma \\ \xrightarrow{pe''} \end{array} B$ so that $p\tau = \gamma \cdot p\chi$,

there exists a lift $X \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \bar{\gamma} \\ \xrightarrow{e''} \end{array} E$ of γ so that $\tau = \bar{\gamma} \cdot \chi$.

$$\begin{array}{ccc} \begin{array}{c} e \xrightarrow{\tau} e'' \\ \chi \searrow \quad \nearrow \bar{\gamma} \\ e' \end{array} & \in & \text{hFun}(X, E) \\ \Downarrow & & \downarrow p_* \\ \begin{array}{c} pe \xrightarrow{p\tau} pe'' \\ p\chi \searrow \quad \nearrow \gamma \\ pe' \end{array} & \in & \text{hFun}(X, B) \end{array}$$

(ii) **conservativity**: Any fibered endomorphism of χ is invertible: if $X \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \zeta \\ \xrightarrow{e'} \end{array} E$ is any natural transformation so that $\zeta \cdot \chi = \chi$ and $p\zeta = \text{id}_{pe'}$, then ζ is invertible.

5.2.2. DEFINITION (cocartesian fibration). An isofibration $p: E \twoheadrightarrow B$ is a **cocartesian fibration** if

(i) Any natural transformation $\beta: pe \Rightarrow b$ as below-left admits a lift $\chi_\beta: e \Rightarrow \beta_*e$ as below-right

$$\begin{array}{ccc} X & \begin{array}{c} \xrightarrow{e} \\ \Downarrow \beta \\ \xrightarrow{b} \end{array} & E \\ & & \downarrow p \\ & & B \end{array} = \begin{array}{ccc} X & \begin{array}{c} \xrightarrow{e} \\ \Downarrow \chi_\beta \\ \xrightarrow{\beta_*e} \end{array} & E \\ & & \downarrow p \\ & & B \end{array}$$

that is a p -cartesian transformation so that $p\chi = \beta$.

(ii) The class of p -cocartesian transformations is closed under restriction along any functor: that

is, if $X \begin{array}{c} \xrightarrow{e} \\ \Downarrow \chi \\ \xrightarrow{e'} \end{array} E$ is p -cocartesian and $f: Y \rightarrow X$ is any functor then $Y \begin{array}{c} \xrightarrow{ef} \\ \Downarrow \chi f \\ \xrightarrow{e'f} \end{array} E$ is p -cocartesian.

The dual to Theorem 5.1.11 asks for left adjoints to $i: E \rightarrow \text{Hom}_B(p, B)$ and $k: E^2 \rightarrow \text{Hom}_B(p, B)$ in place of right adjoints. See Exercise 5.2.i. This result can be deduced immediately by considering the isofibration $p: E \twoheadrightarrow B$ as a map in the dual ∞ -cosmos.

5.2.3. OBSERVATION (dual ∞ -cosmoi). There is an identity-on-objects functor $(-)^{\circ}: \Delta \rightarrow \Delta$ that reverses the ordering of the elements in each ordinal $[n] \in \Delta$. The functor $(-)^{\circ}$ sends a face map $\delta^i: [n-1] \rightarrow [n]$ to the face map $\delta^{n-i}: [n-1] \rightarrow [n]$ and sends the degeneracy map $\sigma^i: [n+1] \rightarrow [n]$ to the degeneracy map $\sigma^{n-i}: [n+1] \rightarrow [n]$. Precomposition with this involutive automorphism induces an involution $(-)^{\text{op}}: \mathcal{S}\text{Set} \rightarrow \mathcal{S}\text{Set}$ that sends a simplicial set X to its **opposite simplicial set** X^{op} , with the orientation of the vertices in each simplex reversed. This construction preserves all conical limits and colimits and induces an isomorphism $(Y^X)^{\text{op}} \cong (Y^{\text{op}})^{X^{\text{op}}}$ on exponentials.

For any ∞ -cosmos \mathcal{K} , there is a **dual ∞ -cosmos** \mathcal{K}^{co} with the same objects but with functor spaces defined by:

$$\text{Fun}_{\mathcal{K}^{\text{co}}}(A, B) := \text{Fun}_{\mathcal{K}}(A, B)^{\text{op}}.$$

The isofibrations, equivalences, and trivial fibrations in \mathcal{K}^{co} coincide with those of \mathcal{K} .

Conical limits in \mathcal{K}^{co} coincide with those in \mathcal{K} , while the cotensor of $A \in \mathcal{K}$ with $U \in \mathcal{S}\text{Set}$ is defined to be $A^{U^{\text{op}}}$. In particular, the cotensor of an ∞ -category with $\mathbf{2}$ is defined to be $A^{\mathbf{2}^{\text{op}}}$, which exchanges the domain and codomain projections from arrow and comma ∞ -categories.

5.2.4. DEFINITION. An isofibration $p: E \rightarrow B$ defines a **bifibration** if p is both a cartesian fibration and a cocartesian fibration.

Projections give trivial examples of bifibrations.

5.2.5. EXAMPLE. For any ∞ -categories A and B the projection functor $\pi: A \times B \rightarrow B$ is a bifibration, in which a 2-cell with codomain $A \times B$ is π -cocartesian or π -cartesian if and only if its composite with the projection $\pi: A \times B \rightarrow A$ is an isomorphism.

5.2.6. PROPOSITION. Let $p: E \rightarrow B$ be a bifibration. Then any arrow $X \begin{smallmatrix} \xrightarrow{a} \\ \Downarrow \beta \\ \xrightarrow{b} \end{smallmatrix} B$ induces a *fibred adjunction*

$$\begin{array}{ccc} E_a & \xrightarrow{\beta_*} & E_b \\ & \perp & \\ p_a \downarrow & \beta^* & \downarrow p_b \\ & X & \end{array} \quad \begin{array}{ccccc} E_a & \xrightarrow{\ell_a} & E & \xleftarrow{\ell_b} & E_b \\ p_a \downarrow & \lrcorner & \downarrow p & \lrcorner & \downarrow p_b \\ X & \xrightarrow{a} & B & \xleftarrow{b} & X \end{array}$$

between the fibers of p over a and b .

As will be remarked upon following the proof of this result, the left adjoint β_* is the covariantly pseudofunctorial action of the arrow β on the fibers of p defined in (5.0.1), while the right adjoint β^* is the dual contravariantly pseudofunctorial action.

PROOF. Write $\ulcorner \beta \urcorner: X \rightarrow B^2$ for the functor induced by β . Note that the pullbacks defining the fibers over its domain edge a and codomain edge b factor as:

$$\begin{array}{ccccccc} E_a & \xrightarrow{\ell_a} & \text{Hom}_B(p, B) & \xrightarrow{p_0} & E & \xleftarrow{p_1} & \text{Hom}_B(B, p) & \xleftarrow{\ell_b} & E_b \\ p_a \downarrow & \lrcorner & q \downarrow & \lrcorner & \downarrow p & \lrcorner & q \downarrow & \lrcorner & \downarrow p_b \\ X & \xrightarrow{\ulcorner \beta \urcorner} & B^2 & \xrightarrow{p_0} & B & \xleftarrow{p_1} & B^2 & \xleftarrow{\ulcorner \beta \urcorner} & X \end{array}$$

$\quad \quad \quad a \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad b \quad \quad \quad$

Now via Remark 5.1.13, Theorem 5.1.11(i) \Rightarrow (iii) and its dual provide a right adjoint right inverse to $k: E^2 \rightarrow \mathbf{Hom}_B(B, p)$ and a left adjoint right inverse to $k: E^2 \rightarrow \mathbf{Hom}_B(p, B)$. Composing the former fibered adjunction with $q: \mathbf{Hom}_B(B, p) \twoheadrightarrow B^2$ and the latter fibered adjunction with $q: \mathbf{Hom}_B(p, B) \twoheadrightarrow B^2$ we obtain a composable pair of adjunctions

$$\begin{array}{ccccc}
 & \xrightarrow{\bar{\ell}} & & \xrightarrow{k} & \\
 \mathbf{Hom}_B(p, B) & \perp & E^2 & \perp & \mathbf{Hom}_B(B, p) \\
 & \xleftarrow{k} & \downarrow p^2 & \xleftarrow{\bar{r}} & \\
 & \xrightarrow{q} & B^2 & \xleftarrow{q} &
 \end{array}$$

fibered over B^2 ; note in both cases that $qk = p^2$. Pulling back the composite adjunction along $\ulcorner \beta \urcorner: X \rightarrow B^2$ yields the fibered adjunction of the statement. \square

5.2.7. REMARK (action of arrows on the fibers of a co/cartesian fibration). If $p: E \twoheadrightarrow B$ is a cocartesian fibration but not a cartesian fibration, the construction in the proof of Proposition 5.2.6 still defines the functor $\beta_*: E_a \rightarrow E_b$. Examining the details of this construction, we see that it produces the functor given this name in (5.0.1). The functor just constructed as the pullback over $\ulcorner \beta \urcorner$ of $k\bar{\ell}$ is induced by the composite commutative square

$$\begin{array}{ccccc}
 E_a & \xrightarrow{\quad} & \mathbf{Hom}_B(p, B) & \xrightarrow{p_1 \bar{\ell}} & E \\
 p_a \downarrow & \lrcorner & q \downarrow & & \downarrow p \\
 X & \xrightarrow{\ulcorner \beta \urcorner} & B^2 & \xrightarrow{p_1} & B
 \end{array}$$

which defines a cone over the pullback defining E_b . The top-horizontal functor takes the codomain-component of the p -cocartesian lift of β with domain ℓ_a . This recovers the description given at the start of this chapter.

Exercises.

5.2.i. EXERCISE. Formulate the dual to Theorem 5.1.11, providing an internal characterization of co-cartesian fibrations.

5.2.ii. EXERCISE. Prove that for any ∞ -category A , the codomain-projection functor $p_1: A^2 \twoheadrightarrow A$ defines a cocartesian fibration.

5.3. The quasi-category theory of cartesian fibrations

In this section, we reinterpret the notion of cartesian fibration and cartesian natural transformation from the point of view of the ∞ -cosmos \mathcal{K} , rather than its quotient homotopy 2-category $\mathbf{h}\mathcal{K}$. In doing so, we recall that the functors $e: X \rightarrow E$ between ∞ -categories are precisely the vertices, or 0 -arrows, in the quasi-categorical functor space $\mathbf{Fun}(X, E)$. The 1-simplices, or 1 -arrows, $\chi: e' \rightarrow e$

of $\mathbf{Fun}(X, E)$ represent natural transformations $X \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{array} E$. Every natural transformation from e'

to e is represented by a 1-arrow $e' \rightarrow e$ and a parallel pair of 1-arrows represent the same natural transformation if and only if they are *homotopic*, bounding a 2-arrow in $\mathbf{Fun}(X, E)$ whose 0th or 2nd edge is degenerate.

Before analyzing the 0- and 1-arrows in the functor spaces in particular, we consider the collection of functor spaces of an ∞ -cosmos globally and prove another important corollary of the internal characterization of cartesian fibrations. The notion of cartesian fibrations are representably defined in the following sense:

5.3.1. PROPOSITION. *Let $p: E \twoheadrightarrow B$ be an isofibration between ∞ -categories in an ∞ -cosmos \mathcal{K} . Then p is a cartesian fibration if and only if:*

- (i) *For all $X \in \mathcal{K}$, the isofibration $p_*: \text{Fun}(X, E) \twoheadrightarrow \text{Fun}(X, B)$ is a cartesian fibration between quasi-categories.*
- (ii) *For all $f: Y \rightarrow X \in \mathcal{K}$, the square*

$$\begin{array}{ccc} \text{Fun}(X, E) & \xrightarrow{f^*} & \text{Fun}(Y, E) \\ p_* \downarrow & & \downarrow p_* \\ \text{Fun}(X, B) & \xrightarrow{f^*} & \text{Fun}(Y, B) \end{array}$$

is a cartesian functor.

PROOF. If $p: E \twoheadrightarrow B$ is a cartesian fibration, then Theorem 5.1.11(i) \Rightarrow (iii) constructs a right adjoint right inverse to $k: E^2 \twoheadrightarrow \text{Hom}_B(B, p)$. The simplicial bifunctor $\text{Fun}(-, -): \mathcal{K}^{\text{op}} \times \mathcal{K} \rightarrow \mathcal{QCat}$ defines a 2-functor $\text{Fun}(-, -): \mathcal{K}^{\text{op}} \times \mathcal{K} \rightarrow \mathcal{QCat}$, which transposes to a Yoneda-type embedding $\text{Fun}(-, -): \mathcal{K} \rightarrow \mathcal{QCat}^{\mathcal{K}^{\text{op}}}$ from the homotopy 2-category of \mathcal{K} to the 2-category of 2-functors, 2-natural transformations, and modifications. This 2-functor carries the adjunction $k \dashv \bar{r}$ to an adjunction in the 2-category $\mathcal{QCat}^{\mathcal{K}^{\text{op}}}$. This latter adjunction defines, for each $X \in \mathcal{K}$, a right adjoint right inverse adjunction

$$\text{Fun}(X, E)^2 \cong \text{Fun}(X, E^2) \begin{array}{c} \xrightarrow{k_*} \\ \perp \\ \xleftarrow{\bar{r}_*} \end{array} \text{Fun}(X, \text{Hom}_B(B, p)) \cong \text{Hom}_{\text{Fun}(X, B)}(\text{Fun}(X, B), p_*)$$

and for each $f: Y \rightarrow X$ in \mathcal{K} , a strict adjunction morphism⁵ commuting strictly with the left adjoints and with the right adjoints:

$$\begin{array}{ccc} \text{Fun}(X, E)^2 \cong \text{Fun}(X, E^2) & \xrightarrow{f^*} & \text{Fun}(Y, E^2) \cong \text{Fun}(Y, E)^2 \\ \bar{r}_* \left(\begin{array}{c} \uparrow \\ \downarrow k_* \end{array} \right) & & \begin{array}{c} \downarrow k_* \\ \uparrow \bar{r}_* \end{array} \\ \text{Hom}(\text{Fun}(X, B), p_*) \cong \text{Fun}(X, \text{Hom}_B(B, p)) & \xrightarrow{f^*} & \text{Fun}(Y, \text{Hom}_B(B, p)) \cong \text{Hom}(\text{Fun}(Y, B), p_*) \end{array} \quad (5.3.2)$$

By Theorems 5.1.11(iii) \Rightarrow (i) and 5.1.19(iii) \Rightarrow (i), this demonstrates the two conditions of the statement.

Conversely, supposing $p: E \twoheadrightarrow B$ satisfies conditions (i) and (ii) by Theorems 5.1.11(i) \Rightarrow (iii) and 5.1.19(i) \Rightarrow (iii) there is a commutative square $k_* f^* = f^* k_*$ where both verticals k_* admit right adjoint right inverses $k_* \dashv \bar{r}$ and the mate of the identity $k_* f^* = f^* k_*$ defines an isomorphism $f^* \bar{r} \cong \bar{r} f^*$. By Proposition ?? in Appendix B, this data suffices to internalize the right adjoints to the representable functors $k_*: \text{Fun}(X, E^2) \rightarrow \text{Fun}(X, \text{Hom}_B(B, p))$ to a functor $\bar{r}_*: \text{Fun}(X, \text{Hom}_B(B, p)) \rightarrow$

⁵A **strict adjunction morphism** is given by a pair of functors, the horizontals of (5.3.2), that define strictly commutative squares with both the left and with the right adjoints and so that the units of each adjunction whisker along these functors to each other and the counits of each adjunction whisker along these functors to each other. See Appendix B for more.

$\text{Fun}(X, E^2)$ arising from post-composition with some $\bar{r}: \text{Hom}_B(B, p) \rightarrow E^2$. This right adjoint \bar{r} is extracted as the image of the identity element

$$\begin{array}{ccc} \text{Fun}(\text{Hom}_B(B, p), \text{Hom}_B(B, p)) & \xrightarrow{\bar{r}} & \text{Fun}(\text{Hom}_B(B, p), E^2) \\ \text{id} \longmapsto & & \bar{r} \end{array}$$

and the unit and counit are internalized similarly; the condition on mates is used to verify the triangle equalities that demonstrate that $k \dashv \bar{r}$. Now Theorem 5.1.11(iii) \Rightarrow (i) proves that $p: E \twoheadrightarrow B$ is a cartesian fibration. \square

An easier argument along the same lines demonstrates:

5.3.3. COROLLARY. *A commutative square between cartesian fibrations as displayed below-left*

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ q \downarrow & & \downarrow p \\ A & \xrightarrow{f} & B \end{array} \rightsquigarrow \begin{array}{ccc} \text{Fun}(X, F) & \xrightarrow{g_*} & \text{Fun}(X, E) \\ q_* \downarrow & & \downarrow p_* \\ \text{Fun}(X, A) & \xrightarrow{f_*} & \text{Fun}(X, B) \end{array}$$

defines a cartesian functor in an ∞ -cosmos \mathcal{K} if and only if for all $X \in \mathcal{K}$, the square displayed above right defines a cartesian functor between cartesian fibrations of quasi-categories.

PROOF. Exercise 5.3.i. \square

Our aim is now to characterize those 1-arrows in $\text{Fun}(X, E)$ that represent p -cartesian natural transformation for some cartesian fibration $p: E \twoheadrightarrow B$. Recall that the 1-arrows in $\text{Fun}(X, E)$ are in bijection with the 0-arrows of $\text{Fun}(X, E)^2 \cong \text{Fun}(X, E^2)$.

5.3.4. DEFINITION (p -cartesian 1-arrow). Let $p: E \twoheadrightarrow B$ be a cartesian fibration and consider a 1-arrow χ in $\text{Fun}(X, E)$, defining an element $\chi \in \text{Fun}(X, E)^2 \cong \text{Fun}(X, E^2)$. Say χ is a **p -cartesian 1-arrow** if it is isomorphic to some object in the image of the right adjoint right inverse functor

$$\text{Fun}(X, \text{Hom}_B(B, p)) \xrightarrow{\bar{r}_*} \text{Fun}(X, E^2)$$

of Theorem 5.1.11(iii).

The new notion of p -cartesian 1-arrow coincides exactly with the previous notion of p -cartesian natural transformation:

5.3.5. LEMMA. *Consider a cartesian fibration $p: E \twoheadrightarrow B$ between ∞ -categories. For a 1-arrow $\chi: e' \rightarrow e$ in $\text{Fun}(X, E)$, the following are equivalent:*

(i) χ is a p -cartesian 1-arrow.

(ii) χ represents a p -cartesian natural transformation $X \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{array} E$.

(iii) χ represents a natural transformation

$$\mathbb{1} \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{array} \text{Fun}(X, E)$$

that is cartesian for $p_*: \mathbf{Fun}(X, E) \rightarrow \mathbf{Fun}(X, B)$.

Conversely, a natural transformation $X \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{array} E$ is p -cartesian if and only if any representing 1-arrow $\ulcorner \chi \urcorner: X \rightarrow E^2$ satisfies all of these equivalent conditions.

PROOF. We start with the final clause. Note from Exercise 3.2.i that homotopic 1-arrows are isomorphic as objects of $\mathbf{Fun}(X, E^2)$ so if some 1-arrow representing a p -cartesian transformation is a p -cartesian 1-arrow then all representatives of that natural transformation are.

Now the equivalence (i) \Leftrightarrow (ii) follows from Theorem 5.1.11(iv) \Leftrightarrow (vi) once we establish that a 1-arrow of $\mathbf{Fun}(X, E)$, when encoded as a functor $\chi: X \rightarrow E^2$ is in the essential image of \bar{r}_* if and only if the component $\bar{\eta}\chi$ of the unit of $k \dashv \bar{r}$ is invertible.

If $\chi: e' \rightarrow e$ is a p -cartesian 1-arrow, then by definition there exists some $\beta: X \rightarrow \mathbf{Hom}_B(B, p)$ and an invertible 2-cell

$$\begin{array}{ccc} X & \xrightarrow{\chi} & E^2 \\ \beta \searrow & \Downarrow \cong & \nearrow \bar{r} \\ & \mathbf{Hom}_B(B, p) & \end{array}$$

The unit $\bar{\eta}$ of the adjunction $k \dashv \bar{r}$ of Theorem 5.1.11(iii) has the property that $\bar{\eta}\bar{r}$ is invertible, so the component $\bar{\eta}\bar{r}\beta$ is invertible and so $\bar{\eta}\chi$ is also invertible. By Theorem 5.1.11(vi) \Rightarrow (iv), this implies that χ represents a p -cartesian natural transformation.

Conversely, if χ defines a p -cartesian natural transformation then Theorem 5.1.11(iv) \Rightarrow (vi) tells us that for any representing 1-arrow $\ulcorner \chi \urcorner: X \rightarrow E^2$, the component $\bar{\eta}\ulcorner \chi \urcorner$ is an isomorphism. In particular, $\ulcorner \chi \urcorner$ is isomorphic to $\bar{r}k\ulcorner \chi \urcorner$, which proves that $\ulcorner \chi \urcorner$ is in the essential image of \bar{r}_* and thus defines a p -cartesian 1-arrow.

Finally, via the characterization of cartesian transformations given in Theorem (vi) and the fact that the adjunction $k \dashv \bar{r}$ in \mathbf{hQC} induces an adjunction $k_* \dashv \bar{r}_*$ in \mathbf{hQCat} , the conditions (ii) and (iii) are tautologically equivalent. The former refers to the adjunction between categories $\mathbf{hFun}(X, E)$ and $\mathbf{hFun}(X, B)$, while the latter refers to the adjunction between categories $\mathbf{hFun}(\mathbf{1}, \mathbf{Fun}(X, E))$ and $\mathbf{hFun}(\mathbf{1}, \mathbf{Fun}(X, B))$ and these are isomorphic. \square

Combining Lemma 5.3.5 with Proposition 5.3.1 we arrive at a new equivalent definition of cartesian fibrations.

5.3.6. COROLLARY. An isofibration $p: E \rightarrow B$ is a *cartesian fibration* if and only if

- (i) Any 1-arrow with codomain B admits a p -cartesian lift with specified codomain 0-arrow.
- (ii) p -cartesian 1-arrows are stable under precomposition with 0-arrows. \square

5.3.7. LEMMA. Let $p: E \rightarrow B$ be a cartesian fibration and consider a 2-arrow

$$\begin{array}{ccc} & e' & \\ \psi' \nearrow & & \searrow \psi \\ e'' & \xrightarrow{\psi''} & e \end{array}$$

in $\mathbf{Fun}(X, E)$.

- (i) If ψ and ψ' are p -cartesian 1-arrows, so is ψ'' .
- (ii) If ψ and ψ'' are p -cartesian 1-arrows, so is ψ' .

(iii) If ψ and ψ'' are p -cartesian 1-arrows and $p\psi'$ is invertible, then ψ' is invertible.

PROOF. Via Lemma 5.3.5, (i) and (ii) are Lemmas 5.1.24(i) and (ii), while (iii) is Lemma 5.1.5. \square

5.3.8. LEMMA. A 2-cell as below left

$$Q \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{array} \text{Fun}(X, E) \quad \mathbb{1} \xrightarrow{q} Q \begin{array}{c} \xrightarrow{e'} \\ \Downarrow \chi \\ \xrightarrow{e} \end{array} \text{Fun}(X, E) \quad \leadsto \quad X \begin{array}{c} \xrightarrow{e'q} \\ \Downarrow \chi q \\ \xrightarrow{eq} \end{array} E$$

is p_* -cartesian if and only if each of its components χq is p -cartesian.

PROOF. If χ is p_* -cartesian, then so is the restriction χq along any element $q: \mathbb{1} \rightarrow Q$. By Lemma 5.3.5 this tells us that χq defines a p -cartesian transformation.

Conversely, if χq is a p -cartesian transformation, then Lemma 5.3.5 tells us that χq is a p_* -cartesian transformation. Now consider the factorization $\chi = \chi_\chi \cdot \theta$ through p_* -cartesian lift χ_χ of $p_*\chi$. Because the components χq of χ are p_* -cartesian, the components θq of θ are isomorphisms. By Lemma ??, an arrow in an exponential $\text{Fun}(X, E)^Q$ is an isomorphism if and only if it is a pointwise isomorphism, so this implies that χ . By isomorphism stability of cartesian transformations, we thus conclude that χ is p_* -cartesian. \square

Exercises.

5.3.i. EXERCISE. Prove Corollary 5.3.3.

5.4. Discrete cartesian fibrations

Recall from Definition 1.2.21 that an object E in an ∞ -cosmos \mathcal{K} is **discrete** if for all $X \in \mathcal{K}$, the functor-space $\text{Fun}(X, E)$ is a Kan complex. Since a quasi-category is a Kan complex just when its homotopy category is a groupoid (see Corollary 1.1.15), equivalently, E is discrete if and only if every natural transformation with codomain E is invertible.

From this definition it follows that an isofibration $p: E \twoheadrightarrow B$, considered as an object of \mathcal{K}_B , is discrete if and only if any 2-cell with codomain E that whisks with p to an identity is invertible. In fact, the discrete objects are exactly those isofibrations that define conservative functors in $\mathbf{h}\mathcal{K}$.

5.4.1. LEMMA. An isofibration $p: E \twoheadrightarrow B$ is a discrete object of \mathcal{K}_B if and only if $p: E \twoheadrightarrow B$ is a **conservative**

functor: meaning any $X \begin{array}{c} \xrightarrow{a} \\ \Downarrow \gamma \\ \xrightarrow{b} \end{array} E$ for which $p\gamma$ is an isomorphism is invertible.

PROOF. Exercise 5.4.i. \square

Our aim in this section is to study a special class of cartesian fibrations and cocartesian fibrations:

5.4.2. DEFINITION. An isofibration $p: E \twoheadrightarrow B$ is a **discrete cartesian fibration** if it is a cartesian fibration and if it is discrete as an object of \mathcal{K}_B . Dually, an isofibration $p: E \twoheadrightarrow B$ is a **discrete cocartesian fibration** if it is a cocartesian fibration and if it is discrete as an object of \mathcal{K}_B .

The fibers of a discrete object $p: E \twoheadrightarrow B$ in \mathcal{K}_B are discrete ∞ -categories; in ∞ -cosmoi whose objects model $(\infty, 1)$ -categories, the discrete cartesian fibrations and discrete cocartesian fibrations are “ ∞ -groupoid-valued pseudofunctors.”

There is also a direct 2-categorical characterization of the discrete cartesian fibrations, which reveals that, unlike the case for cartesian and cocartesian fibrations, for their discrete analogues, there are no special classes of p -cartesian or p -cocartesian cells.

5.4.3. PROPOSITION.

- (i) If $p: E \twoheadrightarrow B$ is a discrete cartesian fibration, every natural transformation with codomain E is p -cartesian.
- (ii) An isofibration $p: E \twoheadrightarrow B$ is a discrete cartesian fibration if and only if every 2-cell $\beta: b \Rightarrow pe$ has an essentially unique lift: given $\chi: e' \Rightarrow e$ and $\psi: e'' \Rightarrow e$ so that $p\chi = p\psi = \beta$, then there exists an isomorphism $\gamma: e'' \Rightarrow e'$ with $\chi \cdot \gamma = \psi$ and $p\gamma = \text{id}$.

Note that (i) implies immediate that any commutative square

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ q \downarrow & & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

from a cartesian fibration q to a discrete cartesian fibration p defines a cartesian functor.

PROOF. By the definition of cartesian fibration, any 2-cell ψ with codomain E factors through a p -cartesian lift of $p\psi$ along a 2-cell γ so that $p\gamma = \text{id}$. The discrete objects of \mathcal{K}_B are exactly those isofibrations with the property that any 2-cell with codomain E that whiskers with p to an identity is invertible. In particular, γ is an isomorphism, and now ψ is isomorphic to a p -cartesian transformation and hence by Lemma 5.1.4 itself p -cartesian.

By (i) and Lemma 5.1.3, it's now clear that if $p: E \twoheadrightarrow B$ is a discrete cartesian fibration, then any 2-cell $\beta: b \Rightarrow pe$ has an essentially unique lift. For the converse, note first that any $p: E \twoheadrightarrow B$ satisfying this hypothesis is a discrete object: if $\psi: e' \Rightarrow e$ is so that $p\psi = \text{id}$, then $\text{id}: e \Rightarrow e$ is another lift of $p\psi$ and essential uniqueness provides an inverse isomorphism $\psi^{-1}: e \Rightarrow e'$.

To complete the proof, we now show that any 2-cell $\chi: e' \Rightarrow e$ is cartesian for p and to that end consider a pair $\tau: e'' \Rightarrow e$ and $\gamma: pe'' \Rightarrow pe'$ so that $p\tau = p\chi \cdot \gamma$. By the hypothesis that every 2-cell admits an essentially unique lift, we can construct a lift $\mu: \bar{e} \Rightarrow e'$ so that $p\mu = \gamma$. Now τ and $\chi \cdot \mu$ are two lifts of $p\tau$ with the same codomain, so there exists an isomorphism $\theta: e'' \Rightarrow \bar{e}$ with $p\theta = \text{id}$. The composite $\mu \cdot \theta$ then defines the desired lift of γ to a cell so that $\tau = \chi \cdot \mu \cdot \theta$. \square

5.4.4. EXAMPLE (domain projection from an element). For an element $b: 1 \rightarrow B$, the domain-projection functor $p_0: \text{Hom}_B(B, b) \twoheadrightarrow B$ is a discrete cartesian fibration. Cartesianness was established in Propo-

sition 5.1.23 and discreteness follows immediately from 2-cell conservativity. If $X \begin{array}{c} \xrightarrow{a} \\ \Downarrow \gamma \\ \xrightarrow{b} \end{array} \text{Hom}_B(B, b)$

is a natural transformation for which $p_0\gamma$ is an identity, then since $p_1\gamma$ is also an identity, γ must be invertible.

Dually, the codomain-projection functor $p_1: \text{Hom}_B(b, B) \twoheadrightarrow B$ is a discrete cocartesian fibration.

5.4.5. LEMMA (pullback stability). *If*

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ q \downarrow & \lrcorner & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

is a pullback square and p is a discrete cartesian fibration then q is a discrete cartesian fibration.

PROOF. In light of Proposition 5.1.20 it remains only to verify that q is discrete. Consider a 2-cell $X \begin{smallmatrix} \xrightarrow{a} \\ \Downarrow \gamma \\ \xrightarrow{b} \end{smallmatrix} F$ so that $q\gamma$ is invertible. Then $f q \gamma = p g \gamma$ is invertible and conservativity of p implies that $g\gamma$ is invertible.

By Lemma 3.1.5, the pullback square of functor spaces

$$\begin{array}{ccc} \text{Fun}(X, F) & \xrightarrow{g_*} & \text{Fun}(X, E) \\ q_* \downarrow & \lrcorner & \downarrow p_* \\ \text{Fun}(X, A) & \xrightarrow{f_*} & \text{Fun}(X, B) \end{array}$$

induces a smothering functor

$$\text{hFun}(X, F) \rightarrow \text{hFun}(X, E) \times_{\text{hFun}(X, B)} \text{hFun}(X, A)$$

We've just verified that the image of γ is an isomorphism, so conservativity implies that γ is also invertible. \square

In analogy with Theorem 5.1.11, there is an internal characterization of discrete cartesian fibrations, which in the discrete case takes a much simpler form. Recall any functor $p: E \rightarrow B$ induces functors $k: E^2 \rightarrow \text{Hom}_B(B, p)$ and $k: E^2 \rightarrow \text{Hom}_B(p, B)$ as in (5.1.10) by applying p to the generic arrow for E .

5.4.6. PROPOSITION (internal characterization of discrete fibrations). *An isofibration $p: E \rightarrow B$ is a discrete cartesian fibration if and only if the functor $k: E^2 \rightarrow \text{Hom}_B(B, p)$ is an equivalence and a discrete cocartesian fibration if and only if the functor $k: E^2 \rightarrow \text{Hom}_B(p, B)$ is an equivalence.*

Recall from Theorem 5.1.11(iii) that $p: E \rightarrow B$ defines a cartesian fibration if and only if $k: E^2 \rightarrow \text{Hom}_B(p, B)$ admits a right adjoint with invertible counit. Proposition 5.4.6 asserts that p defines a discrete cartesian fibration if and only if the unit of that adjunction, a natural transformation that defines the factorization of any natural transformation with codomain E through the canonical p -cartesian lift of its image under p , is an isomorphism, in which case that adjunction defines an adjoint equivalence and all natural transformations with codomain E are p -cartesian.

PROOF. Assume first that $p: E \rightarrow B$ is a discrete cartesian fibration. By Theorem 5.1.11(i) \Rightarrow (iii), $k: E^2 \rightarrow \text{Hom}_B(B, p)$ then admits a right adjoint \bar{r} with invertible counit $\bar{e}: k\bar{r} \cong \text{id}$. We will show that in this case the unit $\bar{\eta}: \text{id} \Rightarrow \bar{r}k$ is also invertible, proving that $k \dashv \bar{r}$ defines an adjoint equivalence.

Since the counit of $k \dashv \bar{r}$ is invertible, $k\bar{\eta}$ is an isomorphism. Thus $p_1 k \bar{\eta} = p_1 \bar{\eta}$ and $p_0 k \bar{\eta} = p p_0 \bar{\eta}$ are both isomorphisms. By conservativity of the discrete fibration $p: E \rightarrow B$ proven in Lemma 5.4.1, this implies that $p_0 \bar{\eta}$ is invertible and now 2-cell conservativity for E^2 reveals that $\bar{\eta}$ is an isomorphism.

Conversely, if $k: E^2 \rightrightarrows \mathrm{Hom}_B(B, p)$ is an equivalence, by Proposition 2.1.11, we may choose a right adjoint equivalence inverse \bar{r} . The counit of this adjoint equivalence is necessarily an isomorphism, so by Theorem 5.1.11(iii) \Rightarrow (i) we know that $p: E \rightrightarrows B$ is a cartesian fibration. Since the unit of $k \dashv \bar{r}$ is also an isomorphism, Theorem 5.1.19(vi) \Rightarrow (iv) tells us that every natural transformation with codomain E is p -cartesian, and now the conservativity property for cartesian transformations of Lemma 5.1.5 tells us that $p: E \rightrightarrows B$ defines a conservative functor, and in particular is discrete. \square

Since equivalences and simplicial limits in an ∞ -cosmos are representably-defined notions, it follows immediately from Proposition 5.4.6 that:

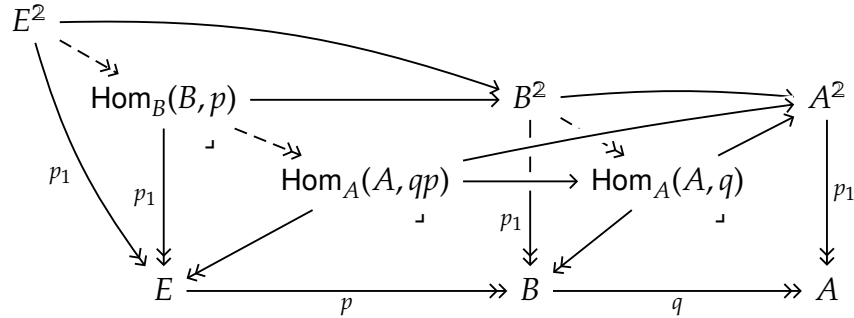
5.4.7. PROPOSITION. *An isofibration $p: E \rightrightarrows B$ in an ∞ -cosmos \mathcal{K} defines a discrete cartesian fibration if and only if for all $X \in \mathcal{K}$, the functor $p_*: \mathrm{Fun}(X, E) \rightrightarrows \mathrm{Fun}(X, B)$ defines a discrete cartesian fibration of quasi-categories.* \square

Using the internal characterization, it is straightforward to verify that discrete cartesian fibrations compose and cancel on the left:

5.4.8. LEMMA.

- (i) *If $p: E \rightrightarrows B$ and $q: B \rightrightarrows A$ are discrete cartesian fibrations, so is $qp: E \rightrightarrows A$.*
- (ii) *If $p: E \rightrightarrows B$ is an isofibration and $q: B \rightrightarrows A$ and $qp: E \rightrightarrows A$ are discrete cartesian fibrations, then so is $p: E \rightrightarrows B$.*

PROOF. By considering the defining pullback diagrams, the map $E^2 \rightrightarrows \mathrm{Hom}_A(A, qp)$ that tests whether $qp: E \rightrightarrows A$ is a discrete cartesian fibration factors as the map $E^2 \rightrightarrows \mathrm{Hom}_B(B, p)$ that tests whether $p: E \rightrightarrows B$ is a discrete cartesian fibration followed by a pullback of the map $B^2 \rightrightarrows \mathrm{Hom}_A(A, q)$ that tests whether $q: B \rightrightarrows A$ is a discrete cartesian fibration:



Both parts now follow from the 2-of-3 property. \square

The internal characterization of discrete cartesian fibrations is useful for establishing further examples.

5.4.9. LEMMA. *A trivial fibration $p: E \rightrightarrows B$ is a discrete bifibration.*

PROOF. Recall from Remark 5.1.13, that the canonical functors $k: E^2 \rightrightarrows \mathrm{Hom}_B(B, p)$ and $k: E^2 \rightrightarrows \mathrm{Hom}_B(p, B)$ can be constructed as the Leibniz cotensor of the monomorphism $1: \mathbf{1} \hookrightarrow \mathbf{2}$ in the first case and $0: \mathbf{1} \hookrightarrow \mathbf{2}$ in the second with the trivial fibration $p: E \rightrightarrows B$. By Lemma 1.2.10, both maps are trivial fibrations and in particular equivalences. Now Proposition 5.4.6 proves that p is a discrete cartesian fibration and also a discrete cocartesian fibration. \square

A final important family of examples of discrete cartesian fibrations are worth establishing. Proposition 5.1.23 proves that for any ∞ -category A , the domain-projection functor $p_0: A^2 \twoheadrightarrow A$ defines a cartesian fibration. Thus functor does *not* define a discrete cartesian fibration in the ∞ -cosmos \mathcal{K} , but recall that p_0 -cartesian lifts can be constructed to project to identity arrows along $p_1: A^2 \twoheadrightarrow A$. This suggests that we might productively consider the domain-projection functor as a map over A , in which case we have the following result:

5.4.10. PROPOSITION. *The functor*

$$\begin{array}{ccc} A^2 & \xrightarrow{(p_1 p_0)} & A \times A \\ p_1 \searrow & & \swarrow \pi \\ & A & \end{array} \quad (5.4.11)$$

defines a discrete cartesian fibration in the slice ∞ -cosmos \mathcal{K}_A .

PROOF. Note that 2-cell conservativity implies that (5.4.11) is a discrete object in $(\mathcal{K}_A)_{/\pi: A \times A \twoheadrightarrow A} \cong \mathcal{K}_{A \times A}$, so it remains only to prove that this functor defines a cartesian fibration. We prove this using Theorem 5.1.11(i) \Leftrightarrow (ii). The first step is to compute the right representable comma object for the functor (5.4.11) by interpreting the formula (3.3.2) in the slice ∞ -cosmos \mathcal{K}_A using Proposition 1.2.17. The 2-cotensor of the object $\pi: A \times A \twoheadrightarrow A$ is $\pi: A \times A^2 \twoheadrightarrow A$, so this right representable comma is computed by the left-hand pullback in \mathcal{K}_A below:

$$\begin{array}{ccccc} \mathrm{Hom}_A(A, p_0) & \xrightarrow{\quad} & A \times A^2 & \xrightarrow{\pi} & A^2 \\ \downarrow & \swarrow p_2 & \downarrow \mathrm{id}_A \times p_1 & \downarrow & \downarrow p_1 \\ A^2 & \xrightarrow{(p_1 p_0)} & A \times A & \xrightarrow{\pi} & A \\ & \searrow p_1 & \swarrow \pi & & \end{array}$$

Pasting with the right-hand pullback in \mathcal{K} , we recognize that the ∞ -category so-constructed coincides with the right representable comma object for the functor $p_0: A^2 \twoheadrightarrow A$ considered as a map in \mathcal{K} . Under the equivalence $\mathrm{Hom}_A(A, p_0) \simeq A^3$ established in the proof of Proposition 5.1.23, the isofibration $p_2: \mathrm{Hom}_A(A, p_0) \twoheadrightarrow A$ is evaluation at the final element $2 \in \mathfrak{Z}$ in the composable pair of arrows. Similarly, the canonical functor $i: A^2 \rightarrow \mathrm{Hom}_A(A, p_0)$ induced by id_{p_0} in \mathcal{K} coincides with the canonical functor $i: A^2 \rightarrow \mathrm{Hom}_A(A, p_0)$ over A induced by $\mathrm{id}_{(p_1 p_0)}$ in \mathcal{K}_A .

Now applying Proposition 5.1.23 and Theorem 5.1.11(i) \Rightarrow (ii) in \mathcal{K} , this functor i admits a right adjoint r over the domain-projection functor

$$\begin{array}{ccc} A^2 & \xrightarrow{i} & \mathrm{Hom}_A(A, p_0) \\ & \perp & \\ p_0 \searrow & & \swarrow p_0 \\ & A & \end{array} \quad \begin{array}{c} \text{dashed arrow } r \text{ from } \mathrm{Hom}_A(A, p_0) \text{ to } A^2 \end{array}$$

By the proofs of Theorem 5.1.11(iii) \Rightarrow (ii) and Proposition 5.1.23 this adjunction can be constructed by cotensoring $A^{(-)}$ the composite adjunction of categories

$$\begin{array}{ccc}
 \begin{array}{c}
 \begin{array}{ccccc}
 & & \sigma^0 & & \\
 & \swarrow & & \searrow & \\
 2 & \xleftarrow{2 \times !} & 2 \times 2 & \xleftarrow{k} & 3 \\
 & \nwarrow & \downarrow \text{T} & \nwarrow & \\
 & 2 \times 0 & & \ell & \\
 & \swarrow & & \searrow & \\
 & (1,0) & \delta^1 & (2,0) & \\
 & \searrow & & \swarrow & \\
 & \mathbb{1} + \mathbb{1} & & &
 \end{array}
 \end{array}
 \rightsquigarrow
 \begin{array}{c}
 \begin{array}{ccc}
 & i & \\
 A^2 & \xrightarrow{\quad} & A^3 \\
 & \perp & \\
 & \xleftarrow{\quad} & \\
 & r & \\
 (p_1, p_0) \swarrow & & \searrow (p_2, p_0) \\
 & A \times A &
 \end{array}
 \end{array}
 \end{array}$$

where $\ell \dashv k$ is described in the proof of Proposition 5.1.23. The composite right adjoint is the functor $\sigma^0: \mathbb{3} \Rightarrow \mathbb{2}$ that sends 0 and 1 to 0 and 2 to 1, while the composite left adjoint is the functor $\delta^1: \mathbb{2} \rhd \mathbb{3}$ that sends 0 to 0 and 1 to 2. In particular, this adjunction lies in the strict slice 2-category under the inclusion of the “endpoints” of $\mathbb{2}$ and $\mathbb{3}$.

It follows that upon cotensoring into A , we obtain a fibered adjunction over $A \times A$, which by Theorem 5.1.11(ii) \Rightarrow (i) implies that (5.4.11) is a cartesian fibration in $\mathcal{K}_{/A}$, completing the proof. \square

Combining Propositions 5.1.23 and Proposition 5.4.10, we can now generalize both results to arbitrary comma ∞ -categories.

5.4.12. COROLLARY. For any functors $C \xrightarrow{g} A \xleftarrow{f} B$ between ∞ -categories in an ∞ -cosmos \mathcal{K} :

- (i) The domain-projection functor $p_0: \text{Hom}_A(f, g) \rightrightarrows B$ is a cartesian fibration. Moreover, a natural transformation χ with codomain $\text{Hom}_A(f, g)$ is p_0 -cartesian if and only if $p_1\chi$ is invertible.
- (ii) The codomain-projection functor $p_1: \text{Hom}_A(f, g) \rightrightarrows C$ is a cocartesian fibration. Moreover, a natural transformation χ with codomain $\text{Hom}_A(f, g)$ is p_1 -cartesian if and only if $p_0\chi$ is invertible.
- (iii) The functor

$$\begin{array}{ccc}
 \text{Hom}_A(f, g) & \xrightarrow{(p_1, p_0)} & C \times B \\
 \downarrow p_1 & & \swarrow \pi \\
 & C &
 \end{array}$$

defines a discrete cartesian fibration in $\mathcal{K}_{/C}$.

- (iv) The functor

$$\begin{array}{ccc}
 \text{Hom}_A(f, g) & \xrightarrow{(p_1, p_0)} & C \times B \\
 \downarrow p_0 & & \swarrow \pi \\
 & B &
 \end{array}$$

defines a discrete cocartesian fibration in $\mathcal{K}_{/B}$.

PROOF. We prove (i) and (iii) and leave the dualizations to the reader. For (iii), we first use the cosmological functor $g^*: \mathcal{K}_{/A} \rightarrow \mathcal{K}_{/C}$, which preserves discrete cartesian fibrations, to establish that

$$\begin{array}{ccc}
 \text{Hom}_A(A, g) & \xrightarrow{(p_1, p_0)} & C \times A \\
 \downarrow p_1 & & \swarrow \pi \\
 & C &
 \end{array}$$

defines a discrete cartesian fibration in \mathcal{K}_C ; this argument works because $p_1: \mathbf{Hom}_A(A, g) \twoheadrightarrow C$ is the pullback of $p_1: A^2 \twoheadrightarrow A$ along g . Now

$$\begin{array}{ccc}
 \mathbf{Hom}_A(f, g) & \xrightarrow{\quad} & \mathbf{Hom}_A(A, g) \\
 (p_1, p_0) \downarrow & \searrow p_1 & \swarrow p_1 \downarrow (p_1, p_0) \\
 C \times B & \xrightarrow{C \times f} & C \times A \\
 \pi \searrow & & \swarrow \pi \\
 & C &
 \end{array}$$

is a pullback square in \mathcal{K}_C , so Lemma 5.4.5 now implies that the pullback is also a discrete cartesian fibration.

Using (iii) we can now prove (i). This follows directly from a general claim that if

$$\begin{array}{ccc}
 E & \xrightarrow{(q, p)} & C \times B \\
 q \searrow & & \swarrow \pi \\
 & C &
 \end{array}$$

defines a cartesian fibration in \mathcal{K}_C then $p: E \twoheadrightarrow B$ defines a cartesian fibration in \mathcal{K} . By Theorem 5.1.11(i) \Leftrightarrow (ii), this functor defines a cartesian fibration in \mathcal{K}_C if and only if the functor i

$$\begin{array}{ccc}
 E & \xrightarrow{i} & \mathbf{Hom}_B(B, p) \\
 \text{\scriptsize \perp} & & \\
 (q, p) \searrow & \text{\scriptsize r} \swarrow & \\
 & C \times B &
 \end{array}$$

admits a right adjoint r over $C \times B$. Composing with $\pi: C \times B \twoheadrightarrow B$, this fibered adjunction defines an adjunction over B , and Theorem 5.1.11(i) \Leftrightarrow (ii) applied this time in \mathcal{K} allows us to conclude that $p: E \twoheadrightarrow B$ is a cartesian fibration. \square

Note that the domain projection $p_0: \mathbf{Hom}_A(f, A) \twoheadrightarrow B$ is the pullback of $p_0: A^2 \twoheadrightarrow A$ along $f: B \rightarrow A$, so Proposition 5.1.20 proves directly from Proposition 5.1.23 that this functor is a cartesian fibration, but $p_0: \mathbf{Hom}_A(A, g) \twoheadrightarrow A$ is not similarly a pullback of $p_0: A^2 \twoheadrightarrow A$. This is why a more circuitous argument to the general result is needed.

Exercises.

5.4.i. EXERCISE. Prove Lemma 5.4.1.

5.5. The external Yoneda lemma

Let $b: 1 \rightarrow B$ be an element of an ∞ -category B and consider its right representation $\mathbf{Hom}_B(B, b)$ as a comma ∞ -category. In this case, there is no additional data given by the codomain-projection functor, but Example 5.4.4 observes that the domain-projection functor $p_0: \mathbf{Hom}_B(B, b) \twoheadrightarrow B$ has a special property: it defines a discrete cartesian fibration. The fibers of this map over an element $a: 1 \rightarrow B$ are the internal mapping spaces $\mathbf{Hom}_B(a, b)$ of Definition 3.3.9. In this way, the right representation of the element b encodes the contravariant functor represented by b , which is why all along we've been referring to the comma ∞ -categories $\mathbf{Hom}_B(B, b)$ as “representable.”

Our aim in this section is to state and prove the Yoneda lemma in this setting, where contravariant representable functors are encoded as discrete cartesian fibrations. A dual statement applies to covariant representable functors encoded as discrete cocartesian fibration $p_1: \mathbf{Hom}_B(b, B) \twoheadrightarrow B$, but for ease of exposition we leave the dualization to the reader. Informally, the Yoneda lemma asserts that “evaluation at the identity defines an equivalence,” so the first step towards the statement of the Yoneda lemma is to introduce this identity element, which in fact is something we’ve already encountered.

The identity arrow id_b induces an element $\ulcorner \mathrm{id}_b \urcorner: 1 \rightarrow \mathbf{Hom}_B(B, b)$ which Corollary 3.4.9 proves is terminal in the ∞ -category $\mathbf{Hom}_B(B, b)$ of arrows in B with codomain b . The identity element inclusion defines a functor over B

$$\begin{array}{ccc} 1 & \xrightarrow{\ulcorner \mathrm{id}_b \urcorner} & \mathbf{Hom}_B(B, b) \\ & \searrow b & \swarrow p_0 \\ & B & \end{array} \quad (5.5.1)$$

Technically, this functor does not live in the sliced ∞ -cosmos $\mathcal{K}_{/B}$ because the domain object $b: 1 \rightarrow B$ is not an isofibration but nevertheless for any isofibration $p: E \twoheadrightarrow B$, restriction along $\ulcorner \mathrm{id}_b \urcorner$ induces a functor between sliced quasi-categorical functor spaces

$$\mathbf{Fun}_B(\mathbf{Hom}_B(B, b) \xrightarrow{p_0} B, E \xrightarrow{p} B) \xrightarrow{\mathrm{ev}_{\ulcorner \mathrm{id}_b \urcorner}} \mathbf{Fun}_B(1 \xrightarrow{b} B, E \xrightarrow{p} B)$$

Here the codomain is the quasi-category defined by the pullback

$$\begin{array}{ccc} \mathbf{Fun}_B(b, p) & \longrightarrow & \mathbf{Fun}(1, E) \\ \downarrow & \lrcorner & \downarrow p_* \\ \mathbb{1} & \xrightarrow{b} & \mathbf{Fun}(1, B) \end{array}$$

which is isomorphic to $\mathbf{Fun}(1, E_b)$, the underlying quasi-category of the fiber E_b of $p: E \twoheadrightarrow B$ over b .

If a discrete cartesian fibration over B is thought of as a B -indexed discrete ∞ -category valued contravariant functor, then maps of discrete cartesian fibrations over B are “natural transformations”: the “naturality in B ” arises because we only allow functors over B . This leads to our first statement of the fibrational Yoneda lemma:

5.5.2. THEOREM (external Yoneda lemma, discrete case). *If $p: E \twoheadrightarrow B$ is a discrete cartesian fibration, then*

$$\mathbf{Fun}_B(\mathbf{Hom}_B(B, b) \xrightarrow{p_0} B, E \xrightarrow{p} B) \xrightarrow{\mathrm{ev}_{\ulcorner \mathrm{id}_b \urcorner}} \mathbf{Fun}_B(1 \xrightarrow{b} B, E \xrightarrow{p} B) \cong \mathbf{Fun}(1, E_b)$$

is an equivalence of Kan complexes.

Theorem 5.5.2 is subsumed by a generalization that allows $p: E \twoheadrightarrow B$ to be any cartesian fibration, not necessarily discrete. In this case, p encodes an “ ∞ -category-valued contravariant B -indexed functor,” as does $p_0: \mathbf{Hom}_B(B, b) \twoheadrightarrow B$. The correct notion of “natural transformation” between two such functors is now given by a cartesian functor over B ; see Exercise 5.1.iii. To that end, for a pair of cartesian fibration $q: F \twoheadrightarrow B$ and $p: E \twoheadrightarrow B$, we write

$$\mathbf{Fun}_B^{\mathrm{cart}}(F \xrightarrow{q} B, E \xrightarrow{p} B) \subset \mathbf{Fun}_B(F \xrightarrow{q} B, E \xrightarrow{p} B)$$

for the sub quasi-category containing all those simplices whose vertices define *cartesian* functors from q to p .⁶

5.5.3. THEOREM (external Yoneda lemma). *If $p: E \twoheadrightarrow B$ is a cartesian fibration, then*

$$\mathbf{Fun}_B^{\text{cart}}(\mathbf{Hom}_B(B, b) \xrightarrow{p_0} B, E \xrightarrow{p} B) \xrightarrow{\text{ev}_{\ulcorner \text{id}_b \urcorner}} \mathbf{Fun}_B(1 \xrightarrow{b} B, E \xrightarrow{p} B) \cong \mathbf{Fun}(1, E_b)$$

is an equivalence of quasi-categories.

The proofs of these theorems overlap significantly and we develop them in parallel. The basic idea is to use the universal property of $\ulcorner \text{id}_b \urcorner$ as a terminal element of $\mathbf{Hom}_B(B, b)$ to define a right adjoint to $\text{ev}_{\ulcorner \text{id}_b \urcorner}$ and prove that when $p: E \twoheadrightarrow B$ is discrete or when the domain is restricted to the sub-quasi-category of cartesian functors, this adjunction defines an adjoint equivalence. Note that the functor $\text{ev}_{\ulcorner \text{id}_b \urcorner}$ is the image of the functor $\ulcorner \text{id}_b \urcorner$ under the 2-functor $\mathbf{Fun}_B(-, p): \mathbf{h}(\mathcal{K}_B)^{\text{op}} \rightarrow \mathbf{QCat}$. If the adjunction $! \dashv \ulcorner \text{id}_b \urcorner$ lived in the slice ∞ -cosmos \mathcal{K}_B , this would directly construct a right adjoint to $\text{ev}_{\ulcorner \text{id}_b \urcorner}$. The main technical difficulty in following the outline just given is that the adjunction that witnesses the terminality of $\ulcorner \text{id}_b \urcorner$ does not live in the slice of the homotopy 2-category $\mathbf{h}\mathcal{K}_B$ but rather in a lax slice of the homotopy 2-category, that we now introduce.

5.5.4. DEFINITION. Consider a 2-category $\mathbf{h}\mathcal{K}$ and an object $B \in \mathbf{h}\mathcal{K}$. The **lax slice 2-category** $\mathbf{h}\mathcal{K}_{//B}$ is the strict 2-category whose

- objects are maps $f: X \rightarrow B$ in $\mathbf{h}\mathcal{K}$ with codomain B ;
- 1-cells are diagrams

$$\begin{array}{ccc} X & \xrightarrow{k} & Y \\ & \searrow f & \swarrow g \\ & B & \end{array} \quad \begin{array}{c} \alpha \\ \Rightarrow \end{array} \quad (5.5.5)$$

in $\mathbf{h}\mathcal{K}$; and

- 2-cells from the 1-cell displayed above to the 1-cell below-right are 2-cells $\theta: k \Rightarrow k'$ so that

$$\begin{array}{ccc} X & \xrightarrow{k'} & Y \\ \uparrow \theta & & \\ X & \xrightarrow{k} & Y \\ & \searrow f & \swarrow g \\ & B & \end{array} \quad = \quad \begin{array}{ccc} X & \xrightarrow{k'} & Y \\ & \searrow f & \swarrow g \\ & B & \end{array}$$

5.5.6. LEMMA. *The identity functor (5.5.1) is right adjoint to the right comma cone*

$$\begin{array}{ccc} \mathbf{Hom}_B(B, b) & \xrightarrow{!} & 1 \\ & \searrow p_0 & \swarrow b \\ & B & \end{array} \quad \begin{array}{c} \phi \\ \Rightarrow \end{array}$$

in $\mathbf{h}\mathcal{K}_{//B}$.

⁶For any quasi-category Q and any subset S of its vertices, there is a “full” sub-quasi-category $Q_S \subset Q$ containing exactly those vertices and all the simplices of Q that they span.

PROOF. Since 1 is the terminal ∞ -category, we take the counit of the postulated adjunction to be the identity. By Definition 5.5.4 to define the unit, we must provide a 2-cell:

$$\begin{array}{ccc} \text{Hom}_B(B, b) & \xrightarrow{\quad \ulcorner \text{id}_b \urcorner! \quad} & \text{Hom}_B(B, b) \\ \uparrow \eta & & \\ \text{Hom}_B(B, b) & \xlongequal{\quad} & \text{Hom}_B(B, b) \\ \downarrow p_0 & & \downarrow p_0 \\ & B & \end{array} = \begin{array}{ccc} \text{Hom}_B(B, b) & \xrightarrow{\quad ! \quad} 1 & \xrightarrow{\quad \ulcorner \text{id}_b \urcorner \quad} \text{Hom}_B(B, b) \\ \downarrow p_0 \Rightarrow \phi & \downarrow b & \downarrow p_0 \\ & B & \end{array}$$

so that $p_0\eta = \phi$. This is the defining property of the unit in Lemma 3.4.8. The forgetful 2-functor $\mathfrak{h}\mathcal{K}_{//B} \rightarrow \mathfrak{h}\mathcal{K}$ is faithful on 1- and 2-cells, so the verification of the triangle equalities in Lemma 3.4.8 proves that they also hold in $\mathfrak{h}\mathcal{K}_{//B}$. \square

Using somewhat non-standard 2-categorical techniques, we will transfer the adjunction of Lemma 5.5.6 to an adjunction between the quasi-categories $\mathbf{Fun}_B(b, p)$ and $\mathbf{Fun}_B(p_0, p)$; see Proposition 5.5.13. Because our initial adjunction lives in the lax rather than the strict slice, the construction will be somewhat delicate, passing through a pair of auxiliary 2-categories that we now introduce.

5.5.7. DEFINITION. Let $\mathfrak{h}\mathcal{K}$ be the homotopy 2-category of an ∞ -cosmos and write $\mathfrak{h}\mathcal{K}^\natural$ for the strict 2-category whose

- objects are cospans

$$A \xrightarrow{f} B \xleftarrow{p} E$$

in which p is a cartesian fibration;

- 1-cells are diagrams of the form

$$\begin{array}{ccccc} A' & \xrightarrow{f'} & B' & \xleftarrow{p'} & E' \\ a \downarrow & \lrcorner \phi & \downarrow b & & \downarrow e \\ A & \xrightarrow{f} & B & \xleftarrow{p} & E \end{array} \quad (5.5.8)$$

- and whose 2-cells consist of triples $\alpha: a \Rightarrow \bar{a}$, $\beta: b \Rightarrow \bar{b}$, and $\epsilon: e \Rightarrow \bar{e}$ between the verticals of parallel 1-cell diagrams so that $p\epsilon = \beta p'$ and $\bar{\phi} \cdot f\alpha = \beta f' \cdot \phi$.

5.5.9. DEFINITION. Let $\mathfrak{h}\mathcal{K}$ be the homotopy 2-category of an ∞ -cosmos and write $\mathfrak{h}\mathcal{K}^\square$ for the strict 2-category whose

- objects are pullback squares

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ q \downarrow & \lrcorner & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

whose verticals are cartesian fibrations;

- 1-cells are cubes

$$\begin{array}{ccccc}
 F' & \xrightarrow{g'} & E' & & \\
 \downarrow q' & \searrow \ell & \downarrow p' & \searrow e & \\
 & F & \xrightarrow{g} & E & \\
 & \downarrow q & \downarrow & \downarrow p & \\
 A' & \xrightarrow{f'} & B' & & \\
 \searrow a & \downarrow & \searrow b & & \\
 & A & \xrightarrow{f} & B &
 \end{array}
 \quad (5.5.10)$$

whose vertical faces commute and in which $\chi: g\ell \Rightarrow eg'$ is a p -cartesian lift of $\phi q'$; and

- whose 2-cells are given by quadruples $\alpha: a \Rightarrow \bar{a}$, $\beta: b \Rightarrow \bar{b}$, $\epsilon: e \Rightarrow \bar{e}$, and $\lambda: \ell \Rightarrow \bar{\ell}$ in which ϵ and λ are, respectively, lifts of $\beta p'$ and $\alpha q'$ and so that $\phi \cdot f\alpha = \beta f' \cdot \phi$ and $\bar{\chi} \cdot g\lambda = \epsilon g' \cdot \chi$.

These definitions are arranged so that there is an evident forgetful 2-functor $\mathfrak{h}\mathcal{K}^\square \rightarrow \mathfrak{h}\mathcal{K}^\triangleleft$.

5.5.11. LEMMA. *The forgetful 2-functor $\mathfrak{h}\mathcal{K}^\square \rightarrow \mathfrak{h}\mathcal{K}^\triangleleft$ is a smothering 2-functor.*

PROOF. Proposition 5.1.20 tells us that $\mathfrak{h}\mathcal{K}^\square \rightarrow \mathfrak{h}\mathcal{K}^\triangleleft$ is surjective on objects. To see that it is full on 1-cells, first form the pullbacks of the cospans in (5.5.8), then define χ to be any p -cartesian lift of $\phi q'$ with codomain eg' . By construction, the domain of χ lies strictly over faq' and so this functor factors uniquely through the pullback leg g defining the map ℓ of (5.5.10).

To prove that $\mathfrak{h}\mathcal{K}^\square \rightarrow \mathfrak{h}\mathcal{K}^\triangleleft$ is full on 2-cells, consider a parallel pair of 1-cells in $\mathfrak{h}\mathcal{K}^\square$. For one of these we use the notation of (5.5.10) and for the other we denote the diagonal functors by $\bar{a}, \bar{b}, \bar{e}$, and $\bar{\ell}$ and denote the 2-cells by $\bar{\phi}$ and $\bar{\chi}$; the requirement that these 1-cells be parallel implies that the pullback faces are necessarily the same. Now consider a triple $\alpha: a \Rightarrow \bar{a}$, $\beta: b \Rightarrow \bar{b}$, and $\epsilon: e \Rightarrow \bar{e}$ satisfying the conditions of Definition 5.5.7. Our task is to define a fourth 2-cell $\lambda: \ell \Rightarrow \bar{\ell}$ so that $q\lambda = \alpha q'$ and $\bar{\chi} \cdot g\lambda = \epsilon g' \cdot \chi$.

To achieve this, we first define a 2-cell $\gamma: g\ell \Rightarrow g\bar{\ell}$ using the induction property of the p -cartesian cell $\bar{\chi}: g\bar{\ell} \Rightarrow \bar{e}g'$ applied to the composite 2-cell $\epsilon g' \cdot \chi: g\ell \Rightarrow \bar{e}g'$ and the factorization $p\epsilon g' \cdot p\chi = \bar{\phi} q' \cdot faq'$. By construction $p\gamma = faq'$ so the pair $\alpha q'$ and γ induces a 2-cell $\lambda: \ell \Rightarrow \bar{\ell}$ so that $q\lambda = \alpha q'$ and $g\lambda = \gamma$. The quadruple $(\alpha, \beta, \epsilon, \lambda)$ now defines the required 2-cell in $\mathfrak{h}\mathcal{K}^\square$.

Finally, for 2-cell conservativity, suppose α, β , and ϵ as above are isomorphisms. By the conservativity property for pullbacks to show that λ is an isomorphism, it suffices to prove that $q\lambda = \alpha q'$ is, which we know already, and that $g\lambda = \gamma$ is invertible. But γ was constructed as a factorization $\epsilon g' \cdot \chi = \bar{\chi} \cdot \gamma$ with $p\gamma = faq'$. Since ϵ is an isomorphism, $\epsilon g' \cdot \chi$ is p -cartesian, so Lemma 5.1.5 proves that γ is an isomorphism. \square

5.5.12. REMARK. While we cannot directly define a pullback 2-functor $\mathfrak{h}\mathcal{K}^\triangleleft \rightarrow \mathfrak{h}\mathcal{K}$ in the homotopy 2-category because the 2-categorical universal property of pullbacks in $\mathfrak{h}\mathcal{K}$ is weak and not strict, the zig zag of 2-functors $\mathfrak{h}\mathcal{K}^\triangleleft \leftarrow \mathfrak{h}\mathcal{K}^\square \rightarrow \mathfrak{h}\mathcal{K}$, in which the backwards map is a smothering 2-functor and the forwards map evaluates at the pullback vertex, defines a reasonable replacement.

Using Lemma 5.5.11, we can now construct the desired adjunction:

5.5.13. PROPOSITION. For any element $b: 1 \rightarrow B$ and any cartesian fibration $p: E \rightarrow B$, the evaluation at the identity functor admits a right adjoint

$$\begin{array}{ccc} & \xrightarrow{\text{ev}_{\text{id}_B}^\top} & \\ \text{Fun}_B(p_0, p) & \perp & \text{Fun}_B(b, p) \\ & \xleftarrow{R} & \end{array}$$

defined by the domain-component of the p_* -cartesian lift of the right comma cone over b :

$$\begin{array}{ccccc} \text{Fun}_B(b, p) & \xrightarrow{\quad} & \text{Fun}(1, E) & \xrightarrow{!^*} & \text{Fun}(\text{Hom}_B(B, b), E) \\ \downarrow \lrcorner & \searrow R & \uparrow \chi & \downarrow p_* & \downarrow p_* \\ & \text{Fun}_B(p_0, p) & \xrightarrow{\quad} & \text{Fun}(\text{Hom}_B(B, b), E) & \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ \mathbb{1} & \xrightarrow{b} & \text{Fun}(1, B) & \xrightarrow{!^*} & \text{Fun}(\text{Hom}_B(B, b), B) \\ & \searrow \lrcorner & \uparrow \phi & \downarrow p_0 & \\ & \mathbb{1} & \xrightarrow{\quad} & \text{Fun}(\text{Hom}_B(B, b), B) & \end{array} \quad (5.5.14)$$

The idea will be to transfer the adjunction of Lemma 5.5.6 through a sequence of 2-functors

$$\begin{array}{ccc} \mathfrak{h}QC\text{at}^\square & \xrightarrow{\text{ev}_\top} & \mathfrak{h}QC\text{at} \\ \downarrow & & \\ \mathfrak{h}\mathcal{K}_{//B}^{\text{op}} & \longrightarrow & \mathfrak{h}QC\text{at}^\lrcorner \end{array}$$

using Lemma 3.5.8 to lift along the middle smothering 2-functor.

PROOF. Fixing a cartesian fibration $p: E \rightarrow B$ in \mathcal{K} , we define a 2-functor⁷ $\mathcal{K}_{//B}^{\text{op}} \rightarrow \mathfrak{h}QC\text{at}^\lrcorner$ that carries a 1-cell (5.5.5) to

$$\begin{array}{ccccc} \mathbb{1} & \xrightarrow{g} & \text{Fun}(Y, B) & \xleftarrow{p_*} & \text{Fun}(Y, E) \\ \parallel & \uparrow \alpha & \downarrow k^* & & \downarrow e \\ \mathbb{1} & \xrightarrow{f} & \text{Fun}(X, B) & \xleftarrow{p_*} & \text{Fun}(X, E) \end{array}$$

and a 2-cell $\theta: k \Rightarrow k'$ to the 2-cell that acts via pre-whiskering with θ in its two non-identity components. By Corollary 5.1.16, the functors p_* are cartesian fibration of quasi-categories.

We now apply the 2-functor $\mathcal{K}_{//B}^{\text{op}} \rightarrow \mathfrak{h}QC\text{at}^\lrcorner$ to the adjunction of Lemma 5.5.6 to obtain an adjunction in $\mathfrak{h}QC\text{at}^\lrcorner$ and then use the smothering 2-functor of Lemma 5.5.11 and Lemma 3.5.8 to lift this to an adjunction in $\mathfrak{h}QC\text{at}^\square$. As elaborated on in Exercise 3.5.ii, the lifted adjunction in $\mathfrak{h}QC\text{at}^\square$ can be constructed using any lifts of the objects, 1-cells, and either the unit or counit of the adjunction in $\mathfrak{h}QC\text{at}^\lrcorner$.

⁷To explain the variance, recall that the 2-functor $\text{Fun}(-, B): \mathfrak{h}\mathcal{K}^{\text{op}} \rightarrow \mathfrak{h}QC\text{at}$ is contravariant on 1-cells but covariant on 2-cells. Such 2-functors, like all 2-functors, preserve adjunctions, though in this case the left and right adjoints are interchanged, while the units and counits retain the same roles.

In particular, we may take the left adjoint of the lifted adjunction in $\mathfrak{h}QCat^\square$ to be any lift of the image in $\mathfrak{h}QCat^\square$ of the right adjoint of the adjunction $! \dashv \ulcorner \text{id}_b \urcorner$ in $\mathfrak{h}\mathcal{K}_{//B}$, and so our left adjoint is

$$\begin{array}{ccccc}
\text{Fun}_B(p_0, p) & \xrightarrow{\quad} & \text{Fun}(\text{Hom}_B(B, b), E) & \xrightarrow{\ulcorner \text{id}_b \urcorner^*} & \text{Fun}(1, E) \\
\downarrow & \swarrow \text{ev} \ulcorner \text{id}_b \urcorner & \downarrow p_* & & \downarrow p_* \\
& & \text{Fun}_B(b, p) & \xrightarrow{\quad} & \text{Fun}(1, E) \\
& & \downarrow & & \downarrow p_* \\
\mathbb{1} & \xrightarrow{p_0} & \text{Fun}(\text{Hom}_B(B, b), B) & \xrightarrow{\ulcorner \text{id}_b \urcorner^*} & \text{Fun}(1, B) \\
& & \downarrow & & \downarrow \\
& & \mathbb{1} & \xrightarrow{b} & \text{Fun}(1, B)
\end{array}$$

We may also take the right adjoint to be any lift of the image of the right adjoint of the adjunction. This proves that the right adjoint is defined by (5.5.14). Since the counit of $! \dashv \ulcorner \text{id}_b \urcorner$ is an identity, the counit of the lifted adjunction may also be taken to be an identity.

Finally, we compose with the forgetful 2-functor $\mathfrak{h}QCat^\square \rightarrow \mathfrak{h}QCat$ that evaluates at the pullback vertex to project our adjunction in $\mathfrak{h}QCat^\square$ to the desired adjunction in $\mathfrak{h}QCat$. \square

The proof of the discrete case of the Yoneda lemma is now one line.

PROOF OF THEOREM 5.5.2. If $p: E \twoheadrightarrow B$ is discrete, then $\text{Fun}_B(p_0, p)$ and $\text{Fun}_B(b, p)$ are Kan complexes, so the adjunction defined in Proposition 5.5.13 is an adjoint equivalence. \square

Specializing to the case of two right representable discrete cartesian fibrations, we conclude that the Kan complex of natural transformations is equivalent to the underlying quasi-category of their internal mapping space.

5.5.15. COROLLARY (external Yoneda embedding). *For any elements $x, y: 1 \rightrightarrows A$ in an ∞ -category A , evaluation at the identity of x induces an equivalence of Kan complexes*

$$\text{Fun}_A(\text{Hom}_A(A, x), \text{Hom}_A(A, y)) \xrightarrow[\sim]{\text{ev} \ulcorner \text{id}_x \urcorner} \text{Fun}(1, \text{Hom}_A(x, y)) \quad \square$$

It remains to prove the general case of Theorem 5.5.3. The next step is to observe that the right adjoint in the adjunction of Proposition 5.5.13 lands in the sub quasi-category of cartesian functors from p_0 to p . Lemma 5.5.16 proves this after which it is short work to complete the proof of Theorem 5.5.3 by arguing that this restricted adjunction defines an adjoint equivalence.

5.5.16. LEMMA. *For each vertex in $\text{Fun}_B(b, p)$ below-left*

$$\begin{array}{ccc}
\text{Fun}_B(b, p) & \xrightarrow{R} & \text{Fun}_B(p_0, p) \\
\begin{array}{ccc} 1 & \xrightarrow{e} & E \\ & \searrow b & \swarrow p \\ & B & \end{array} & \mapsto & \begin{array}{ccc} \text{Hom}_B(B, b) & \xrightarrow{Re} & E \\ & \searrow p_0 & \swarrow p \\ & B & \end{array}
\end{array}$$

the map Re in $\text{Fun}_B(p_0, p)$ above-right defines a cartesian functor in \mathcal{K}_B .

PROOF. From the definition of the right adjoint in (5.5.14) and Lemma 5.3.5, we see that Re is the domain component of a p -cartesian lift χ of the composite natural transformation below-left

$$\begin{array}{ccc} \mathrm{Hom}_B(B, b) & \xrightarrow{!} 1 & \xrightarrow{e} E \\ \searrow \uparrow \phi & \downarrow b & \swarrow p \\ & B & \end{array} \quad p_0 \searrow \rightarrow B \quad = \quad \begin{array}{ccc} \mathrm{Hom}_B(B, b) & \xrightarrow{e!} E \\ \searrow p_0 & \uparrow \chi & \swarrow Re \\ & B & \end{array} \quad p \searrow \rightarrow B$$

Since $p_0: \mathrm{Hom}_B(B, b) \twoheadrightarrow B$ is discrete, every natural transformation ψ with codomain $\mathrm{Hom}_B(B, b)$ is p_0 -cartesian, so to prove that Re defines a cartesian functor, we must show that $Re\psi$ is p -cartesian. To that end, consider the horizontal composite

$$\begin{array}{ccccc} X & \xrightarrow{y} & \mathrm{Hom}_B(B, b) & \xrightarrow{e!} & E \\ & \uparrow \psi & & \uparrow \chi & \\ & x & & Re & \end{array}$$

By naturality of whiskering, we have $\chi y \cdot Re\psi = e!\psi \cdot \chi x = \chi x$, since 1 is the terminal ∞ -category and hence $e!\psi$ is an identity. Now Lemma 5.1.24(ii) implies that $Re\psi$ is p -cartesian. \square

PROOF OF THEOREM 5.5.3. By Lemma 5.5.16, the adjunction of Proposition 5.5.13 restricts to define an adjunction

$$\begin{array}{ccc} \mathrm{Fun}_B^{\mathrm{cart}}(p_0, p) & \xrightarrow{\mathrm{ev}_{r_{\mathrm{id}_b}^\gamma}} & \mathrm{Fun}_B(b, p) \\ & \perp & \\ & \xleftarrow{R} & \end{array}$$

Since the counit of the original adjunction $! \dashv r_{\mathrm{id}_b}^\gamma$ is an isomorphism and smothering 2-functors are conservative on 2-cells, the counit of the adjunction of Proposition 5.5.13 and hence also of the restricted adjunction is an isomorphism. As in the proof of Theorem 5.5.2, we will prove that $\mathrm{ev}_{r_{\mathrm{id}_b}^\gamma}$ is an equivalence by demonstrating that the unit of the restricted adjunction is also invertible. By Lemma ??, it suffices to verify this elementwise, proving that the component of the unit indexed by a cartesian functor

$$\begin{array}{ccc} \mathrm{Hom}_B(B, b) & \xrightarrow{f} & E \\ & \searrow p_0 & \swarrow p \\ & B & \end{array}$$

is an isomorphism.

Unpacking the proof of Proposition 5.5.13, the unit $\hat{\eta}$ of $\mathrm{ev}_{r_{\mathrm{id}_b}^\gamma} \dashv R$ is defined to be a factorization

$$\begin{array}{ccccc} \mathrm{Fun}_B(p_0, p) & \hookrightarrow & \mathrm{Fun}(\mathrm{Hom}_B(B, b), E) & \xrightarrow{r_{\mathrm{id}_b}^{\gamma*}} & \mathrm{Fun}(1, E) \\ & \Downarrow & & \uparrow \mathrm{Fun}(\eta, E) & \downarrow !^* \\ \mathrm{Fun}_B(p_0, p) & \xrightarrow{\mathrm{ev}_{r_{\mathrm{id}_b}^\gamma}} & \mathrm{Fun}_B(b, p) & \hookrightarrow & \mathrm{Fun}(1, E) \\ & \uparrow \hat{\eta} & \downarrow R & \uparrow \chi & \downarrow !^* \\ & & \mathrm{Fun}_B(p_0, p) & \hookrightarrow & \mathrm{Fun}(\mathrm{Hom}_B(B, b), E) \end{array}$$

of the pre-whiskering 2-cell $\mathbf{Fun}(\eta, E)$ through the p_* -cartesian lift χ . The component of the pre-whiskering 2-cell $\mathbf{Fun}(\eta, E)$ at the cartesian functor f is $f\eta$. Since $p_0: \mathbf{Hom}_B(B, b) \rightarrow B$ is a discrete cartesian fibration, any 2-cell, such as η , which has codomain $\mathbf{Hom}_B(B, b)$ is p_0 -cartesian, and since f is a cartesian functor, we then see that $f\eta$ is p -cartesian.

By Lemma 5.3.8, the components of the p_* -cartesian cell χ define p -cartesian natural transformations in \mathcal{K} . As $\hat{\eta}$ is a natural transformation with codomain $\mathbf{Fun}_B(p_0, p)$ its components project along p to the identity. In this way, we see that $\hat{\eta}f$ is a factorization of the p -cartesian transformation $f\eta$ through a p -cartesian lift of ϕ over an identity, and Lemma 5.1.5 proves that $\hat{\eta}f$ is an isomorphism, as desired. \square

Exercises.

5.5.i. EXERCISE. Given an element $f: 1 \rightarrow \mathbf{Hom}_A(x, y)$ in the internal mapping space between a pair of elements in an ∞ -category A , use the explicit description of the inverse equivalence to the map of Corollary 5.5.15 to construct a map

$$\begin{array}{ccc} \mathbf{Hom}_A(A, x) & \xrightarrow{\quad f_* \quad} & \mathbf{Hom}_A(A, y) \\ & \searrow p_0 \quad \swarrow p_0 & \\ & A & \end{array}$$

which represents the “natural transformation” defined by post-composing with f .⁸

⁸Hint: this construction is a special case of the construction given in the first half of the proof of Lemma 5.5.16.

Part II

Homotopy coherent category theory

Simplicial computads and homotopy coherence

Consider a diagram $d: 1 \rightarrow A^J$ in an ∞ -category A indexed by a 1-category J . Via the isomorphism $\text{Fun}(1, A^J) \cong \text{Fun}(1, A)^J$, an element in the ∞ -category of diagrams A^J equally defines a functor $d: J \rightarrow \text{Fun}(1, A)$ valued in the underlying quasi-category of A . Applying $\mathbf{h}: \mathbf{QCat} \rightarrow \mathbf{Cat}$, this descends to a diagram $\mathbf{h}d: J \rightarrow \mathbf{h}A$ of shape J in the homotopy category of A ; such diagrams are called *homotopy commutative*. But the original diagram d has a much richer property, defining what is called a *homotopy coherent* diagram of shape J in the quasi-category $\text{Fun}(1, A)$.

To make the data involved in defining a homotopy coherent diagram most explicit, we first introduce a general notion of homotopy coherent diagram as a simplicial functor valued in a simplicial category whose hom-spaces are Kan complexes. What makes such diagrams “homotopy coherent” and not just “simplicially enriched” is that their domains are required to be “free” simplicial categories of a particular form that we refer to by the name *simplicial computads*. Because every quasi-category can be presented up to equivalence by a Kan-complex enriched category, it will follow that “all diagrams valued in quasi-categories are homotopy coherent.”

To build intuition for the general notion of a homotopy coherent diagram, it is helpful to consider a special case of diagrams indexed by the category

$$\omega := \quad 0 \longrightarrow 1 \longrightarrow 2 \longrightarrow 3 \longrightarrow \cdots$$

whose objects are finite ordinals and with a morphism $j \rightarrow k$ if and only if $j \leq k$ and valued in the Kan-complex enriched category of spaces \mathbf{Space} . A ω -shaped graph in \mathbf{Space} is comprised of spaces X_k for each $k \in \omega$ together with continuous maps $f_{j,k}: X_j \rightarrow X_k$ whenever $j < k$.¹ This data defines a *homotopy commutative diagram* just when $f_{i,k} \simeq f_{j,k} \circ f_{i,j}$ whenever $i < j < k$.²

To extend this data to a *homotopy coherent diagram* $\omega \rightarrow \mathbf{Space}$ requires:

- Chosen homotopies $h_{i,j,k}: f_{i,k} \simeq f_{j,k} \circ f_{i,j}$ whenever $i < j < k$. This amounts to specifying a path in $\text{Map}(X_i, X_k)$ from the vertex $f_{i,k}$ to the vertex $f_{j,k} \circ f_{i,j}$, which is obtained as the composite of the two vertices $f_{i,j} \in \text{Map}(X_i, X_j)$ and $f_{j,k} \in \text{Map}(X_j, X_k)$.

¹To simplify somewhat we adopt the convention that $f_{j,j}$ is the identity, making this data into a reflexive directed graph with implicitly designated identities.

²This data defines a strictly commutative diagram (aka a functor $\omega \rightarrow \mathbf{Space}$) just when $f_{i,k} = f_{j,k} \circ f_{i,j}$ whenever $i < j < k$. Strictly commutative diagrams are certainly homotopy commutative. Homotopy coherent category theory arose from the search for conditions under which something like the converse implication held: a homotopy commutative diagram is realized by (i.e., naturally isomorphic to up to homotopy) a strictly commutative diagram, if and only if it extends to a homotopy coherent diagram [18, 2.5].

- For $i < j < k < \ell$, the chosen homotopies provide four paths in $\mathbf{Map}(X_i, X_\ell)$

$$\begin{array}{ccc} f_{i,\ell} & \xrightarrow{h_{i,k,\ell}} & f_{k,\ell} \circ f_{i,k} \\ h_{i,j,\ell} \Big\downarrow & & \Big\downarrow f_{k,\ell} \circ h_{i,j,k} \\ f_{j,\ell} \circ f_{i,j} & \xrightarrow{h_{j,k,\ell} \circ f_{i,j}} & f_{k,\ell} \circ f_{j,k} \circ f_{i,j} \end{array}$$

We then specify a higher homotopy — a *2-homotopy* — filling in this square.

- For $i < j < k < \ell < m$, the previous choices provide 12 paths and six 2-homotopies in $\mathbf{Map}(X_i, X_m)$ that assemble into the boundary of a cube. We then specify a *3-homotopy*, a homotopy between homotopies between homotopies, filling in this cube.
- Etc.

Even in this simple case of the category ω , this data is a bit unwieldy. Our task is to define a category to index this homotopy coherent data arising from ω : the objects X_i , the functions $X_i \rightarrow X_j$, the 1-homotopies $h_{i,j,k}$, the 2-homotopies, and so on. This data will assemble into a simplicial category whose objects are the same as the objects of ω but which will have n -morphisms in each dimension $n \geq 0$, to index the n -homotopies. Importantly, this simplicial category will be “freely generated” from a much smaller collection of data. We begin by studying such “freely generated” simplicial categories under the name **simplicial computads**.

6.1. Simplicial computads

6.1.1. DEFINITION (free categories and atomic arrows). An arrow f in a 1-category is **atomic** if it is not an identity and if it admits no non-trivial factorizations: i.e., if whenever $f = g \circ h$, either g or h is an identity.

A 1-category is **free** if every arrow may be expressed uniquely as a composite of atomic arrows, with the convention that empty composites correspond to identity arrows.³

6.1.2. DIGRESSION (on free categories and reflexive directed graphs). The category of presheaves on the truncation

$$\Delta_{\leq 1} := \bullet \begin{array}{c} \xrightarrow{s} \\ \xleftarrow{i} \\ \xrightarrow{t} \end{array} \bullet \quad is = it = \text{id}$$

defines the category \mathcal{Gph} of (reflexive, directed) graphs: for us, a **graph** consists of a set of vertices, a set of edges each with a specified source and target vertex, and a distinguished “identity” endo-edge for each vertex. Any category has an underlying reflexive directed graph, and this forgetful functor admits a left adjoint, defining the free category whose atomic and identity arrows are the arrows in the given graph:

$$\begin{array}{ccc} & \xleftarrow{F} & \\ \text{Cat} & \perp & \mathcal{Gph} \\ & \xrightarrow{U} & \end{array}$$

Recall, from Digression 1.2.2, that a simplicial category \mathcal{A} may be presented by a family of 1-categories \mathcal{A}_n of n -arrows, for $n \geq 0$, each with a common set of objects, that assemble into a diagram $\mathcal{A}_\bullet : \Delta^{\text{op}} \rightarrow$

³Alternatively, a 1-category is **free** if every non-identity arrow may be expressed uniquely as a non-empty composite of atomic arrows and if identity arrows admit no non-trivial factorizations.

Cat comprised of identity-on-objects functors. The notion of “free” simplicial category was first introduced by Dwyer and Kan [19, 4.5].

6.1.3. DEFINITION (simplicial computad). A simplicial category \mathcal{A} is a **simplicial computad** if and only if

- Each category \mathcal{A}_n of n -arrows is freely generated by the graph of atomic n -arrows.
- If f is an atomic n -arrow in \mathcal{A}_n and $\sigma: [m] \twoheadrightarrow [n]$ is an epimorphism in Δ , then the degenerated m -arrow $f \cdot \sigma$ is atomic in \mathcal{A}_m .

By the Eilenberg-Zilber lemma⁴, a simplicial category \mathcal{A} is a simplicial computad if and only if all of its non-identity arrows can be expressed uniquely as a composite

$$f = (f_1 \cdot \alpha_1) \circ (f_2 \cdot \alpha_2) \circ \cdots \circ (f_\ell \cdot \alpha_\ell)$$

in which each f_i is non-degenerate and atomic and each α_i is a degeneracy operator in Δ .

6.1.4. EXAMPLE. A 1-category A may be regarded as a simplicial category A_\bullet in which $A_n := A$ for all n . In the construction, the hom-spaces of A coincide with the hom-sets of A . Such “constant” simplicial categories define simplicial computads if and only if the 1-category A is free.

6.1.5. EXAMPLE. For any simplicial set U , let $2[U]$ denote the simplicial category with two objects “−” and “+” and with hom-spaces defined by

$$2[U](+, -) := \emptyset, \quad 2[U](+, +) := \mathbb{1} =: 2[U](-, -), \quad 2[U](-, +) := U.$$

This simplicial category is a simplicial computad because there are no composable sequences of arrows in $2[U]$ containing more than one non-identity arrow. Every arrow from − to + is atomic.

6.1.6. DEFINITION. A simplicial functor $G: \mathcal{A} \rightarrow \mathcal{B}$ between simplicial computads defines a **simplicial computad morphism** if it maps every atomic arrow f in \mathcal{A} to an arrow Gf which is either atomic or an identity in \mathcal{B} . Write $\mathcal{SSet}\text{-}Cptd \subset \mathcal{SSet}\text{-}Cat$ for the non-full subcategory of simplicial computads and their morphisms.

The axioms of Definition 6.1.3 assert that the atomic and identity n -arrows of a simplicial computad assemble into a diagram in $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$ and a simplicial computad morphism restricts to define a natural transformation between the underlying $\Delta_{\text{epi}}^{\text{op}}$ -indexed graphs of atomic and identity arrows; in this way, restricting to the atomic or identity arrows defines a functor $\text{atom}: \mathcal{SSet}\text{-}Cptd \rightarrow \mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$. The next lemma tells us that the category $\mathcal{SSet}\text{-}Cptd$ is canonically isomorphic to the intersection of $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$ and $\mathcal{SSet}\text{-}Cat$ in $Cat^{\Delta_{\text{epi}}^{\text{op}}}$.

6.1.7. LEMMA. *The functor that carries a simplicial computad to its underlying diagram of atomic and identity arrows and the inclusion of simplicial computads into simplicial categories define the legs of a pullback cone:*

$$\begin{array}{ccc} \mathcal{SSet}\text{-}Cptd & \hookrightarrow & \mathcal{SSet}\text{-}Cat \\ \text{atom} \downarrow & \lrcorner & \downarrow \\ \mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}} & \xrightarrow{F^{\Delta_{\text{epi}}^{\text{op}}}} & Cat^{\Delta_{\text{epi}}^{\text{op}}} \end{array}$$

⁴The Eilenberg-Zilber lemma asserts that any degenerate simplex in a simplicial set may be uniquely expressed as a degenerated image of a non-degenerate simplex; see [21, II.3.1, pp. 26-27].

Moreover since $\mathcal{SSet}\text{-}Cat$ and $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$ have colimits, the functors to $Cat^{\Delta_{\text{epi}}^{\text{op}}}$ preserve them, and $F^{\Delta_{\text{epi}}^{\text{op}}}$ is an isofibration, it follows that $\mathcal{SSet}\text{-}Cptd$ has colimits created by either of the functors to $\mathcal{SSet}\text{-}Cat$ or to $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$.

PROOF. If \mathcal{A} is a simplicial category, presented as a simplicial object $\mathcal{A}_\bullet: \Delta^{\text{op}} \rightarrow Cat$, then \mathcal{A} is a simplicial computad if and only if there exists a dotted lift as below-left

$$\begin{array}{ccc}
 \Delta_{\text{epi}}^{\text{op}} & \xrightarrow{-\exists!-} & \mathcal{Gph} \\
 \downarrow & & \downarrow F \\
 \Delta^{\text{op}} & \xrightarrow{\mathcal{A}_\bullet} & Cat
 \end{array}
 \qquad
 \begin{array}{ccc}
 \Delta_{\text{epi}}^{\text{op}} & \xrightarrow{\quad \Downarrow \exists! \quad} & \mathcal{Gph} \\
 \downarrow & \nearrow \mathcal{A}_\bullet & \downarrow F \\
 \Delta^{\text{op}} & \xrightarrow{\quad \Downarrow G \quad} & Cat \\
 & \searrow \mathcal{B}_\bullet &
 \end{array}$$

in which case this lift is necessarily unique. Correspondingly, as simplicial functor $G: \mathcal{A} \rightarrow \mathcal{B}$ defines a computad morphism if and only if the restricted natural transformation above-right also lifts through the free category functor, again necessarily uniquely. These facts verify that the category $\mathcal{SSet}\text{-}Cptd$ is captured as the stated pullback.

Now consider a diagram $D: J \rightarrow \mathcal{SSet}\text{-}Cptd$ and form its colimit cone in $\mathcal{SSet}\text{-}Cat$ and in $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$. The functors to $Cat^{\Delta_{\text{epi}}^{\text{op}}}$ carry these to a pair of isomorphic colimit cones under the same diagram and since $F^{\Delta_{\text{epi}}^{\text{op}}}$ is an isofibration (any category isomorphic to a free category is itself a free category and this isomorphism necessarily restricts to underlying graphs of atomic arrows), there exists a colimit cone under D in $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$ whose image under $F^{\Delta_{\text{epi}}^{\text{op}}}$ is equal to the image of the colimit cone under D in $\mathcal{SSet}\text{-}Cat$. Now the universal property of the pullback allows us to lift this cone to $\mathcal{SSet}\text{-}Cptd$, and a similar argument using the 2-categorical universal property of the pullback diagram of categories demonstrates that the lifted cone is a colimit cone. \square

6.1.8. DEFINITION (simplicial subcomputads). A simplicial computad morphism $\mathcal{A} \hookrightarrow \mathcal{B}$ that is injective on objects and faithful — i.e., carries every atomic arrow in \mathcal{A} to an atomic arrow in \mathcal{B} — displays \mathcal{A} as a **simplicial subcomputad** of \mathcal{B} .

The simplicial subcomputad \bar{S} **generated by** a set of arrows S in a simplicial computad \mathcal{A} is the smallest simplicial subcomputad of \mathcal{A} containing those arrows. The objects of \bar{S} are those objects that appear as domains or codomains of arrows in S and its set of morphisms is the smallest subset of morphisms containing S that have the following closure properties:

- if $f \in \bar{S}$ and $\alpha: [n] \rightarrow [m] \in \Delta$, then $f \cdot \alpha \in \bar{S}$.
- If $f, g \in \bar{S}$ are composable then $f \circ g \in \bar{S}$.

Lemma 6.1.7 proves that simplicial computads and computad morphisms are closed under colimits formed in the category of simplicial categories. For certain special colimit shapes, the property of being a simplicial subcomputad is also preserved:

6.1.9. LEMMA. A simplicial subcategory $\mathcal{A} \hookrightarrow \mathcal{B}$ of a simplicial computad \mathcal{B} displays \mathcal{A} as a simplicial subcomputad of \mathcal{B} just when \mathcal{A} is closed under factorizations: if f and g are composable arrows of \mathcal{B} and $f \circ g \in \mathcal{A}$ then f and g are in \mathcal{A} .

PROOF. Exercise 6.1.i. \square

6.1.10. LEMMA. *Simplicial subcomputads are closed under coproduct, pushout, and colimit of countable sequences.*

PROOF. Simplicial subcomputad inclusions are precisely those morphisms in $\mathcal{SSet}\text{-}Cptd$ whose images in $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$ are pointwise monomorphisms. Lemma 6.1.7 proves that colimits in $\mathcal{SSet}\text{-}Cptd$ are crated in $\mathcal{Gph}^{\Delta_{\text{epi}}^{\text{op}}}$. As colimits in this presheaf category are formed pointwise and as monomorphisms are stable under coproduct, pushout, and colimit of countable sequences, the result follows. \square

6.1.11. DEFINITION (relative simplicial computad). The class of all **relative simplicial computads** is the class of all simplicial functors that can be expressed as a countable composite of pushouts of coproducts of

- the unique simplicial functor $\emptyset \hookrightarrow \mathbf{1}$ and
- the simplicial subcomputad inclusion $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$ for $n \geq 0$.

The next lemma reveals that relative simplicial computads differ from simplicial subcomputad inclusions only in the fact that the domains of relative simplicial computads need not be simplicial computads — but when they are, the codomain is also a simplicial computad and the map is a simplicial subcomputad inclusion.

6.1.12. LEMMA. *If \mathcal{A} is a simplicial computad, then an inclusion of simplicial categories $\mathcal{A} \hookrightarrow \mathcal{B}$ is a simplicial computad inclusion if and only if it is a relative simplicial computad. In particular, a simplicial category \mathcal{B} is a simplicial computad if and only if $\emptyset \hookrightarrow \mathcal{B}$ is a relative simplicial computad.*

PROOF. First note that $\emptyset \hookrightarrow \mathbf{1}$ and $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$ are simplicial subcomputad inclusions: the first case is trivial and for the latter, all the non-identity arrows in $2[U]$ are atomic. By Lemma 6.1.10, to prove that any relative simplicial computad $\mathcal{A} \hookrightarrow \mathcal{B}$ whose domain is a simplicial computad is a subcomputad inclusion, it suffices to prove that for any simplicial computad \mathcal{A} and any simplicial functor $f: 2[\partial\Delta[n]] \rightarrow \mathcal{A}$, not necessarily a computad morphism, the pushout of $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$ along f is a simplicial computad containing \mathcal{A} as a simplicial subcomputad.

The subcomputad inclusion $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$ is full on r -arrows for $r < n$; for $r > n$, the codomain is constructed by adjoining one atomic arrow from $-$ to $+$ for each epimorphism $[r] \twoheadrightarrow [n]$. It follows that the pushout $\mathcal{A} \hookrightarrow \mathcal{A}'$ is similarly full on r -arrows for $r < n$, and for $r \geq n$, the category of r -arrows of \mathcal{A}' is obtained from that of \mathcal{A} by adjoining one atomic r -arrow for each degeneracy operator $[r] \twoheadrightarrow [n]$ with boundary specified by the attaching map f . If we adjoin an arrow to a free category along its boundary we get a free category with that arrow as an extra generator, so each of the categories of r -arrows of \mathcal{A}' are freely generated, and it is clear from this description that on degenerating one of these extra adjoined arrows we just map it to one of the generating arrows we've adjoined at a higher dimension. This proves that $\mathcal{A} \hookrightarrow \mathcal{A}'$ is a simplicial subcomputad inclusion as claimed. It follows inductively that the codomain of a relative simplicial computad is a simplicial computad whenever its domain is, in which case the inclusion is a subcomputad inclusion.

For the converse, we inductively present any simplicial subcomputad inclusion $\mathcal{A} \hookrightarrow \mathcal{B}$ as a sequential composite of pushouts of coproducts of the maps $\emptyset \hookrightarrow \mathbf{1}$ and $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$. Note that $2[\Delta[n]]$ contains a single non-degenerate atomic arrow not present in $2[\partial\Delta[n]]$, namely the unique non-degenerate n -arrow representing the n -simplex.

At stage “ -1 ,” use the inclusion $\emptyset \hookrightarrow \mathbf{1}$ to attach any object in $\mathcal{B} \setminus \mathcal{A}$ to \mathcal{A} . At stage “ 0 ,” use the inclusion $2[\emptyset] \hookrightarrow 2[\Delta[0]]$ to attach each atomic 0 -arrows of \mathcal{B} that is not in \mathcal{A} . Iteratively, at

stage “ r ,” use the inclusion $2[\partial\Delta[r]] \hookrightarrow 2[\Delta[r]]$ to attach each atomic r -arrows of \mathcal{B} that is not in \mathcal{A} . There is a canonical map from the codomain of the relative simplicial computad defined in this way to \mathcal{B} , which by construction is bijective on objects and sends the unique atomic arrow attached by each cell to an atomic arrow in \mathcal{B} ; in particular this comparison functor, which by construction lies in $\mathcal{SSet}\text{-}\mathcal{Cptd}$ is in fact a simplicial subcomputad inclusion. The comparison is surjective on atomic n -arrows by construction and hence surjective on all arrows, because the unique factorization any arrow into non-degenerate atomics is present in the colimit at the stage corresponding to the dimension of that arrow. Thus, we have presented $\mathcal{A} \hookrightarrow \mathcal{B}$ as a relative simplicial computad inclusion. \square

The morphisms listed in Definition 6.1.11 are the generating cofibrations in the Bergner model structure on simplicial categories [4]. Hence, the relative simplicial computads are precisely the *cellular cofibrations*, those that are built as sequential composites of pushouts of coproducts of generating cofibrations (without closing under retracts). For non-cofibrant domains, the notion of Bergner cofibration is more general than the notion of relative simplicial computad. However:

6.1.13. LEMMA. *Every retract of a simplicial computad is a simplicial computad.*

PROOF. A simplicial category \mathcal{A} is a retract of a simplicial computad \mathcal{B} if there exist simplicial functors

$$\mathcal{A} \xleftarrow{S} \mathcal{B} \xrightarrow{R} \mathcal{A}$$

so that $RS = \text{id}$. The category \mathcal{A} is then recovered as the coequalizer (or the equalizer) of SR and the identity, so if we knew that this idempotent defined a computad morphism, we could appeal to Lemma 6.1.7 and be done; but we do not know this, so we must argue further.

First we demonstrate that every retract of a free category is free. To see this, we’ll first show that the inclusion $\mathcal{A}_n \hookrightarrow \mathcal{B}_n$ satisfies the “2-of-3” property: of f and g are composable morphisms of \mathcal{B}_n so that two of three of f , g , and $f \circ g$ lie in \mathcal{A}_n , then so does the third. This is clear in the case where $f, g \in \mathcal{A}_n$ so suppose that $f, f \circ g \in \mathcal{A}_n$. Then f and $f \circ g$ are fixed points for the idempotent SR and so we have $f \circ g = SR(f \circ g) = SR(f) \circ SR(g) = f \circ SR(g)$. In the free category \mathcal{B}_n , all morphisms are both monic and epic, so $g = SR(g)$ lies in \mathcal{A}_n as well. Now by induction it is easy to verify that every arrow in \mathcal{A}_n factors uniquely as a product of composites of atomic arrows in \mathcal{B}_n , with each of these composites defining an atomic arrow in \mathcal{A}_n .

This verifies the first condition of Definition 6.1.3. It remains only to verify that degenerate images of atomic arrows in \mathcal{A}_n are atomic. To that end consider an epimorphism $\alpha: [m] \twoheadrightarrow [n]$ and an atomic n -arrow f in \mathcal{A}_n . If $f \cdot \alpha = g \circ h$ is a non-trivial factorization in $\mathcal{A}_m \hookrightarrow \mathcal{B}_m$ then since \mathcal{B} is a simplicial computad we must have $S(f) = g' \circ h'$ with $g' \cdot \alpha = S(g)$ and $h' \cdot \alpha = S(h)$. Since $f = RS(f) = Rg' \circ Rh'$ is atomic, we must have Rg' or Rh' an identity, but then $Rg' \cdot \alpha = RS(g) = g$ or $Rh' \cdot \alpha = RS(h) = h$ is an identity, and so the factorization $f \cdot \alpha = g \circ h$ is trivial after all. \square

Consequently:

6.1.14. COROLLARY. *The simplicial computads are precisely the cofibrant simplicial categories in the Bergner model structure.* \square

Exercises.

6.1.i. EXERCISE. Prove Lemma 6.1.9.

6.1.ii. EXERCISE. Prove that the r -skeleton of a simplicial computad, defined by discarding all arrows of dimension⁵ greater than r , is the simplicial subcomputad generated by the atomic arrows of dimension r .

6.2. Free resolutions and homotopy coherent simplices

The original example of a simplicial computad, also due to Dwyer and Kan [19], is given by the *free resolution* of a 1-category C .

6.2.1. DEFINITION (free resolutions). Write $F \dashv U$ for the free category and underlying graph functors of Digression 6.1.2. Note that the components of the counit and comultiplication of the comonad

$$(FU: Cat \rightarrow Cat, \epsilon: FU \Rightarrow \text{id}, F\eta U: FU \Rightarrow FUFU)$$

define identity-on-objects functors.

For any 1-category C , we will define a simplicial category $FU_{\bullet}C$ with the same objects and with the category of n -arrows defined to be $(FU)^{n+1}C$. A 0-arrow is a sequence of composable arrows in C . A non-identity n -arrow is a sequence of composable arrows in C with each arrow in the sequence enclosed in exactly n pairs of well-formed parentheses.

The simplicial object $\Delta^{\text{op}} \rightarrow Cat$ is formed by evaluating the comonad resolution at $C \in Cat$:

$$FUC \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} (FU)^2C \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} (FU)^3C \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} (FU)^4C \quad \dots \quad (6.2.2)$$

For $j \geq 1$, the face maps

$$(FU)^k \epsilon (FU)^j: (FU)^{k+j+1}C \rightarrow (FU)^{k+j}C$$

remove the parentheses that are contained in exactly k others, while $FU \cdots FU \epsilon$ composes the morphisms inside the innermost parentheses. For $j \geq 1$, the degeneracy maps

$$F(UF)^k \eta (UF)^j U: (FU)^{k+j-1}C \rightarrow (FU)^{k+j}C$$

double up the parentheses that are contained in exactly k others, while $F \cdots UF \eta U$ inserts parentheses around each individual morphism.

6.2.3. EXAMPLE (free resolution of a group). A classically important special case is given by the free resolution of a 1-object groupoid, whose automorphisms are the elements of a discrete group G . In this case, each category of n -arrows is again a 1-object groupoid. The category of 0-arrows is the group of words in the non-identity elements of G . The category of 1-arrows is the group of words of words, and so on.

We now explain the sense in which free resolutions are “resolutions” of the original 1-category. As discussed in Example 6.1.4, a 1-category C can be regarded as a constant simplicial category C_{\bullet} , whose hom-spaces coincide with the hom-sets of C . There is a canonical “augmentation” map $\epsilon: FU_{\bullet}C \rightarrow C$ in $\mathcal{SSet}\text{-}Cat$ that is determined by its degree zero component $\epsilon: FUC \rightarrow C$ which is just given by composition in C .

⁵An n -arrow f in a simplicial category \mathcal{A} has **dimension** r if there exists a non-degenerate r -arrow g and an epimorphism $\alpha: [n] \rightarrow [r]$ so that $f = g \cdot \alpha$.

6.2.4. PROPOSITION. *The functor $\epsilon: FU_{\bullet}C \rightarrow C$ is a local homotopy equivalence of simplicial sets. That is, for any pair of objects $x, y \in C$, the map $\epsilon: FU_{\bullet}C(x, y) \rightarrow C(x, y)$ is a simplicial homotopy equivalence: $FU_{\bullet}C(x, y)$ is homotopy equivalent to the discrete set $C(x, y)$ of arrows in C from x to y .*

PROOF. The augmented simplicial object

$$\begin{array}{ccccccc}
 C & \xleftarrow{\quad} & (FU)C & \xrightleftharpoons{\quad} & (FU)^2C & \xrightleftharpoons{\quad} & (FU)^3C & \xrightleftharpoons{\quad} & (FU)^4C & \cdots \\
 & \searrow \text{---} & \swarrow \text{---} & \searrow \text{---} & \swarrow \text{---} & \searrow \text{---} & \swarrow \text{---} & \searrow \text{---} & \swarrow \text{---} & \\
 & & & & & & & & &
 \end{array}$$

is split at the level of reflexive directed graphs (i.e., after applying U). These splittings are not functors, but that won't matter. These directed graph morphisms displayed here are all identity on objects, which means that for any $x, y \in C$ there is a split augmented simplicial set

$$\begin{array}{ccccccc}
 C(x, y) & \xleftarrow{\quad} & (FU)C(x, y) & \xrightleftharpoons{\quad} & (FU)^2C(x, y) & \xrightleftharpoons{\quad} & (FU)^3C(x, y) & \xrightleftharpoons{\quad} & (FU)^4C(x, y) & \cdots \\
 & \searrow & \swarrow & \searrow & \swarrow & \searrow & \swarrow & \searrow & \swarrow & \\
 & & & & & & & & &
 \end{array}$$

and now some classical simplicial homotopy theory of Meyer [42] reviewed in Appendix C proves that $\epsilon: FU_{\bullet}C(x, y) \rightarrow C(x, y)$ is a simplicial homotopy equivalence. \square

As the name suggests, free resolutions are simplicial computads:

6.2.5. PROPOSITION (free resolutions are simplicial computads). *The free resolution of any 1-category defines a simplicial computad in which the atomic n -arrows are those enclosed in precisely one pair of outermost parentheses.*

PROOF. In the free resolution of a 1-category C , the category of n -arrows is $(FU)^{n+1}C$. The category FUC is the free category on the underlying graph of C . Its arrows are sequences of composable non-identity arrows of C ; the atomic 0-arrows are the non-identity arrows of C . An n -arrow is a sequence of composable arrows in C with each arrow in the sequence enclosed in exactly n pairs of parentheses. The atomic n -arrows are those enclosed in precisely one pair of parentheses on the outside. Since composition in a free category is by concatenation, the unique factorization property is clear. Since degeneracy arrows “double up” on parentheses, these preserve atomics as required. \square

The atomic n -arrows in the free resolution of a 1-category index the generating n -homotopies in a homotopy coherent diagram, such as enumerated for the homotopy coherent ω -simplex at the start of this chapter.

6.2.6. DEFINITION (the homotopy coherent ω -simplex). The **homotopy coherent ω -simplex** $\mathfrak{C}\Delta[\omega]$ is a simplicial category defined to be the free resolution of the category

$$\omega := \quad 0 \longrightarrow 1 \longrightarrow 2 \longrightarrow 3 \longrightarrow \cdots$$

The objects of $\mathfrak{C}\Delta[\omega]$ are natural numbers $k \geq 0$. Unpacking Definition 6.2.1 we can completely describe its arrows:

- A non-identity 0-arrow from j to k is a sequence of non-identity composable morphisms from j to k , the data of which is uniquely determined by the objects being passed through. In particular, there are no 0-arrows from j to k if $j > k$, and the only 0-arrow from k to k is the identity. If $j < k$, the non-identity 0-arrows from j to k correspond to subsets

$$\{j, k\} \subset T^0 \subset [j, k]$$

of the closed interval $[j, k] = \{t \in \omega \mid j \leq t \leq k\}$ containing both endpoints.

- A 1-arrow from j to k is a once bracketed sequence of non-identity composable morphisms from j to k . This data is specified by two nested subsets

$$\{j, k\} \subset T^0 \subset T^1 \subset [j, k]$$

the larger one T^1 specifying the underlying unbracketed sequence and the smaller one T^0 specifying the placement of the brackets.

- A r -arrow from j to k is an r times bracketed sequence of non-identity composable morphisms from j to k , the data of which is specified by nested subsets

$$\{j, k\} \subset T^0 \subset \cdots \subset T^r \subset [j, k] \quad (6.2.7)$$

indicating the locations of all of the parentheses.⁶

The face and degeneracy maps of (6.2.2) are the obvious ones, either duplicating or omitting one of the sets T^i . In particular, the r -arrows just enumerated are non-degenerate if and only if each of the inclusions $T^0 \subset \cdots \subset T^r$ is proper.

We now describe the geometry of the mapping spaces $\mathfrak{C}\Delta[\omega](j, k)$.

6.2.8. LEMMA (homs in the homotopy coherent ω -simplex are cubes). *The mapping spaces of the homotopy coherent ω -simplex are defined for $j, k \in \omega$ by*

$$\mathfrak{C}\Delta[\omega](j, k) \cong \begin{cases} \emptyset & j > k \\ \Delta[0] & k = j \text{ or } k = j + 1 \\ \Delta[1]^{k-j-1} & j < k. \end{cases}$$

PROOF. Because ω has no arrows from j to k when $j > k$ these hom-spaces of $\mathfrak{C}\Delta[\omega]$ are similarly empty. When $k = j$ or $k = j + 1$ we have $\{j, k\} = [j, k]$, using the notation of Definition 6.2.6, so $\mathfrak{C}\Delta[\omega](j, k) \cong \Delta[0]$ is comprised of a single point.

For $k > j$, there are $k-j-1$ elements of $[j, k]$ excluding the endpoints and so we see that $\mathfrak{C}\Delta[\omega](j, k)$ has 2^{k-j-1} vertices. The r -simplices of $\mathfrak{C}\Delta[\omega](j, k)$ are given by specifying $r+1$ vertices — each a subset $\{j, k\} \subset T^i \subset [j, k]$ — that respect the ordering of subsets relation. From this we see that

$$\mathfrak{C}\Delta[\omega](j, k) \cong \Delta[1]^{k-j-1}$$

⁶The nesting is because parenthesizations should be “well formed” with open brackets closed in the reverse order to that in which they were opened.

is the nerve of the poset of subsets $\{j, k\} \subset T \subset [j, k]$ ordered by inclusion, as displayed for instance in the case $j = 0$ and $k = 4$:

$$\mathfrak{C}\Delta[\omega](0, 4) := \left(\begin{array}{ccccc} & & \{0, 4\} & \xrightarrow{\quad} & \{0, 1, 4\} \\ & \swarrow & \downarrow & \searrow & \downarrow \\ \{0, 3, 4\} & \xrightarrow{\quad} & & \{0, 1, 3, 4\} & \\ & \downarrow & \downarrow & \downarrow & \\ & & \{0, 2, 4\} & \xrightarrow{\quad} & \{0, 1, 2, 4\} \\ \downarrow & \swarrow & \downarrow & \searrow & \downarrow \\ \{0, 2, 3, 4\} & \xrightarrow{\quad} & & \{0, 1, 2, 3, 4\} & \end{array} \right) \quad \square$$

Proposition 6.2.5 proves that the homotopy coherent ω -simplex is a simplicial computad and its proof identifies its atomic arrows.

6.2.9. LEMMA. *The simplicial category $\mathfrak{C}\Delta[\omega]$ is a simplicial computad whose atomic r -arrows are those with a single outermost parenthesis: i.e., those sequences of subsets*

$$\{j, k\} = T^0 \subset \dots \subset T^r \subset [j, k]$$

for which $T^0 = \{j, k\}$. Geometrically, the atomic arrows from j to k are precisely the simplices in the hom-cube $\mathfrak{C}\Delta[\omega](j, k) \cong \Delta[1]^{k-j-1}$ that contain the initial vertex $\{j, k\}$. \square

The finite ordinals define full subcategories of ω . In this way, the homotopy coherent ω -simplex restricts to define homotopy coherent simplices in each finite dimension.

6.2.10. DEFINITION (the homotopy coherent n -simplex). The **homotopy coherent n -simplex** $\mathfrak{C}\Delta[n]$ is the full subcategory of the homotopy coherent ω -simplex $\mathfrak{C}\Delta[\omega]$ spanned by the objects $0, \dots, n$. Equivalently, it is the free resolution of the ordinal category with $n + 1$ objects.

Explicitly the homotopy coherent n -simplex has mapping spaces given for $j, k \in [n]$ by cubes

$$\mathfrak{C}\Delta[n](j, k) \cong \begin{cases} \emptyset & j > k \\ \Delta[0] & k = j \text{ or } k = j + 1 \\ \Delta[1]^{k-j-1} & j < k. \end{cases}$$

each of which may be understood as the nerve of the poset of subsets $\{j, k\} \subset T \subset [j, k]$ ordered by inclusion. An r -arrow may be represented as a nested sequence of subsets

$$\{j, k\} \subset T^0 \subset \dots \subset T^r \subset [j, k]$$

The homotopy coherent n -simplex is a simplicial computad whose atomic r -arrows are those sequences for which $T^0 = \{j, k\}$ or those simplices that contain the initial vertex in the hom-cube.

Exercises.

6.2.i. EXERCISE. Compute the free resolution of the commutative square category 2×2 and compare it with the product $\mathfrak{C}\Delta[1] \times \mathfrak{C}\Delta[1]$ of two copies of the free resolution of 2 . This computation implies that the functor $\mathfrak{C}: \mathbf{SSet} \rightarrow \mathbf{SSet-Cptd}$ to be introduced in Definition 6.3.2 does not preserve products.

6.3. Homotopy coherent realization and the homotopy coherent nerve

Our aim now is to introduce the *homotopy coherent realization* of any simplicial set X , which will define a simplicial computad $\mathfrak{C}X$ whose objects are the vertices of X . The homotopy coherent realization of $\Delta[n]$ will be the homotopy coherent n -simplex $\mathfrak{C}\Delta[n]$ of Definition 6.2.10. The homotopy coherent realization of X will be defined by “gluing together” homotopy coherent n -simplices in a canonical way: succinctly, $\mathfrak{C}X$ is defined as a colimit in $\mathcal{SSet}\text{-}Cptd$ of a diagram of homotopy coherent simplices indexed by the category of simplices of X . We will then leverage Lemma 6.2.9 into an explicit presentation of $\mathfrak{C}X$ as a simplicial computad stated as Theorem 6.3.10, recovering a result of Dugger and Spivak.

The homotopy coherent realization and homotopy coherent nerve functors are determined by the cosimplicial object

$$\begin{aligned} \Delta &\xrightarrow{\mathfrak{C}\Delta[\bullet]} \mathcal{SSet}\text{-}Cat \\ [n] &\longmapsto \mathfrak{C}\Delta[n] \end{aligned}$$

where a simplicial operator $\alpha: [n] \rightarrow [m]$ acts on an r -arrow from j to k , as described in Definition 6.2.10, by taking the direct image of the sequence of subsets (6.2.7).

We introduce these functors in turn.

6.3.1. DEFINITION (homotopy coherent nerve). The **homotopy coherent nerve** of a simplicial category \mathcal{A} is the simplicial set $\mathfrak{N}\mathcal{A}$ whose n -simplices

$$\mathfrak{N}\mathcal{A}_n := \mathcal{SSet}\text{-}Cat(\mathfrak{C}\Delta[n], \mathcal{A})$$

are defined to be diagrams $\mathfrak{C}\Delta[n] \rightarrow \mathcal{A}$; the simplicial operators act contravariantly on $\mathfrak{N}\mathcal{A}$ by precomposition.

Explicitly, a homotopy coherent n -simplex in \mathcal{A} is given by:

- a sequence of objects $a_0, \dots, a_n \in \mathcal{A}$ and
- a sequence of simplicial maps

$$a_{i,j}: \Delta[1]^{k-j-1} \rightarrow \mathcal{A}(a_j, a_k)$$

for each $0 \leq j < k \leq n$

- satisfying the simplicial functoriality condition:

$$\begin{array}{ccc} \Delta[1]^{k-j-1} \times \Delta[1]^{j-i-1} & \xrightarrow{\vee_j} & \Delta[1]^{k-i-1} \\ a_{j,k} \times a_{i,j} \downarrow & & \downarrow a_{i,k} \\ \mathcal{A}(a_j, a_k) \times \mathcal{A}(a_i, a_j) & \xrightarrow{\circ} & \mathcal{A}(a_i, a_k) \end{array}$$

where

$$\begin{array}{ccc} \Delta[1]^{k-j-1} \times \Delta[1]^{j-i-1} & \cong & \Delta^{k-i-2} \xrightarrow{\vee_j} \Delta[1]^{k-i-1} \\ \Downarrow & & \Downarrow \\ \mathfrak{C}\Delta[n](j, k) \times \mathfrak{C}\Delta[n](i, j) & \xrightarrow{\circ} & \mathfrak{C}\Delta[n](i, k) \end{array}$$

is the map that sends a pair of r -simplices

$$\{i, j\} \subset S^0 \subset \dots \subset S^r \subset [i, j] \quad \text{and} \quad \{j, k\} \subset T^0 \subset \dots \subset T^r \subset [j, k]$$

to their union

$$\{i, k\} \subset S^0 \cup T^0 \subset \dots \subset S^r \cup T^r \subset [i, k].$$

If the $\{0, 1\}$ -valued coordinates of the cube $\Delta[1]^{k-i-1}$ are indexed by integers $i < t < k$, then the image of \vee_j is the $j = 1$ face of the cube.

6.3.2. DEFINITION (homotopy coherent realization). The **homotopy coherent realization** functor \mathfrak{C} is the pointwise left Kan extension of the cosimplicial object $\mathfrak{C}\Delta[\bullet]$ along the Yoneda embedding:

$$\begin{array}{ccc} & \mathcal{S}\mathcal{S}et & \\ \wr \nearrow & \uparrow \cong & \dashrightarrow \mathfrak{C} \\ \Delta & \xrightarrow{\mathfrak{C}\Delta[\bullet]} & \mathcal{S}\mathcal{S}et-Cat \end{array}$$

The value of a pointwise left Kan extension at an object $X \in \mathcal{S}\mathcal{S}et$ can be computed as a colimit indexed by the comma category $\mathbf{Hom}_{\mathcal{S}\mathcal{S}et}(\wr, X)$ [48, 6.2.1]. This comma category is better known as the **category of simplices of X** , whose objects are simplices of X and in which a morphism from an n -simplex x to an m -simplex y is a simplicial operator $\alpha: [n] \rightarrow [m]$ so that $y \cdot \alpha = x$. In this case, the colimit formula gives

$$\mathfrak{C}X := \operatorname{colim}_{[n] \in \Delta, x \in X_n} \mathfrak{C}\Delta[n].$$

By general abstract nonsense:

6.3.3. PROPOSITION. *The homotopy coherent realization functor is left adjoint to the homotopy coherent nerve:*

$$\begin{array}{ccc} & \mathfrak{C} & \\ \mathcal{S}\mathcal{S}et & \begin{array}{c} \xrightarrow{\quad} \\ \perp \\ \xleftarrow{\quad} \end{array} & \mathcal{S}\mathcal{S}et-Cat \\ & \mathfrak{N} & \end{array}$$

PROOF. The homotopy coherent nerve was defined so that this adjoint correspondence would hold for the standard simplices and the general result follows since every simplicial set is a colimit, indexed by its category of simplices, of standard simplices. See [48, 6.5.9] for more details. \square

6.3.4. LEMMA. *The homotopy coherent realization functor takes its values in the subcategory of simplicial computads and computad morphisms.*

$$\begin{array}{ccc} \mathcal{S}\mathcal{S}et & \xrightarrow{\quad \mathfrak{C} \quad} & \mathcal{S}\mathcal{S}et-Cat \\ & \searrow \mathfrak{C} \quad \nearrow & \\ & \mathcal{S}\mathcal{S}et-Cptd & \end{array}$$

PROOF. By Lemma 6.1.7, which proves that the category of simplicial computads is closed under colimits in the category of simplicial categories, it suffices to demonstrate that the cosimplicial object $\mathfrak{C}\Delta[\bullet]$ is valued in the subcategory of simplicial computads and simplicial computad morphisms. We know already that the homotopy coherent simplices are simplicial computads, so we need only verify that the simplicial operators act by computad morphisms.

A simplicial operator $\alpha: [n] \rightarrow [m]$ acts on the r -arrow from j to k described in Definition 6.2.10 by taking the direct image of the sequence of subsets (6.2.7). The condition that characterizes the atomic arrows, $\{j, k\} = T^0$, is preserved by direct images, so we see that α defines a computad morphism $\mathfrak{C}\alpha: \mathfrak{C}\Delta[n] \rightarrow \mathfrak{C}\Delta[m]$. As the subcategory $\mathcal{S}\mathcal{S}et-Cptd \hookrightarrow \mathcal{S}\mathcal{S}et-Cat$ is closed under colimits,

it follows that every homotopy coherent realization is a simplicial computad and any simplicial map $X \rightarrow Y$ induces a morphism of simplicial computads $\mathfrak{C}X \rightarrow \mathfrak{C}Y$. \square

6.3.5. LEMMA. *For any inclusion $X \hookrightarrow Y$ of simplicial sets, the morphism $\mathfrak{C}X \hookrightarrow \mathfrak{C}Y$ is a simplicial subcomputad inclusion. Moreover, in the case of $X \hookrightarrow \Delta[n]$, an atomic r -arrow*

$$\{j, k\} = T^0 \subset \cdots \subset T^r \subset [j, k]$$

from j to k of $\mathfrak{C}\Delta[n]$ lies in the subcomputad $\mathfrak{C}X$ if and only if the simplex spanned by the vertices of T^r lies in X .

PROOF. Recall that every monomorphism of simplicial sets $X \hookrightarrow Y$ admits a canonical decomposition as a sequential composite of pushouts of coproducts of the simplex boundary inclusions $\partial\Delta[n] \hookrightarrow \Delta[n]$. Since all colimits are preserved by the left adjoint \mathfrak{C} and Lemma 6.1.10 proves that simplicial subcomputads are closed under colimits of this form, it suffices to prove that $\mathfrak{C}\partial\Delta[n] \hookrightarrow \mathfrak{C}\Delta[n]$ is a simplicial subcomputad inclusion. We'll argue more generally that for $X \subset \Delta[n]$, $\mathfrak{C}X \hookrightarrow \mathfrak{C}\Delta[n]$ is a simplicial subcomputad inclusion where the atomic arrows of $\mathfrak{C}X$ are as described in the second clause of the statement.

We argue using ideas from Reedy category theory reviewed in Appendix C. Our task is to show that the image of $X \hookrightarrow \Delta[n]$ under the functor

$$\mathcal{S}Set \xrightarrow{\mathfrak{C}} \mathcal{S}Set\text{-}Cptd \xrightarrow{\text{atom}} \mathcal{G}ph^{\Delta_{\text{epi}}^{\text{op}}}$$

that takes a simplicial set to its $\Delta_{\text{epi}}^{\text{op}}$ -indexed graph of atomic and identity arrows is a pointwise monomorphism.

The simplicial subset $X \subset \Delta[n]$ can be described as a colimit of certain faces of $\Delta[n]$ glued along their common faces; the functor just described preserves these colimits. Our claim asserts that the composite cosimplicial object $\mathfrak{C}\Delta[\bullet]: \Delta \rightarrow \mathcal{S}Set \rightarrow \mathcal{S}Set\text{-}Cptd \rightarrow \mathcal{G}ph^{\Delta_{\text{epi}}^{\text{op}}}$ is *Reedy monomorphic*: meaning that every atomic r -arrow T^\bullet in the homotopy coherent n -simplex is uniquely expressible in the form $\alpha \cdot S^\bullet$ where $\alpha: [m] \rightarrow [n]$ is a monomorphism in Δ and S^\bullet is “non-co-degenerate,” i.e., not in the image of any monomorphism. This is clear: take $m = |T^r| - 1$ and define $\alpha: [m] \rightarrow [n]$ to be the inclusion with image $T^r \subset [n]$. Then take S^\bullet to be the atomic r -arrow from 0 to m in $\mathfrak{C}\Delta[m]$ whose direct image under α is T^\bullet . It is clear that S^\bullet is not in the image of any smaller face map. This argument also reveals that the atomic r -arrows T^\bullet of $\mathfrak{C}\Delta[n]$ that are present in the subcomputad $\mathfrak{C}X$ are exactly those for which the vertices of T^\bullet are contained in one of its faces. \square

Lemma 6.3.5 allows us to compute the following subcomputads of the homotopy coherent simplex. Before stating the results of these computations, we introduce notation that suggests the correct geometric intuition:

6.3.6. NOTATION (cubes, boundaries, and cubical horns). We introduce special notation for the following simplicial sets:

- Write \square^k for the **simplicial cube** $\Delta[1]^k$.
- Write $\partial\square^k$ for the **boundary of the k -cube**. Formally, $\partial\square^k$ is the domain of the iterated Leibniz product $(\partial\Delta[1] \hookrightarrow \Delta[1])^{\times k}$. If an r -simplex in \square^k is represented by a k -tuple of maps $\rho_i: [r] \rightarrow [1]$, then that r -simplex lies in $\partial\square^k$ if and only if there is some i for which ρ_i is constant at either vertex of $[1]$.

- Write $\square_e^{kj} \subset \partial \square^k$ for the **cubical horn** containing only the face $e \in [1]$ in direction $1 \leq j \leq k$. Formally, \square_e^{kj} is the domain of the iterated Leibniz product

$$(\partial \Delta[1] \hookrightarrow \Delta[1])^{\hat{\times} j-1} \hat{\times} (\Delta[0] \xrightarrow{e} \Delta[1]) \hat{\times} (\partial \Delta[1] \hookrightarrow \Delta[1])^{\hat{\times} k-j}.$$

An r -simplex in \square^k represented by a k -tuple of map $\rho_i: [r] \rightarrow [1]$ lies in \square_e^{kj} if and only if for some $i \neq j$ the map ρ_i is constant or ρ_j is the constant operator at $e \in [1]$.

6.3.7. LEMMA (coherent subsimplices). *The homotopy coherent realizations of the simplicial sphere and inner and outer horns define subcomputads of the homotopy coherent n -simplex containing all of the objects and defined on homs by:*

- (i) **spheres:** $\mathfrak{C}\partial\Delta[n] \hookrightarrow \mathfrak{C}\Delta[n]$ is full on all arrows except those from 0 to n and has

$$\begin{array}{ccc} \mathfrak{C}\partial\Delta[n](0, n) & \hookrightarrow & \mathfrak{C}\Delta[n](0, n) \\ \Downarrow & & \Downarrow \\ \partial\square^{n-1} & \hookrightarrow & \square^{n-1} \end{array}$$

- (ii) **inner horns:** For $0 < k < n$, $\mathfrak{C}\Lambda^k[n] \hookrightarrow \mathfrak{C}\Delta[n]$ is full on all arrows except those from 0 to n and has

$$\begin{array}{ccc} \mathfrak{C}\Lambda^k[n](0, n) & \hookrightarrow & \mathfrak{C}\Delta[n](0, n) \\ \Downarrow & & \Downarrow \\ \square_1^{n-1, k} & \hookrightarrow & \square^{n-1} \end{array}$$

- (iii) **outer horns:** $\mathfrak{C}\Lambda^n[n] \hookrightarrow \mathfrak{C}\Delta[n]$ is full on all arrows except those from 0 to $n-1$ or n and has

$$\begin{array}{ccc} \mathfrak{C}\Lambda^n[n](0, n-1) & \hookrightarrow & \mathfrak{C}\Delta[n](0, n-1) \\ \Downarrow & & \Downarrow \\ \partial\square^{n-2} & \hookrightarrow & \square^{n-2} \end{array} \quad \begin{array}{ccc} \mathfrak{C}\Lambda^n[n](0, n) & \hookrightarrow & \mathfrak{C}\Delta[n](0, n) \\ \Downarrow & & \Downarrow \\ \square_0^{n-1, n-1} & \hookrightarrow & \square^{n-1} \end{array}$$

Similarly, $\mathfrak{C}\Lambda^0[n] \hookrightarrow \mathfrak{C}\Delta[n]$ is full on all arrows except those from 0 or 1 to n and has

$$\begin{array}{ccc} \mathfrak{C}\Lambda^0[n](1, n) & \hookrightarrow & \mathfrak{C}\Delta[n](1, n) \\ \Downarrow & & \Downarrow \\ \partial\square^{n-2} & \hookrightarrow & \square^{n-2} \end{array} \quad \begin{array}{ccc} \mathfrak{C}\Lambda^0[n](0, n) & \hookrightarrow & \mathfrak{C}\Delta[n](0, n) \\ \Downarrow & & \Downarrow \\ \square_0^{n-1, 1} & \hookrightarrow & \square^{n-1} \end{array}$$

PROOF. For (i), the only non-degenerate simplex of $\Delta[n]$ that is not present in $\partial\Delta[n]$ is the top dimensional n -simplex. Consequently, the only atomic r -arrows T^\bullet that are not present in $\mathfrak{C}\partial\Delta[n]$ are those with $T^r = [0, n]$. The atomic r -arrows must also have $T^0 = \{0, n\}$ and consequently correspond precisely to those r -simplices of the cube \square^{n-1} that contain both the first and last vertex. Thus, we see that $\mathfrak{C}\partial\Delta[n](0, n)$ is isomorphic to the cubical boundary $\partial\square^{n-1}$.

For (ii), the only non-degenerate simplex of $\partial\Delta[n]$ that is not present in an inner horn $\Lambda^k[n]$ is the k -th face of the top dimensional simplex. Consequently, the only atomic r -arrows T^\bullet that are not present in $\mathfrak{C}\Lambda^k[n]$ but are present in $\mathfrak{C}\partial\Delta[n]$ are those with $T^r = [0, n] \setminus \{k\}$. The atomic r -arrows must also have $T^0 = \{0, n\}$ and consequently correspond precisely to those r -simplices of the cube \square^{n-1} that contain both the first vertex and last vertex of the $k = 0$ face of the cube \square^{n-1} . Thus, we see that $\mathfrak{C}\Lambda^k[n](0, n)$ is isomorphic to the cubical horn $\square_1^{n-1, k}$.

For (iii), the only non-degenerate simplex of $\partial\Delta[n]$ that is not present in the outer horn $\Lambda^n[n]$ is the n -th face of the top dimensional simplex. Consequently, the only atomic r -arrows T^\bullet that are not

present in $\mathfrak{C}\Lambda^n[n]$ but are present in $\mathfrak{C}\partial\Delta[n]$ are those with $T^r = [0, n-1]$; note that the source of such r -arrows is 0 and the target is $n-1$. The atomic r -arrows must also have $T^0 = \{0, n-1\}$, and so, as in the proof of (i), this identifies the inclusion $\mathfrak{C}\Lambda^n[n](0, n-1) \hookrightarrow \mathfrak{C}\Delta[n](0, n-1)$ as $\partial\Box^{n-2} \hookrightarrow \Box^{n-2}$. The subcomputad $\mathfrak{C}\Lambda^n[n]$ is also missing non-atomic r -arrows that are present in $\mathfrak{C}\partial\Delta[n]$, namely those composites of the unique arrow from $n-1$ to n with the atomic r -arrows from 0 to $n-1$ just described. Such non-atomic r -arrows are represented by sets of inclusions with $T^0 = \{0, n-1, n\}$ and $T^r = [0, n]$ and thus are found in the $n-1 = 1$ face of the cube \Box^{n-1} . Thus, we see that $\mathfrak{C}\Lambda^n[n](0, n)$ is isomorphic to the cubical horn $\Box_0^{n-1, n-1}$. \square

6.3.8. DEFINITION (bead shapes). We call the atomic r -arrows of $\mathfrak{C}\Delta[n](0, n)$ that are not present in $\mathfrak{C}\partial\Delta[n](0, n)$ **bead shapes**. By Lemma 6.3.7, an r -dimensional bead shape corresponds to a sequence of subsets

$$\{0, n\} = T^0 \subset T^1 \subset \dots \subset T^{r-1} \subset T^r = [0, n] \quad (6.3.9)$$

and is non-degenerate if and only if each of the inclusions is proper.

Putting this together we can now explicitly present the simplicial computad structure on the homotopy coherent realization of any simplicial set.

6.3.10. THEOREM (homotopy coherent realizations, explicitly). *For any simplicial set X , the homotopy coherent realization $\mathfrak{C}X$ is a simplicial computad in which:*

- The objects of $\mathfrak{C}X$ are the vertices of the simplicial set X .
- The atomic 0-arrows are non-degenerate 1-simplices of X , with the initial vertex of the simplex defining the source of the 0-arrow and the final vertex of the simplex defining the target of the 0-arrow.
- The atomic 1-arrows are non-degenerate n -simplices of X , with the initial vertex of the simplex defining the source of the 0-arrow and the final vertex of the simplex defining the target of the 0-arrow.
- The atomic k -arrows are pairs comprised of a non-degenerate n -simplex in X together with a k -dimensional bead shape in $\mathfrak{C}\Delta[n]$. This source of this k -arrow is the initial vertex of the n -simplex, while the target is the final vertex of the n -simplex, and the arrow is non-degenerate if and only if the bead shape is non-degenerate.

Note that the description of atomic k -arrows subsumes those of the atomic 0-arrows and atomic 1-arrows as there is a unique 1-dimensional bead shape in $\mathfrak{C}\Delta[n]$ and a 0-dimensional bead shape exists only in the case $n = 1$. The data of a non-degenerate atomic k -arrow from x to y in $\mathfrak{C}X$ is given by a “bead,” that is a non-degenerate n -simplex in X from x to y , together with the additional data of a “bead shape”: sequence of proper subset inclusions (6.3.9), which Dugger and Spivak refer to as a “flag of vertex data” [16]. Non-atomic k -arrows are then “necklaces,” that is strings of beads in X joined head to tail, together with accompanying “vertex data” for each simplex.

PROOF. As observed in the proof of Lemma 6.3.5, using the canonical skeletal decomposition of the simplicial set X

$$\begin{array}{ccccccc} \coprod_{X_n \setminus L_n X} \partial\Delta[n] & \hookrightarrow & \coprod_{X_n \setminus L_n X} \Delta[n] \\ \downarrow & & \downarrow \\ \emptyset \hookrightarrow \mathrm{sk}_0 X \hookrightarrow \dots \hookrightarrow \mathrm{sk}_{n-1} X & \xrightarrow{\quad r \quad} & \mathrm{sk}_n X \hookrightarrow \dots \hookrightarrow \mathrm{colim} = X \end{array}$$

the homotopy coherent realization $\mathfrak{C}X$ is constructed iteratively by a process that adjoints one copy of $\mathfrak{C}\Delta[n]$ along a map of its boundary $\mathfrak{C}\partial\Delta[n]$ for each non-degenerate n -simplex of X . Thus, each atomic k -arrow arises from a unique pushout of this form, as the image of an atomic k -arrow in $\mathfrak{C}\Delta[n]$ that is not present in the subcomputad $\mathfrak{C}\partial\Delta[n]$. \square

6.3.11. REMARK. From the description of Theorem 6.3.10, the subcomputad inclusions $\mathfrak{C}X \hookrightarrow \mathfrak{C}Y$ induced by monomorphisms of simplicial sets $X \hookrightarrow Y$ are easily understood: an r -arrow in $\mathfrak{C}Y$ lies in $\mathfrak{C}X$ if and only if each bead in its representing necklace in Y lies in X . This generalizes the description given to subcomputads of homotopy coherent simplices in Lemma 6.3.5.

Our convention is to identify 1-categories with their nerves. The homotopy coherent realization of these simplicial sets then produces a simplicial computad. But we have already encountered a way to produce a simplicial computad from a 1-category: namely via the free resolution of Definition 6.2.1. This would lead to a potential source of ambiguity were it not for the happy coincidence that these two constructions are isomorphic:⁷

6.3.12. PROPOSITION (free resolutions are homotopy coherent realizations). *For any 1-category, the free resolution is naturally isomorphic to the homotopy coherent realization of its nerve.*

PROOF. Proposition 6.2.5 and Theorem 6.3.10 present both simplicial categories as simplicial computads. We will argue that they have the same objects and non-degenerate atomic k -arrows.

Both have the same set of objects, the objects of the 1-category coinciding with the vertices in its nerve. Atomic 0-arrows of the free resolution are morphisms in the category; while atomic 0-arrows in the coherent realization are non-degenerate 1-simplices of the nerve — these are the same thing. Atomic non-degenerate 1-arrows of the free resolution are sequences of at least two morphisms (enclosed in a single set of outer parentheses), while atomic 1-arrows of the coherent realization are non-degenerate simplices of dimension at least two — again these are the same. Finally a non-degenerate atomic k -arrow is a sequence of n composable morphisms with $(k-1)$ non-repeating bracketings; this non-degeneracy necessitates $n > k$. This data defines a n -simplex in the nerve together with a non-degenerate atomic k -arrow in $\mathfrak{C}\Delta[n](0, n)$, i.e., an atomic k -arrow in the coherent realization. \square

We now exploit the description of the subcomputads of the homotopy coherent n -simplex in Lemma 6.3.7 to prove a key source of examples of quasi-categories, a result first stated in this form in [13].

6.3.13. THEOREM. *The homotopy coherent nerve $\mathfrak{N}\mathcal{S}$ of a Kan-complex enriched category \mathcal{S} is a quasi-category.*

PROOF. By adjunction, to extend along an inner horn inclusion $\Lambda^k[n] \hookrightarrow \Delta[n]$ mapping into the homotopy coherent nerve $\mathfrak{N}\mathcal{S}$ is to extend along simplicial subcomputad inclusions $\mathfrak{C}\Lambda^k[n] \hookrightarrow \mathfrak{C}\Delta[n]$ mapping into the Kan complex enriched category \mathcal{S} . By Lemma 6.3.7(ii), the only missing r -arrows

⁷Note the isomorphism between the homotopy coherent realization of the n -simplex and the free resolution of the ordinal category $[n]$ is tautologous. The left Kan extension along the Yoneda embedding is defined so as to agree with $\mathfrak{C}\Delta[\bullet]: \Delta \rightarrow \mathcal{SSet}\text{-}\mathcal{Cptd}$ on the subcategory of representables. Many arguments involving simplicial sets can be reduced to a check on representables, with the extension to the general case following formally by “taking colimits.” This result, however, is not one of them since we are trying to prove something for all *categories* and the embedding $\mathcal{Cat} \hookrightarrow \mathcal{SSet}$ does not preserve colimits.

are in the mapping space from 0 to n , so we are asked to solve a single lifting problem

$$\begin{array}{ccc} \mathfrak{C}\Lambda^k[n](0, n) \cong \square_1^{n-1, k} & \longrightarrow & \mathbf{Map}(X_0, X_n) \\ \downarrow & \nearrow \text{dashed} & \\ \mathfrak{C}\Delta[n](0, n) \cong \square^{n-1} & & \end{array}$$

Cubical horn inclusions can be filled in the Kan complex $\mathbf{Map}(X_0, X_n)$, completing the proof. \square

We conclude by giving a precise meaning to the notion that motivated this chapter.

6.3.14. DEFINITION. Let X be a simplicial set. A **homotopy coherent diagram** of shape X in a Kan complex enriched category \mathcal{S} is a simplicial functor $\mathfrak{C}X \rightarrow \mathcal{S}$ from the homotopy coherent realization of X to \mathcal{S} .

Exercise 6.2.i reveals that there are two possible notions of natural transformation between homotopy coherent diagram. We opt for the more structured of the two:

6.3.15. DEFINITION. Let $F, G: \mathfrak{C}X \rightrightarrows \mathcal{S}$ be homotopy coherent diagrams of shape X in a Kan complex enriched category \mathcal{S} . A **homotopy coherent natural transformation** $\alpha: F \Rightarrow G$ is a homotopy coherent diagram of shape $X \times \mathbf{2}$

$$\begin{array}{ccc} \mathfrak{C}X & & \\ \downarrow 0 & \searrow F & \\ \mathfrak{C}[X \times \mathbf{2}] & \xrightarrow{\alpha} & \mathcal{S} \\ \uparrow 1 & \nearrow G & \\ \mathfrak{C}X & & \end{array}$$

that restricts to F and to G along the edges of the cylinder.

These notions are originally due to Boardman and Vogt in [8] who observed that homotopy coherent natural transformations do not define a the morphisms of a 1-category. Instead, as they observed, they define the 1-arrows of a quasi-category.

6.3.16. COROLLARY. *Homotopy coherent diagrams of shape X valued in a Kan complex enriched category \mathcal{S} and homotopy coherent natural transformations between them define the objects and 1-arrows of a quasi-category $\mathbf{Coh}(X, \mathcal{S})$ whose n -simplices are homotopy coherent diagram $\mathfrak{C}[X \times \Delta[n]] \rightarrow \mathcal{S}$.*

PROOF. By adjunction $\mathfrak{C} \dashv \mathfrak{N}$, the simplicial set $\mathbf{Coh}(X, \mathcal{S})$ is isomorphic to $(\mathfrak{N}\mathcal{S})^X$. As the quasi-categories form an exponential ideal in the category of simplicial sets, this follows immediately from Theorem 6.3.13. \square

6.3.17. REMARK (all diagrams in homotopy coherent nerves are homotopy coherent). Corollary 6.3.16 explains that any homotopy coherent diagram $\mathfrak{C}X \rightarrow \mathcal{S}$ of shape X in a Kan complex enriched category \mathcal{S} transposes to define a map of simplicial sets $X \rightarrow \mathfrak{N}\mathcal{S}$ valued in the quasi-category defined as the homotopy coherent nerve of \mathcal{S} . While not every quasi-category is isomorphic to a homotopy coherent nerve of a Kan complex enriched category, once consequence of the *internal* Yoneda lemma, to be proven much later, is that every quasi-category is equivalent to a homotopy coherent nerve. This explains the slogan introduced at the beginning of this chapter and the title for this part of the book: all diagrams in quasi-categories are homotopy coherent, thus quasi-category theory can be understood as “homotopy coherent category theory.”

Exercises.

6.3.i. EXERCISE. Compare the simplicial computad structure of the homotopy coherent ω -simplex as given by Theorem 6.3.10 with the simplicial computad structure of Lemma 6.2.9.

Weighted limits in ∞ -cosmoi

7.1. Weighted limits and colimits

Let $(\mathcal{V}, \times, \mathbb{1})$ denote a complete and cocomplete cartesian closed monoidal category. The examples we have in mind are $(\mathbf{SSet}, \times, \mathbb{1})$, its cartesian closed subcategory $(\mathbf{Cat}, \times, \mathbb{1})$, or its further cartesian closed subcategory $(\mathbf{Set}, \times, \mathbb{1})$.

Ordinary limits and colimits are objects representing the functor of cones with a given apex over or under a fixed diagram. *Weighted* limits and colimits are defined analogously, except that the cones over or under a diagram might have exotic “shapes,” which are allowed to vary with the objects indexing the diagram. More formally, in the \mathcal{V} -enriched context, the *weight*, defining the “shape” of a cone over a diagram indexed by \mathcal{A} or under a diagram indexed by \mathcal{A}^{op} , takes the form of a functor in $\mathcal{V}^{\mathcal{A}}$.

Before introducing the general notion of weighted limit and colimit, we first reacquaint ourselves an example that we have seen already in Digression 1.2.4.

7.1.1. EXAMPLE (tensors and cotensors). A diagram indexed by the category $\mathbb{1}$ valued in a \mathcal{V} -enriched category \mathcal{M} is just an object A in \mathcal{M} . In this case, the weight is just an object U of \mathcal{V} . The U -weighted limit of the diagram A is an object of \mathcal{M} denoted A^U — or denoted $\{U, A\}$ whenever superscripts are inconvenient — called the **cotensor** of $A \in \mathcal{M}$ with $U \in \mathcal{V}$ defined by the universal property

$$\mathcal{M}(X, A^U) \cong \mathcal{V}(U, \mathcal{M}(X, A)),$$

this isomorphism between mapping spaces in \mathcal{V} . Dually, the U -weighted colimit of A is an object $U \otimes A \in \mathcal{M}$ called the **tensor** of $A \in \mathcal{M}$ with $U \in \mathcal{V}$ defined by the universal property

$$\mathcal{M}(U \otimes A, X) \cong \mathcal{V}(U, \mathcal{M}(A, X)),$$

this isomorphism again between mapping spaces in \mathcal{V} . Assuming such objects exist, the cotensor and tensor define \mathcal{V} -enriched bifunctors

$$\mathcal{V}^{\text{op}} \times \mathcal{M} \xrightarrow{-} \mathcal{M} \quad \mathcal{V} \times \mathcal{M} \xrightarrow{- \otimes -} \mathcal{M}$$

in a unique way making the defining isomorphisms natural in U and A as well.

Since \mathcal{V} is cartesian closed, it is tensored and cotensored over itself, with $U \otimes V := U \times V$ and $V^U := \mathcal{V}(U, V)$. In particular, the defining natural isomorphisms characterizing tensors and cotensors in \mathcal{M} can be rewritten as

$$\mathcal{M}(X, A^U) \cong \mathcal{M}(X, A)^U \quad \text{and} \quad \mathcal{M}(U \otimes A, X) \cong \mathcal{M}(A, X)^U.$$

The fact that the natural isomorphisms defining tensors and cotensors are required to exist in \mathcal{V} (and not merely in \mathbf{Set}) has the following consequence:

7.1.2. LEMMA (associativity of tensors and cotensors). *If \mathcal{M} is a \mathcal{V} -category with tensors and cotensors then for any $U, V \in \mathcal{V}$ and $A \in \mathcal{M}$, there exist natural isomorphisms*

$$U \otimes (V \otimes A) \cong (U \times V) \otimes A \quad \text{and} \quad (A^V)^U \cong A^{U \times V}.$$

PROOF. By the defining universal property

$$\begin{aligned}\mathcal{M}(X, (A^V)^U) &\cong \mathcal{V}(U, \mathcal{M}(X, A^V)) \cong \mathcal{V}(U, \mathcal{V}(V, \mathcal{M}(X, A))) \\ &\cong \mathcal{V}(U \times V, \mathcal{M}(X, A)) \cong \mathcal{M}(X, A^{U \times V})\end{aligned}$$

for all $X \in \mathcal{M}$. By the Yoneda lemma $(A^V)^U \cong A^{U \times V}$. The case for tensors is similar. \square

We now introduce the general notions of weighted limit and weighted colimit from three different viewpoints. We introduce these perspectives in the reverse of the logical order, because we find this route to be the most intuitive. We first describe the axioms that characterize the weighted limit and colimit bifunctors, whenever they exist. We then explain how weighted limits and colimits can be constructed, again assuming these exist. We then finally introduce the general universal property that defines a particular weighted limit or colimit, which tells us when the notions just introduced do in fact exist.

7.1.3. DEFINITION (weighted limits and colimits, axiomatically). For a small \mathcal{V} -enriched category \mathcal{A} and a large \mathcal{V} -enriched category \mathcal{M} , the **weighted limit** and **weighted colimit bifunctors**

$$\lim_{-}^{\mathcal{A}} -: (\mathcal{V}^{\mathcal{A}})^{\text{op}} \times \mathcal{M}^{\mathcal{A}} \rightarrow \mathcal{M} \quad \text{and} \quad \text{colim}_{-}^{\mathcal{A}} -: \mathcal{V}^{\mathcal{A}} \times \mathcal{M}^{\mathcal{A}^{\text{op}}} \rightarrow \mathcal{M}$$

are characterized by the following pair of axioms whenever they exist:

(i) Weighted (co)limits with representable weights evaluate at the representing object:

$$\lim_{\mathcal{A}(a, -)}^{\mathcal{A}} F \cong F(a) \quad \text{and} \quad \text{colim}_{\mathcal{A}(-, a)}^{\mathcal{A}} G \cong G(a).$$

(ii) The weighted (co)limit bifunctors are cocontinuous in the weight: for any diagrams $F \in \mathcal{M}^{\mathcal{A}}$ and $G \in \mathcal{M}^{\mathcal{A}^{\text{op}}}$, the functor $\text{colim}_{-}^{\mathcal{A}} G$ preserves colimits, while the functor $\lim_{-}^{\mathcal{A}} F$ carries colimits to limits.¹

We interpret axiom (ii) to mean that weights can be “made-to-order”: a weight constructed as a colimit of representables — as all \mathcal{V} -valued functors are — will stipulate the expected universal property.

7.1.4. DEFINITION (weighted limits and colimits, constructively). The **limit** of $F \in \mathcal{M}^{\mathcal{A}}$ **weighted by** $W \in \mathcal{V}^{\mathcal{A}}$ is computed by the functor cotensor product:

$$\lim_W^{\mathcal{A}} F := \int_{a \in \mathcal{A}} F(a)^{W(a)} := \text{eq} \left(\prod_{a \in \mathcal{A}} F(a)^{W(a)} \rightrightarrows \prod_{a, b \in \mathcal{A}} F(b)^{\mathcal{A}(a, b) \times W(a)} \right), \quad (7.1.5)$$

where the product and equalizer should be interpreted as *conical limits*; see Digression 1.2.4 or Definition 7.1.14 below. The maps in the equalizer diagram are induced by the actions $\mathcal{A}(a, b) \times W(a) \rightarrow W(b)$ and $F(a) \rightarrow F(b)^{\mathcal{A}(a, b)}$ of the hom-object $\mathcal{A}(a, b)$ on the \mathcal{V} -functors W and F ; the latter case makes use of the natural isomorphism $F(b)^{\mathcal{A}(a, b) \times W(a)} \cong (F(b)^{\mathcal{A}(a, b)})^{W(a)}$ of Lemma 7.1.2.

¹More precisely, as will be proven in Proposition 7.1.12, the weighted colimit functor $\text{colim}_{-}^{\mathcal{A}} G$ preserves weighted colimits, while the weighted limit functor $\lim_{-}^{\mathcal{A}} F$ carries weighted colimits to weighted limits.

Dually, the **colimit** of $G \in \mathcal{M}^{\mathcal{A}^{\text{op}}}$ weighted by $W \in \mathcal{V}^{\mathcal{A}}$ is computed by the functor tensor product:

$$\text{colim}_W^{\mathcal{A}} G := \int^{a \in \mathcal{A}} W(a) \otimes G(a) := \text{coeq} \left(\coprod_{a, b \in \mathcal{A}} (W(a) \times \mathcal{A}(a, b)) \otimes G(b) \rightrightarrows \coprod_{a \in \mathcal{A}} W(a) \otimes G(a) \right), \quad (7.1.6)$$

where the coproduct and coequalizer should be interpreted as *conical colimits*. One of the maps in the coequalizer diagram is induced by the action $\mathcal{A}(a, b) \otimes G(b) \rightarrow G(a)$ of $\mathcal{A}(a, b)$ on the contravariant \mathcal{V} -functor G and the natural isomorphism $(W(a) \times \mathcal{A}(a, b)) \otimes G(b) \cong W(a) \otimes (\mathcal{A}(a, b) \otimes G(b))$ of Lemma 7.1.2; the other uses the covariant action of $\mathcal{A}(a, b)$ on W as before.

7.1.7. DEFINITION (weighed limits and colimits, the universal property). The **limit** $\lim_W^{\mathcal{A}} F$ of the diagram $F \in \mathcal{M}^{\mathcal{A}}$ weighted by $W \in \mathcal{V}^{\mathcal{A}}$ and the **colimit** $\text{colim}_W^{\mathcal{A}} G$ of $G \in \mathcal{M}^{\mathcal{A}^{\text{op}}}$ weighted by $W \in \mathcal{V}^{\mathcal{A}}$ are characterized by the universal properties:

$$\mathcal{M}(X, \lim_W^{\mathcal{A}} F) \cong \mathcal{V}^{\mathcal{A}}(W, \mathcal{M}(X, F)) \quad \text{and} \quad \mathcal{M}(\text{colim}_W^{\mathcal{A}} G, X) \cong \mathcal{V}^{\mathcal{A}}(W, \mathcal{M}(G, X)), \quad (7.1.8)$$

each of these defining an isomorphism between objects of \mathcal{V} .

When the indexing category \mathcal{A} is clear from context, as is typically the case, we frequently drop it from the notation for the weighted limit and weighted colimit. We now argue that these three definitions characterize the same objects. Along the way, we obtain results of interest in their own right, that we record separately.

7.1.9. LEMMA. *The category \mathcal{V} admits all weighted limits, as defined by the formula of (7.1.5) satisfying the natural isomorphism of (7.1.8). Explicitly, for a weight $W: \mathcal{A} \rightarrow \mathcal{V}$ and a diagram $F: \mathcal{A} \rightarrow \mathcal{V}$, the weighted limit*

$$\lim_W^{\mathcal{A}} F := \mathcal{V}^{\mathcal{A}}(W, F),$$

is the \mathcal{V} -object of \mathcal{V} -natural transformations from W to F .

PROOF. The \mathcal{V} -functor $\mathcal{V}(\mathbb{1}, -): \mathcal{V} \rightarrow \mathcal{V}$ represented by the monoidal unit is naturally isomorphic to the identity functor. So taking $X = \mathbb{1}$ in the universal property of (7.1.8) in the case where the diagram $F \in \mathcal{V}^{\mathcal{A}}$ is valued in the \mathcal{V} -category \mathcal{V} , we have

$$\lim_W^{\mathcal{A}} F \cong \mathcal{V}^{\mathcal{A}}(W, F).$$

Simultaneously, the formula (7.1.5) computes the \mathcal{V} -object $\mathcal{V}^{\mathcal{A}}(W, F)$ of \mathcal{V} -natural transformations from W to F defined in Definition A.3.8. \square

The \mathcal{V} -object of \mathcal{V} -natural transformations satisfies the natural isomorphism $\mathcal{V}(V, \mathcal{V}^{\mathcal{A}}(W, F)) \cong \mathcal{V}^{\mathcal{A}}(W, \mathcal{V}(V, F))$ for any $V \in \mathcal{V}$. Applying the observation that W -weighted limits of \mathcal{V} -valued functors are \mathcal{V} -objects of natural transformations to the functor $\mathcal{M}(X, F-)$ and $\mathcal{M}(G-, X)$ in the case of $F \in \mathcal{M}^{\mathcal{A}}$ and $G \in \mathcal{M}^{\mathcal{A}^{\text{op}}}$, we may re-express the natural isomorphism (7.1.8) as:

7.1.10. COROLLARY. *The weighted limits and weighted colimits of (7.1.8) are representably defined as weighted limits in \mathcal{V} : for $W \in \mathcal{V}^{\mathcal{A}}$ and $F \in \mathcal{M}^{\mathcal{A}}$ and $G \in \mathcal{M}^{\mathcal{A}^{\text{op}}}$ the weighted limit and colimit are characterized by isomorphisms*

$$\mathcal{M}(X, \lim_W F) \cong \lim_W \mathcal{M}(X, F) \quad \text{and} \quad \mathcal{M}(\text{colim}_W G, X) \cong \lim_W \mathcal{M}(G, X) \quad (7.1.11)$$

natural in X in \mathcal{V} . \square

We now unify the Definitions 7.1.3, 7.1.4, and 7.1.7.

7.1.12. PROPOSITION. *When the limits and colimits of (7.1.5) and (7.1.6) exist they define objects satisfying the universal properties (7.1.8) or equivalently (7.1.11) and bifunctors satisfying the axioms of Definition 7.1.3.*

PROOF. The proofs are dual, so we confine our attention to the limit case. The general case of the implication Definition 7.1.4 \Rightarrow 7.1.7 — for either weighted limits or weighted colimits — is a direct consequence of the special case of this implication for weighted limits valued in $\mathcal{M} = \mathcal{V}$ proven as Lemma 7.1.9 and Corollary 7.1.10. The limits of (7.1.5) in \mathcal{M} are also defined representably in terms of the analogous limits in \mathcal{V} . So the object defined by (7.1.5) represents the \mathcal{V} -functor $\lim_W \mathcal{M}(-, F)$ that defines the weighted limit $\lim_W F$.

It remains to prove that the weighted limits of Definitions 7.1.4 and 7.1.7 satisfy the axioms of Definition 7.1.3. In the case of a \mathcal{V} -valued diagram $F \in \mathcal{V}^{\mathcal{A}}$, axiom (i) is the \mathcal{V} -Yoneda lemma:

$$\mathcal{V}^{\mathcal{A}}(\mathcal{A}(a, -), F) \cong F(a)$$

proven in Theorem A.3.11. Once again, the general case for $F \in \mathcal{M}^{\mathcal{A}}$ follows from the special case for \mathcal{V} -valued diagrams, for to demonstrate an isomorphism $\lim_{\mathcal{A}(a, -)} F \cong F(a)$ in \mathcal{M} it suffices to demonstrate an isomorphism $\mathcal{M}(X, \lim_{\mathcal{A}(a, -)} F) \cong \mathcal{M}(X, F(a))$ in \mathcal{V} for all $X \in \mathcal{M}$ and have such a natural isomorphism by applying (7.1.11) and the observation just made to the functor $\mathcal{M}(X, F-) \in \mathcal{V}^{\mathcal{A}}$.

For the axiom (ii), consider a diagram $K: \mathcal{J}^{\text{op}} \rightarrow \mathcal{V}^{\mathcal{A}}$ of weights and a weight $V \in \mathcal{V}^{\mathcal{J}}$ so that $\text{colim}_{\mathcal{V}}^{\mathcal{J}} K \cong W$. For any $F \in \mathcal{M}^{\mathcal{A}}$, we will show that the \mathcal{V} -functor $\lim_{\mathcal{V}}^{\mathcal{A}} F: (\mathcal{V}^{\mathcal{A}})^{\text{op}} \rightarrow \mathcal{M}$ carries the V -weighted colimit of K to the V -weighted limit of the composite diagram $\lim_K^{\mathcal{A}} F: \mathcal{J} \rightarrow \mathcal{M}$.

The universal property (7.1.8), applied first to the $\text{colim}_{\mathcal{V}}^{\mathcal{J}} K$ -weighted limit of the diagram F and the object X , and then to the V -weighted colimit of the diagram K and the object $\mathcal{M}(X, F)$, supplies isomorphisms:

$$\mathcal{M}(X, \lim_{\text{colim}_{\mathcal{V}}^{\mathcal{J}} K}^{\mathcal{A}} F) \cong \mathcal{V}^{\mathcal{A}}(\text{colim}_{\mathcal{V}}^{\mathcal{J}} K, \mathcal{M}(X, F)) \cong \mathcal{V}^{\mathcal{J}}(V, \mathcal{V}^{\mathcal{A}}(K, \mathcal{M}(X, F))).$$

Applying (7.1.8) twice more, first for the weights Kj for each $j \in \mathcal{J}$ and then for the weight V and the diagram $\lim_K^{\mathcal{A}} F: \mathcal{J} \rightarrow \mathcal{M}$, we have

$$\cong \mathcal{V}^{\mathcal{J}}(V, \mathcal{M}(X, \lim_K^{\mathcal{A}} F)) \cong \mathcal{M}(X, \lim_{\mathcal{V}}^{\mathcal{J}} \lim_K^{\mathcal{A}} F).$$

By the Yoneda lemma, this proves that

$$\lim_{\text{colim}_{\mathcal{V}}^{\mathcal{J}} K}^{\mathcal{A}} F \cong \lim_{\mathcal{V}}^{\mathcal{J}} \lim_H^{\mathcal{A}} F,$$

i.e., that the weighted limit functor $\lim_{\mathcal{V}}^{\mathcal{A}} F$ carries a weighted colimit of weights to the analogous weighted limit of weights. \square

7.1.13. REMARK (for unenriched indexing categories). When the indexing category is unenriched, the limit and colimit formulas from Definition 7.1.4 simplify

$$\begin{aligned} \lim_W^{\mathcal{A}} F &\cong \text{eq} \left(\prod_{a \in \mathcal{A}} F(a)^{W(a)} \rightrightarrows \prod_{\mathcal{A}(a, b)} F(b)^{W(a)} \right) \\ \text{colim}_W^{\mathcal{A}} G &\cong \text{coeq} \left(\prod_{\mathcal{A}(a, b)} (W(a) \otimes G(b)) \rightrightarrows \prod_{a \in \mathcal{A}} W(a) \otimes G(a) \right) \end{aligned}$$

and in fact, it suffices to consider only non-identity arrows or even just atomic arrows.

7.1.14. DEFINITION (conical limits and colimits). The unit for the cartesian product defines a terminal object $\mathbb{1} \in \mathcal{V}$. The constant diagram at the terminal object then defines a terminal object $\mathbb{1} \in \mathcal{V}^{\mathcal{A}}$. A limit weighted by the terminal weight is called a **conical limit** and a colimit weighted by the terminal weight is called a **conical colimit**. It is common to use the simplified notation $\lim F := \lim_{\mathbb{1}}^{\mathcal{A}} F$ and $\operatorname{colim} G := \operatorname{colim}_{\mathbb{1}}^{\mathcal{A}} G$.

Conical limits and colimits satisfy the defining universal properties

$$\mathcal{M}(X, \lim F) \cong \mathcal{V}^{\mathcal{A}}(\mathbb{1}, \mathcal{M}(X, F)) \quad \text{and} \quad \mathcal{M}(\operatorname{colim} G, X) \cong \mathcal{V}^{\mathcal{A}}(\mathbb{1}, \mathcal{M}(G, X)),$$

which say that $\lim F$ and $\operatorname{colim} G$ represent the functors of \mathcal{V} -enriched conical cones over F or under G , respectively.

We can now properly understand the formulae for weighted limits and colimits given in Definition 7.1.4. In particular, these formulae give criteria under which weighted limits or colimits are guaranteed to exist.

7.1.15. COROLLARY. If \mathcal{M} is a \mathcal{V} -enriched category that admits cotensors and conical limits of all unenriched diagram shapes, then \mathcal{M} admits all weighted limits. Dually, if \mathcal{M} admits tensors and conical colimits of all unenriched diagram shapes, then \mathcal{M} admits all weighted colimits.

7.1.16. REMARK. If \mathcal{M} is a \mathcal{V} -category whose underlying unenriched category admits all small limits, then if \mathcal{M} admits cotensors and tensors over \mathcal{V} , then \mathcal{M} admits all weighted limits. Via the Yoneda lemma, the presence of tensors suffices to internalize the isomorphism of sets expressing the unenriched universal property of limits to an isomorphism in \mathcal{V} that expresses the universal property of conical limits. See Exercise 7.1.i.

7.1.17. EXAMPLE (commas). The comma ∞ -category is the limit in the ∞ -cosmos \mathcal{K} of the diagram $\lrcorner \rightarrow \mathcal{K}$ given by the cospan

$$C \xrightarrow{g} A \xleftarrow{f} B$$

weighted by the diagram $\lrcorner \rightarrow \mathcal{S}Set$ given by the cospan

$$\mathbb{1} \xleftarrow{1} 2 \xleftarrow{0} \mathbb{1}$$

Under the simplification of Remark 7.1.13, the formula for the weighted limit reduces to the equalizer

$$\operatorname{eq} \left(\begin{array}{ccccc} & & \pi & \rightarrow & A^2 & \xrightarrow{(p_1, p_0)} & A \times A \\ C \times A^2 \times B & & & & & & \\ & \searrow \pi & & \nearrow g \times f & & & \\ & & C \times B & & & & \end{array} \right)$$

which computes the pullback of (3.3.2). The universal property (7.1.8) says that functors $X \rightarrow \operatorname{Hom}_A(f, g)$ in \mathcal{K} correspond to simplicial natural transformations, the data of which is given by the three dashed vertical maps that fit into two commutative squares:

$$\begin{array}{ccccc} \mathbb{1} & \xleftarrow{1} & 2 & \xleftarrow{0} & \mathbb{1} \\ \downarrow c! & & \downarrow \alpha & & \downarrow b \\ \operatorname{Fun}(X, C) & \xrightarrow{g_*} & \operatorname{Fun}(X, A) & \xleftarrow{f_*} & \operatorname{Fun}(X, B) \end{array}$$

7.1.18. EXAMPLE (Bousfield-Kan homotopy limits). In their classic book on homotopy limits and colimits [11], Bousfield and Kan define the **homotopy limit** of a diagram indexed by a 1-category A and valued in a Kan-complex enriched category \mathcal{M} to be the limit weighted by the functor

$$\begin{aligned} A &\longrightarrow \mathcal{S}\mathcal{S}et \\ a &\longmapsto A_{/a} \end{aligned}$$

which carries each object $a \in A$ to the nerve of the slice category over a .

7.1.19. EXAMPLE (Kan extensions as weighted co/limits). The usual colimit or limit formula that computes the value of a pointwise left or right Kan extension of an unenriched functor $F: C \rightarrow E$ along $K: C \rightarrow D$ at an object $d \in D$ can be succinctly expressed by the weighted colimit or weighted limit

$$\mathrm{lan}_K F(d) := \mathrm{colim}_{D(K-, d)} F \quad \text{and} \quad \mathrm{ran}_K F(d) := \mathrm{lim}_{D(d, K-)} F.$$

We conclude with a few results from the general theory of weighted limits and colimits. Immediately from their defining universal properties, it can be verified that:

7.1.20. LEMMA (weighted limits of restricted diagrams). *Suppose given a \mathcal{V} -functor $K: \mathcal{A} \rightarrow \mathcal{B}$, a weight $W: \mathcal{A} \rightarrow \mathcal{V}$, and diagrams $F: \mathcal{B} \rightarrow \mathcal{M}$ and $G: \mathcal{B}^{\mathrm{op}} \rightarrow \mathcal{M}$. Then the W -weighted limit or colimit of the restricted diagram is isomorphic to the $\mathrm{lan}_K W$ -weighted limit or colimit of the original diagram:*

$$\lim_{\mathcal{W}}^{\mathcal{A}} (F \circ K) \cong \lim_{\mathrm{lan}_K W}^{\mathcal{B}} F \quad \text{and} \quad \mathrm{colim}_{\mathcal{W}}^{\mathcal{A}} (G \circ K) \cong \mathrm{colim}_{\mathrm{lan}_K W}^{\mathcal{B}} G.$$

PROOF. Exercise 7.1.iii. □

An enriched adjunction is comprised of a pair of \mathcal{V} -functors $F: \mathcal{B} \rightarrow \mathcal{A}$ and $U: \mathcal{A} \rightarrow \mathcal{B}$ together with a family of isomorphisms $\mathcal{A}(Fb, a) \cong \mathcal{B}(b, Ua)$ that are \mathcal{V} -natural in both variables; see Definition A.3.15. The usual Yoneda-style argument enriches to show:

7.1.21. PROPOSITION (weighted RAPL/LAPC). *A \mathcal{V} -enriched right adjoint functor $U: \mathcal{A} \rightarrow \mathcal{B}$ preserves all weighted limits that exist in \mathcal{A} , while its \mathcal{V} -enriched left adjoint $F: \mathcal{B} \rightarrow \mathcal{A}$ preserves all weighted colimits that exist in \mathcal{B} .*

PROOF. Exercise 7.1.iv. □

By the axioms of Definition 1.2.1, ∞ -cosmoi will admit a large class of simplicially-enriched weighted limits built from the simplicial cotensors and conical simplicial limits enumerated in 1.2.1(i). In practice, ∞ -cosmoi often arise as subcategories (of “fibrant objects”) in a larger category that is also admits simplicially-enriched weighted colimits, which can then be reflected back into the ∞ -cosmos to defined *weighted bicolimits*. This is a story for much later, so we will confine our attention to the case of weighted limits for the rest of this chapter.

Exercises.

7.1.i. EXERCISE. Suppose \mathcal{M} is a tensored and \mathcal{V} -enriched category whose underlying unenriched category admits limits of all unenriched diagram shapes. Show that \mathcal{M} admits conical limits of all unenriched diagram shapes, proving the extension of Corollary 7.1.15 described in Remark 7.1.16.

7.1.ii. EXERCISE. Taking the base for enrichment \mathcal{V} to be $\mathcal{S}et$, compute the following weighted limits of a simplicial set X , regarded as a diagram in $\mathcal{S}et^{\Delta^{\mathrm{op}}}$, weighted by:

- (i) the standard n -simplex $\Delta[n] \in \mathbf{Set}^{\Delta^{\text{op}}}$,
- (ii) the **spine** of the n -simplex, the simplicial subset $\Gamma[n] \hookrightarrow \Delta[n]$ obtained by gluing together the n edges from i to $i + 1$ into a composable path,
- (iii) the n -simplex boundary $\partial\Delta[n] \in \mathbf{Set}^{\Delta^{\text{op}}}$.²

7.1.iii. EXERCISE. Prove Lemma 7.1.20.

7.1.iv. EXERCISE. Prove Proposition 7.1.21.

7.2. Flexible weighted limits and the collage construction

Our aim in this section is to introduce a special class of \mathbf{SSet} -valued weights whose associated weighted limit notions are homotopically well-behaved. Borrowing a term from 2-category theory, we refer to these weights as *flexible*. All of the limits enumerated in 1.2.1(i) are flexible limits. In fact, we will prove that ∞ -cosmoi admit all flexible weighted limits because these can be built out of the limits enumerated in 1.2.1(i). In §7.4, we will use this observation to help us verify the limit axiom for newly constructed ∞ -cosmoi in a more systematic way.

In this section, we will characterize the class of flexible weights as precisely those whose associated *collages* define relative simplicial computads, which will allow us to readily produce examples. In §7.3, we will establish the homotopical properties of flexible weighted limits and make precise the relationships between this class of the limits and limits assumed present in any ∞ -cosmos by axiom 1.2.1(i).

7.2.1. DEFINITION (flexible weights and projective cell complexes). Let \mathcal{A} be a simplicial category.

- A simplicial natural transformation of the form

$$\partial\Delta[n] \times \mathcal{A}(a, -) \hookrightarrow \Delta[n] \times \mathcal{A}(a, -)$$

is called a **projective n -cell at $a \in \mathcal{A}$** .

- A natural transformation $\alpha: V \hookrightarrow W$ in $\mathbf{SSet}^{\mathcal{A}}$ that can be expressed as a countable composite of pushouts of coproducts of projective cells is called a **projective cell complex**.
- A weight $W \in \mathbf{SSet}^{\mathcal{A}}$ is **flexible** just when $\emptyset \hookrightarrow W$ is a projective cell complex.

7.2.2. REMARK (on generalized projective cells). Since any monomorphism of simplicial sets $U \hookrightarrow V$ can be decomposed as a sequential composite of pushouts of coproducts of boundary inclusions $\partial\Delta[n] \hookrightarrow \Delta[n]$, the class of projective cell complexes may be also be described as the class of maps in $\mathbf{SSet}^{\mathcal{A}}$ that can be expressed as a countable composite of pushouts of coproducts of monomorphisms $U \times \mathcal{A}(a, -) \hookrightarrow V \times \mathcal{A}(a, -)$ for some $a \in \mathcal{A}$.

7.2.3. EXAMPLE. Since any simplicial set can be decomposed as a sequential composite of pushouts of coproducts of boundary inclusions $\partial\Delta[n] \hookrightarrow \Delta[n]$, simplicial cotensors are flexible weights.

7.2.4. EXAMPLE. Conical products also define flexible weighted limits, built by attaching one projective 0-cell for each object in the indexing set.

7.2.5. NON-EXAMPLE. Conical limits indexed by any 1-category that contains non-identity arrows are *not* flexible because the legs of a conical cone over the domain and codomain of each arrow in the diagram are required to define a strictly commutative triangle of 0-arrows. The specifications for a

²The limit of a simplicial object weighted by $\partial\Delta[n]$ is called the *n th-matching object*; see Appendix C.

flexible weight allow us to free attach n -arrows of any dimension, but do not provide a mechanism for demanding strict commutativity of any diagram of n -arrows — only commutativity up to the presence of a higher cell.

7.2.6. DIGRESSION (on flexible limits in 2-category theory). Simplicial limits weighted by flexible weights should be thought of as analogous to **flexible 2-limits**, i.e., 2-limits built out of products, inserters, equifiers, and retracts (splittings of idempotents) [6]. More precisely, simplicial limits weighted by flexible weights are analogous to the **PIE limits**, those built just from products, inserters, and equifiers, but we choose to adopt the moniker from the slight larger class of weights because we find it to be more evocative. The PIE limits also include iso-inserters, descent objects, comma objects, and Eilenberg-Moore objects, as well as all pseudo, lax, and oplax limits. Many important 2-categories, such as the 2-category of accessible categories and accessible functors, fail to admit all 2-categorical limits, but do admit all PIE-limits [40].

The weights for flexible limits are the cofibrant objects in a model structure on the diagram 2-category $\mathbf{Cat}^{\mathcal{A}}$ that is enriched over the folk model structure on \mathbf{Cat} ; the PIE weights are exactly the *cellular* cofibrant objects. Correspondingly, the projective cell complexes of Definition 7.2.1 are exactly the cellular cofibrations in the projective model structure on $\mathbf{SSet}^{\mathcal{A}}$.

Recall that a weight is intended to describe the “shape” of cones over diagrams indexed by a particular category. In the case a weight $W: \mathcal{A} \rightarrow \mathbf{SSet}$ valued in simplicial sets, we can describe the shape of W -cones directly as a simplicial category called the *collage* of the weight.

7.2.7. DEFINITION (collage construction). The **collage** of a weight $W: \mathcal{A} \rightarrow \mathbf{SSet}$ is a simplicial category $\text{coll}W$ which contains \mathcal{A} as a full subcategory together with one additional object \top whose endomorphism space is the point. The mapping spaces from any object $a \in \mathcal{A}$ to \top are empty, while the mapping spaces from \top to the image of $\mathcal{A} \hookrightarrow \text{coll}W$ are defined by:

$$\text{coll}W(\top, a) := W(a)$$

with the action maps $\mathcal{A}(a, b) \times W(a) \rightarrow W(b)$ from the simplicial functor W used to define composition. This defines a simplicial category together with a canonical inclusion $\mathbb{1} + \mathcal{A} \hookrightarrow \text{coll}W$ that is bijective on objects and fully faithful on $\mathbb{1}$ and \mathcal{A} separately.

7.2.8. PROPOSITION (collage adjunction).

(i) The collage construction defines a fully faithful functor

$$\mathbf{SSet}^{\mathcal{A}} \xrightarrow{\text{coll}} \mathbb{1} + \mathcal{A} / \mathbf{SSet}\text{-Cat}$$

from the category of \mathcal{A} -indexed weights to the category of simplicial categories under $\mathbb{1} + \mathcal{A}$ whose essential image is comprised of those $\langle e, F \rangle: \mathbb{1} + \mathcal{A} \rightarrow \mathcal{E}$ that are bijective on objects, fully faithful when restricted to $\mathbb{1}$ and \mathcal{A} , and have the property that there are no arrows in \mathcal{E} from the image of F to e .

(ii) The collage functor admits a right adjoint

$$\begin{array}{ccc} & \xrightarrow{\text{coll}} & \\ \mathbf{SSet}^{\mathcal{A}} & \perp & \mathbb{1} + \mathcal{A} / \mathbf{SSet}\text{-Cat} \\ & \xleftarrow{\text{wgt}} & \end{array}$$

which carries a pair $\langle e, F \rangle: \mathbb{1} + \mathcal{A} \rightarrow \mathcal{E}$ to the weight $\mathcal{E}(e, F-): \mathcal{A} \rightarrow \mathbf{SSet}$.

PROOF. The construction of the collage functor is straightforward and left to the reader. The characterization of its essential image follows from the observation that to define a simplicial functor $W: \mathcal{A} \rightarrow \mathcal{S}\mathcal{S}et$ requires no more and no less than

- the specification of simplicial sets $W(a)$ for each $a \in \mathcal{A}$ and
- and the specification of simplicial maps $\mathcal{A}(a, b) \times W(a) \rightarrow W(b)$ for each $a, b \in \mathcal{A}$

so that this action is associative in sense that the diagram

$$\begin{array}{ccc} \mathcal{A}(b, c) \times \mathcal{A}(a, b) \times W(a) & \xrightarrow{\circ} & \mathcal{A}(a, c) \times W(a) \\ \downarrow & & \downarrow \\ \mathcal{A}(b, c) \times W(b) & \longrightarrow & W(c) \end{array}$$

commutes. This is the same as what is required to extend $\mathbb{1} + \mathcal{A}$ to a simplicial category in which all of the additional maps start at \top and end at an object in \mathcal{A} .

The adjunction asserts that simplicial functors

$$\begin{array}{ccc} & \mathbb{1} + \mathcal{A} & \\ \swarrow & & \searrow \langle e, F \rangle \\ \text{coll}W & \xrightarrow{G} & \mathcal{E} \end{array}$$

from $\text{coll}W$ to \mathcal{E} under $\mathbb{1} + \mathcal{A}$ stand in natural bijective correspondence with simplicial natural transformations $\gamma: W \Rightarrow \mathcal{E}(e, F-)$. Since the inclusion $\mathbb{1} + \mathcal{A} \hookrightarrow \text{coll}W$ is bijective on objects and full on most homs, the data of the simplicial functor requires only the specification of the maps $\text{coll}W(\top, a) = W(a) \rightarrow \mathcal{E}(e, Fa)$. These define the components of the simplicial natural transformation γ and functoriality of G corresponds to naturality of γ . \square

The collage adjunction has a useful and important interpretation.

7.2.9. COROLLARY. *The collage of a weight $W: \mathcal{A} \rightarrow \mathcal{S}\mathcal{S}et$ realizes the shape of W -weighted cones in the sense that simplicial functors $G: \text{coll}W \rightarrow \mathcal{E}$ with domain $\text{coll}W$ stand in bijection to W -cones over the diagram $G|_{\mathcal{A}}$ with summit $G(\top)$.* \square

On account of Lemma 7.1.20, we'll be interested in computing left Kan extensions of weights encoded as collages.

7.2.10. LEMMA. *For any weight $W: \mathcal{A} \rightarrow \mathcal{S}\mathcal{S}et$ and simplicial functor $K: \mathcal{A} \rightarrow \mathcal{B}$, the pushout of simplicial categories*

$$\begin{array}{ccc} \mathbb{1} + \mathcal{A} & \xrightarrow{\mathbb{1}+K} & \mathbb{1} + \mathcal{B} \\ \downarrow & \ulcorner & \downarrow \\ \text{coll}W & \longrightarrow & \text{coll}(\text{lan}_K W) \end{array}$$

computes the collage of the weight $\text{lan}_K W: \mathcal{B} \rightarrow \mathcal{S}\mathcal{S}et$.

PROOF. By the defining universal property, a simplicial functor out of the pushout is given by a pair of functors $\langle e, F \rangle: \mathbb{1} + \mathcal{B} \rightarrow \mathcal{E}$ and $G: \text{coll}W \rightarrow \mathcal{E}$ so that

$$\begin{array}{ccc} & \mathbb{1} + \mathcal{A} & \\ \swarrow & & \searrow \langle e, FK \rangle \\ \text{coll}W & \xrightarrow{G} & \mathcal{E} \end{array}$$

By Corollary 7.2.9, this data defines a W -cone with summit e over the diagram $FK: \mathcal{A} \rightarrow \mathcal{E}$. By Lemma 7.1.20 such data equivalently describes a $\text{lan}_K W$ -cone with summit e over the diagram $F: \mathcal{B} \rightarrow \mathcal{E}$. Applying Corollary 7.2.9 again, we conclude that the pushout is given by the simplicial category $\text{coll}(\text{lan}_K W)$ as claimed. \square

In analogy with Corollary 4.3.5, we can encode simplicial W -weighted limits as a right Kan extension from the indexing simplicial category to the simplicial category that describes the shape of W -cones.

7.2.11. LEMMA. *For any simplicial functor $F: \mathcal{A} \rightarrow \mathcal{E}$ and any weight $W: \mathcal{A} \rightarrow \mathcal{SSet}$, the weighted limit $\lim_W F$ exists if and only if the pointwise right Kan extension of F along $\mathcal{A} \hookrightarrow \text{coll}W$ exists, in which case $\text{lan } F(\top) \cong \lim_W F$.*

PROOF. Since $\mathcal{A} \hookrightarrow \text{coll}W$ is fully faithful, pointwise right Kan extensions may be chosen to define genuine extensions

$$\begin{array}{ccc} & \mathcal{A} & \\ \swarrow & & \searrow F \\ \text{coll}W & \overset{\text{ran } F}{\dashrightarrow} & \mathcal{E} \end{array}$$

By Corollary 7.2.9, this data defines a W -cone over F with summit $\text{ran } F(\top)$ that we denote by $\lambda: W \Rightarrow \mathcal{E}(\text{ran } F(\top), F(-))$.

By Corollary 7.2.9 again, the data of a cone over the right Kan extension diagram displayed below-left

$$\begin{array}{ccc} & \mathcal{A} & \\ \swarrow & \uparrow \alpha & \searrow F \\ \text{coll}W & & \mathcal{E} \end{array} \quad \overset{G}{\curvearrowright} \quad \begin{array}{ccc} & \mathcal{A} & \\ \swarrow & \xrightarrow{\text{ran } F} & \searrow F \\ \text{coll}W & \xrightarrow{\exists! \uparrow \eta} & \mathcal{E} \end{array} \quad \overset{G}{\curvearrowright}$$

defines a W -cone

$$W \xRightarrow{\gamma} \mathcal{E}(G(\top), G|_{\mathcal{A}}(-)) \xRightarrow{\alpha_*} \mathcal{E}(G(\top), F(-))$$

over F . The universal property of the right Kan extension depicted above-right says this cone factors uniquely through the W -cone λ along a map $\eta_{\top}: G(\top) \rightarrow \text{ran } F(\top)$. Thus, the right Kan extension of F along $\mathcal{A} \hookrightarrow \text{coll}W$ equips the resulting W -cone with the universal property of the W -weighted limit. \square

A particularly convenient aspect of the collage construction is that it allows us to detect the class of flexible weights.

7.2.12. THEOREM (flexible weights and collages). *A natural transformation $\alpha: V \hookrightarrow W$ between weights in $\mathcal{SSet}^{\mathcal{A}}$ is a projective cell complex if and only if $\text{coll}(\alpha): \text{coll}V \hookrightarrow \text{coll}W$ is a relative simplicial computad. In particular, W is a flexible weight if and only if $\mathbb{1} + \mathcal{A} \hookrightarrow \text{coll}W$ is a relative simplicial computad.*

PROOF. If $\alpha: V \hookrightarrow W$ is a projective cell complex, then it can be presented as a countable composite of pushouts of coproducts of projective cells of varying dimensions indexed by the objects $a \in \mathcal{A}$. Since the collage construction is a left adjoint, it preserves these colimits, and hence the map $\text{coll}(\alpha): \text{coll}V \hookrightarrow \text{coll}W$ as a transfinite composite of pushouts of coproducts of simplicial functors $\text{coll}(\partial \Delta[n] \times \mathcal{A}(a, -)) \hookrightarrow \text{coll}(\Delta[n] \times \mathcal{A}(a, -))$ in $\mathbb{1}^{+\mathcal{A}}/\mathcal{SSet}\text{-Cat}$. This composite colimit diagram is connected — note $\text{coll}\emptyset = \mathbb{1} + \mathcal{A}$, so this cell complex presentation is also preserved by the

forgetful functor $\mathbb{1}^{+\mathcal{A}}/\mathcal{SSet}\text{-Cat} \rightarrow \mathcal{SSet}\text{-Cat}$ and the simplicial functor $\text{coll}(\alpha): \text{coll}V \hookrightarrow \text{coll}W$ can be understood as a transfinite composite of pushouts of coproducts of $\text{coll}(\partial\Delta[n] \times \mathcal{A}(a, -)) \hookrightarrow \text{coll}(\Delta[n] \times \mathcal{A}(a, -))$ in $\mathcal{SSet}\text{-Cat}$.

This is advantageous because there is a pushout square in $\mathcal{SSet}\text{-Cat}$

$$\begin{array}{ccc} 2[\partial\Delta[n]] & \longrightarrow & \text{coll}(\partial\Delta[n] \times \mathcal{A}(a, -)) \\ \downarrow & \lrcorner & \downarrow \\ 2[\Delta[n]] & \longrightarrow & \text{coll}(\Delta[n] \times \mathcal{A}(a, -)) \end{array} \quad \rightsquigarrow \quad \begin{array}{ccc} \partial\Delta[n] & \xrightarrow{\text{id}_a} & \partial\Delta[n] \times \mathcal{A}(a, a) \\ \downarrow & & \downarrow \\ \Delta[n] & \xrightarrow{\text{id}_a} & \Delta[n] \times \mathcal{A}(a, a) \end{array} \quad (7.2.13)$$

whose horizontals sends the two objects $-$ and $+$ of the simplicial computads defined in Example 6.1.5 to \top and a and act on the non-trivial hom-spaces via the inclusions whose component in $\mathcal{A}(a, a)$ is constant at the identity element at a . The fact that $\text{coll}(\partial\Delta[n] \times \mathcal{A}(a, -)) \hookrightarrow \text{coll}(\Delta[n] \times \mathcal{A}(a, -))$ is a pushout of $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$ can be verified by transposing across the adjunction of Proposition 7.2.8 and applying the Yoneda lemma. From this we see that $\text{coll}(\alpha): \text{coll}V \hookrightarrow \text{coll}W$ is a transfinite composite of pushouts of coproducts of simplicial functors $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$, which proves that this map is a relative simplicial computad.

Conversely, if $\text{coll}(\alpha): \text{coll}V \hookrightarrow \text{coll}W$ is a relative simplicial computad, then it can be presented as a countable composite of pushouts of coproducts of simplicial functors $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$; since this inclusion is bijective on objects the inclusion $\emptyset \hookrightarrow \mathbb{1}$ is not needed. Since the only arrows of $\text{coll}W$ that are not present in $\text{coll}V$ have domain \top and codomain $a \in \mathcal{A}$, the characterization of the essential image of the collage functor of Proposition 7.2.8(i) allows us to identify each stage of the countable composite

$$\text{coll}V \hookrightarrow \text{coll}(W^1) \hookrightarrow \dots \hookrightarrow \text{coll}(W^i) \hookrightarrow \text{coll}(W^{i+1}) \hookrightarrow \dots \hookrightarrow \text{coll}W$$

as the collage of some weight $W^i: \mathcal{A} \rightarrow \mathcal{SSet}$. Each attaching map $2[\partial\Delta[n]] \rightarrow \text{coll}W^i$ in the cell complex presentation acts on objects by mapping $-$ and $+$ to \top and a for some $a \in \mathcal{A}$, and hence factors through the top horizontal of the pushout square (7.2.13). Hence, the inclusion $\text{coll}(W^i) \hookrightarrow \text{coll}(W^{i+1})$ is a pushout of a coproduct of the maps $\text{coll}(\partial\Delta[n] \times \mathcal{A}(a, -)) \hookrightarrow \text{coll}(\Delta[n] \times \mathcal{A}(a, -))$, one for each cell $2[\partial\Delta[n]] \hookrightarrow 2[\Delta[n]]$ whose attaching map sends $+$ to $a \in \text{coll}(W^i)$. As the collage functor is fully faithful, we have now expressed $\text{coll}(\alpha): \text{coll}V \hookrightarrow \text{coll}W$ as a countable composite of pushouts of coproducts of simplicial functors $\text{coll}(\partial\Delta[n] \times \mathcal{A}(a, -)) \hookrightarrow \text{coll}(\Delta[n] \times \mathcal{A}(a, -))$. A fully faithful functor that preserves colimits also reflects them, so in this way we see that $\alpha: V \hookrightarrow W$ is a countable composite of pushouts of coproducts of projective cells, proving that it is a projective cell complex as claimed. \square

As the first of many applications, we introduce the weights for pseudo limits by constructing their collages and observe immediately that this class of weights is flexible.

7.2.14. DEFINITION (weights for pseudo limits). For any simplicial set X , the coherent realization of the canonical inclusion $\mathbb{1} + X \hookrightarrow X^\triangleleft$ defines a collage $\mathbb{1} + \mathbb{C}X \hookrightarrow \mathbb{C}(X^\triangleleft)$. By Lemma 6.3.5, $\mathbb{1} + \mathbb{C}X \hookrightarrow \mathbb{C}(X^\triangleleft)$ is a simplicial subcomputad inclusion and hence by Lemma 6.1.12 a relative simplicial computad. Thus, Theorem 7.2.12 tells us that the collage $\mathbb{1} + \mathbb{C}X \hookrightarrow \mathbb{C}(X^\triangleleft)$ encodes a flexible weight $W_X: \mathbb{C}X \rightarrow \mathcal{SSet}$, which we call the **weight for the pseudo limit of a homotopy coherent diagram of shape X** . The W_X -weighted limit of a homotopy coherent diagram of shape X is then referred to as the **pseudo weighted limit** of that diagram.

Since the left adjoint of the collage adjunction is fully faithful, its unit is an isomorphism, and this permits us to define the weight W_X explicitly: for a vertex $x \in X$,

$$W_X(x) := \mathfrak{C}(X^\triangleleft)(\top, x).$$

We call W_X the weight for a “pseudo” limit because we anticipate considering homotopy coherent diagrams valued in Kan-complex enriched categories, in which all arrows in positive dimension are automatically invertible. By Corollary 7.3.3, W_X -weighted limits also exist for diagrams valued in ∞ -cosmoi, which are only quasi-categorically enriched. In such contexts, it would be more appropriate to refer to W_X as the weight for *lax* limits, since in that context the 1-arrows of $\mathfrak{C}(X^\triangleleft)$ will likely map to non-invertible morphisms.

Exercises.

7.2.i. EXERCISE. Compute the collage of the weight $U: \mathbb{1} \rightarrow \mathcal{S}\mathcal{S}et$ and use Theorem 7.2.12 to give a second proof that simplicial cotensors are flexible weighted limits. Compare this argument with that given in Example 7.2.3.

7.2.ii. EXERCISE. The inclusion into the join $\mathbb{1} + X \hookrightarrow X^\triangleleft \cong \mathbb{1} \star X$ is bijective on vertices. The complement of the image contains a non-degenerate $(n + 1)$ -simplex for each non-degenerate n -simplex of X whose initial vertex is \top and whose 0th face is isomorphic to the image of that simplex. Use Theorem 6.3.10 to describe the atomic arrows of the simplicial computad $\mathfrak{C}(X^\triangleleft)$ that are not in the image of $\mathbb{1} + \mathfrak{C}X$.

7.3. Homotopical properties of flexible weighed limits

In a \mathcal{V} -model category \mathcal{M} , the fibrant objects are closed under weighted limits whose weights are projective cofibrant. For instance, the fibrant objects in a *Cat*-enriched model structure are closed under flexible weighted limits [33, 5.4] in the sense of [6]. Specializing this argument to the case of ∞ -cosmoi, we obtain the following result:

7.3.1. PROPOSITION (flexible weights are homotopical). *Let $W: \mathcal{A} \rightarrow \mathcal{S}\mathcal{S}et$ be a flexible weight and let \mathcal{K} be an ∞ -cosmos.*

- (i) *The weighted limit $\lim_W^{\mathcal{A}} F$ of any diagram $F: \mathcal{A} \rightarrow \mathcal{K}$ may be expressed as a countable inverse limit of pullbacks of products of isofibrations*

$$Fa^{\Delta[n]} \longrightarrow Fa^{\partial\Delta[n]} \tag{7.3.2}$$

one for each projective n -cell at a in the given projective cell complex presentation of W .

- (ii) *If $V \hookrightarrow W \in \mathcal{S}\mathcal{S}et^{\mathcal{A}}$ is a projective cell complex between flexible weights, then for any diagram $F: \mathcal{A} \rightarrow \mathcal{K}$, the induced map between weighted limits*

$$\lim_W F \twoheadrightarrow \lim_V F$$

is an isofibration.

- (iii) *If $\alpha: F \Rightarrow G$ is a simplicial natural transformation between a pair of diagrams $F, G: \mathcal{A} \rightrightarrows \mathcal{K}$ whose components $\alpha_a: Fa \rightrightarrows Ga$ are equivalences, then the induced map*

$$\lim_W F \xrightarrow[\sim]{\alpha} \lim_W G$$

is an equivalence.

PROOF. To begin, observe that the axioms of Definition 7.1.3 imply that the limit of F weighted by the weight $U \times \mathcal{A}(a, -)$, for $U \in \mathcal{S}Set$ and $a \in \mathcal{A}$, is the cotensor Fa^U . Consequently, the map of weighted limits induced by the projective n -cell at a is the isofibration (7.3.2). By definition, any flexible weight is built as a countable composite of pushouts of coproducts of these projective cells and the weighted limit functor $\lim_{-}^{\mathcal{A}} F$ carries each of these conical colimits to the corresponding limit notion. So it follows that $\lim_{\mathcal{W}}^{\mathcal{A}} F$ may be expressed as a countable inverse limit of pullbacks of products of the maps (7.3.2). This proves 9.2.

The same argument proves (ii). By definition, a relative cell complex $V \hookrightarrow W$ is built as a countable composite of pushouts of coproducts of these projective cells and the weighted limit functor $\lim_{-}^{\mathcal{A}} F$ carries each of these conical colimits to the corresponding limit notion. So it follows that $\lim_{\mathcal{W}}^{\mathcal{A}} F$ is the limit of a countable tower of isofibrations whose base is $\lim_V^{\mathcal{A}} F$, where each of these isofibrations is the pullback of products of the maps (7.3.2) appearing in the projective cell complex decomposition of $V \hookrightarrow W$. As products, pullbacks, and limits of towers of isofibrations are isofibrations, (ii) follows.

In 9.2, we have decomposed each weighted limit $\lim_{\mathcal{W}}^{\mathcal{A}} F$ as the limit of a tower of isofibrations, in which each of these isofibrations is the pullback of a product of the isofibrations (7.3.2). We argue inductively that if $\alpha: F \Rightarrow G$ is a componentwise equivalence, then the map induced between the towers of isofibrations for F and for G by the projective cell complex presentation of W is a level-wise equivalence. It follows from the standard argument in abstract homotopy theory reviewed in Appendix C that the inverse limit is then an equivalence, proving (iii).

The bottom of the tower of isofibrations is $\lim_{\emptyset} F \cong 1 \cong \lim_{\emptyset} G$, which is certainly an equivalence. For the inductive step, observe that upon taking the map of weighted limits induced by each projective n -cell at a in W , we obtain a commutative square

$$\begin{array}{ccc} Fa^{\Delta[n]} & \xrightarrow[\sim]{\alpha_a^{\Delta[n]}} & Ga^{\Delta[n]} \\ \downarrow & & \downarrow \\ Fa^{\partial\Delta[n]} & \xrightarrow[\sim]{\alpha_a^{\partial\Delta[n]}} & Ga^{\partial\Delta[n]} \end{array}$$

defining a pointwise equivalence between the isofibrations; the simplicial cotensor, as cosmological functor, preserves equivalences. Now the product of squares of this form gives a commutative square whose horizontals are isofibrations and whose verticals are equivalences. A pullback of this square forms the next layer in the tower of isofibrations; by the inductive hypothesis, the map between the codomains of the pulled back isofibrations is already known to be an equivalence. Now the equivalence-invariance of pullbacks of isofibrations established in Appendix C completes the proof. \square

Immediately from the construction of Proposition 7.3.19.2:

7.3.3. COROLLARY (∞ -cosmoi admit all flexible weighted limits). *∞ -cosmoi admit all flexible weighted limits and cosmological functors preserve them.* \square

Our aim is now to describe a converse of sorts to Proposition 7.3.19.2, which proves that the flexible weighted limit of any diagram in an ∞ -cosmos can be constructed out of the limits of diagrams of isofibrations axiomatized in 1.2.1(i). Over a series of lemmas, we will construct each of the limits listed there as instances of flexible weighted limits. It will follow that any quasi-categorically enriched category equipped with a class of representably-defined isofibrations that possesses flexible weighted

limits will admit all of the simplicial limits of 1.2.1(i). This will help us identify new examples of ∞ -cosmoi.

To start, simplicial cotensors are flexible weighted limits. For any simplicial set U , the collage of $U: \mathbb{1} \rightarrow \mathcal{S}Set$ is the simplicial computad $2[U]$. As $\mathbb{1} + \mathbb{1} \hookrightarrow 2[U]$ is a simplicial subcomputad inclusion, Theorem 7.2.12 tells us that $U: \mathbb{1} \rightarrow \mathcal{S}Set$ is a flexible weight; this solves Exercise 7.2.i.

This leaves only the conical limits. The weights for products are easily seen to be flexible directly from Definition 7.2.1. However, the weights for conical pullbacks or limits of towers of isofibrations are not flexible because the definition of a cone over either diagram shape imposes composition relations on 0-arrows.

7.3.4. EXAMPLE (the collage of the conical pullback). Let \lrcorner denote the 1-category $c \rightarrow a \leftarrow b$. Its collage is the 1-category with four objects and five non-identity 0-arrows as displayed

$$\begin{array}{ccc} \top & \longrightarrow & b \\ \downarrow & \searrow & \downarrow \\ c & \longrightarrow & a \end{array}$$

regarded as a constant simplicial category as in Example 6.1.4. Because the square commutes, this category is not free and hence does *not* define a simplicial computad, though the subcategory $\mathbb{1} + \lrcorner$ is free and hence is a simplicial computad. Lemma 6.1.11 tells us that the inclusion is not a relative simplicial computad and so by Theorem 7.2.12, the weight for the conical pullback is not flexible.

Our strategy is to modify the weights for pullbacks and for limits of countable towers so that each composition equation involved in defining cones over such diagrams is replaced by the insertion of an “invertible” arrow of one dimension up, where we must also take care to define this “invertibility” without specifying any equations between arrows in the next dimension. We have a device for specifying just this sort of isomorphism: recall from Exercise 1.1.iv(i) a diagram $\mathbb{I} \rightarrow \mathbf{Fun}(A, B)$ specifies a “homotopy coherent isomorphism” between a pair of 0-arrows f and g from A to B , given by:

- a pair of 1-arrows $\alpha: f \rightarrow g$ and $\beta: g \rightarrow f$
- a pair of 2-arrows

$$\begin{array}{ccc} & g & \\ \alpha \nearrow & & \searrow \beta \\ f & \xlongequal{\quad \Phi \quad} & f \end{array} \qquad \begin{array}{ccc} & f & \\ \beta \nearrow & & \searrow \alpha \\ g & \xlongequal{\quad \Psi \quad} & g \end{array}$$

- a pair of 3-arrows whose outer faces are Φ and Ψ and whose inner faces are degenerate
- etc

We now introduce the weight for pullback diagrams whose cone shapes are given by squares inhabited by a homotopy coherent isomorphism.

7.3.5. DEFINITION (iso-commas). The **iso-comma object** $C \mathbin{\dot{\times}}_A B$ of a cospan

$$C \xrightarrow{g} A \xleftarrow{f} B$$

in a simplicially-enriched and cotensored category \mathcal{M} is the limit weighted by a weight $W_{\dot{\times}}: \lrcorner \rightarrow \mathcal{S}Set$ defined by the cospan

$$\mathbb{1} \xrightarrow{1} \mathbb{I} \xleftarrow{0} \mathbb{1}$$

Under the simplification of Remark 7.1.13, the formula for the weighted limit reduces to the equalizer

$$\mathrm{eq} \left(\begin{array}{ccc} & & A^{\mathbb{I}} \\ C \times A^{\mathbb{I}} \times B & \xrightarrow{\pi} & \\ & \searrow \pi & \nearrow g \times f \\ & C \times B & \end{array} \xrightarrow{(q_1, q_0)} A \times A \right)$$

where the maps $(q_1, q_0): A^{\mathbb{I}} \rightarrow A \times A$ are defined by restricting along the endpoint inclusion $\mathbb{1} + \mathbb{1} = \partial \mathbb{I} \hookrightarrow \mathbb{I}$. In an ∞ -cosmos, this map is an isofibration and the equalizer defining the iso-comma object is computed by the pullback

$$\begin{array}{ccc} C \dot{\times}_A B & \longrightarrow & A^{\mathbb{I}} \\ (q_1, q_0) \downarrow & \lrcorner & \downarrow (q_1, q_0) \\ C \times B & \xrightarrow{g \times f} & A \times A \end{array} \quad (7.3.6)$$

7.3.7. LEMMA. *Iso-comma objects are flexible weighted limits and in particular exist in any ∞ -cosmos.*

PROOF. Reprising the notation for the category \mathcal{A} used in Example 7.3.4, the weight W_{\times} is constructed by the pushout

$$\begin{array}{ccc} \partial \mathbb{I} \times \mathcal{A}(a, -) & \longrightarrow & \mathcal{A}(b, -) \sqcup \mathcal{A}(c, -) \\ \downarrow & & \downarrow \\ \mathbb{I} \times \mathcal{A}(a, -) & \longrightarrow & W_{\times} \end{array}$$

where the attaching map picks out the two arrows in the cospan \mathcal{A} . As a projective cell complex, W_{\times} is built from a project 0-cell at b , a projective 0-cell at c , and two projective k -cells at a for each $k > 0$, corresponding to the non-degenerate simplices of \mathbb{I} . As described by Remark 7.2.2, these may be attached all at once. In this way, we see that W_{\times} is a flexible weight, so Corollary 7.3.3 tells us that iso-comma objects exist in any ∞ -cosmos, a fact that is also evident from the pullback (7.3.6). \square

7.3.8. REMARK. In the homotopy 2-category of an ∞ -cosmos, there is a canonical invertible 2-cell defining the **iso-comma cone**:

$$\begin{array}{ccc} & C \dot{\times}_A B & \\ q_1 \swarrow & & \searrow q_0 \\ C & \xrightarrow{\phi \cong} & B \\ g \searrow & & \swarrow f \\ & A & \end{array}$$

that has a weak universal property analogous to that of the comma cone presented in Proposition 3.3.6. The proof, like the proof of that result, makes use of the fact that $A^{\mathbb{I}}$ is the weak \mathbb{I} -cotensor in the homotopy 2-category. The proof of this fact is somewhat delicate, making use of marked simplicial sets as appeared already in the proof of Corollary 1.1.16, which gives 1-cell induction.

Our notation for iso-commas is deliberately similar to the usual notation for pullbacks. In an ∞ -cosmos, iso-commas can be used to compute “homotopy pullbacks” of diagrams in which neither map is an isofibration. When at least one map of the cospan is an isofibration, these constructions are equivalent.

7.3.9. LEMMA (iso-commas and pullbacks). In an ∞ -cosmos \mathcal{K} , pullbacks and iso-commas of cospans in which at least one map is an isofibration are equivalent. More precisely, given a pullback square as below-left and an iso-comma square as below-right

$$\begin{array}{ccc} P & \xrightarrow{b} & B \\ c \downarrow & \lrcorner & \downarrow f \\ C & \xrightarrow{g} & A \end{array} \qquad \begin{array}{ccc} C \times_A B & \xrightarrow{q_0} & B \\ q_1 \downarrow & \phi_{\cong} & \downarrow f \\ C & \xrightarrow{g} & A \end{array}$$

$P \simeq C \times_A B$ over C and up to isomorphism over B .

PROOF. Applying Lemma 1.2.12 to the functor $b: P \rightarrow B$, we can replace the span $(c, b): P \rightarrow C \times B$ by a span $(cq, p): Pb \rightarrow C \times B$ whose legs are both isofibrations that is related via an equivalence $s: P \simeq Pb$ that lies over C on the nose and over B up to isomorphism. We will show that under the hypothesis that f is an isofibration, this new span is equivalent to the iso-comma span.

To see this, note that the factorization constructed in (1.2.13) is in fact defined using an iso-comma, constructed via the pullback in the top square of the diagram below-left. Since the map b is itself defined by a pullback, the bottom square of the diagram below-left is also a pullback, defining the left-hand pullback rectangle:

$$\begin{array}{ccc} Pb & \xrightarrow{\quad} & B^{\mathbb{I}} \\ (q, p) \downarrow & \lrcorner & \downarrow (q_1, q_0) \\ P \times B & \xrightarrow{b \times B} & B \times B \\ c \times B \downarrow & \lrcorner & \downarrow f \times B \\ C \times B & \xrightarrow{g \times B} & A \times B \end{array} \qquad \begin{array}{ccccc} C \times_A B & \longrightarrow & A \times_A B & \longrightarrow & A^{\mathbb{I}} \\ (q_1, q_0) \downarrow & \lrcorner & \downarrow (q_1, q_0) & \lrcorner & \downarrow (q_1, q_0) \\ C \times B & \xrightarrow{g \times B} & A \times B & \xrightarrow{A \times f} & A \times A \end{array}$$

Now the iso-comma is constructed by a similar pullback rectangle, displayed above-right. And because f is an isofibration, Lemma 1.2.10 tells us that the Leibniz tensor $i_0 \hat{\cap} f: B^{\mathbb{I}} \simeq A \times_A B$ of $i_0: \mathbb{1} \hookrightarrow \mathbb{I}$ with $f: B \rightarrow A$ is a trivial fibration. This equivalence commutes with the projections to $A \times B$ and hence the maps $(cq, p): Pb \rightarrow C \times B$ and $(q_1, q_0): C \times_A B \rightarrow C \times B$, defined as pullbacks of an equivalence pair of isofibrations along $g \times B$, are equivalent as claimed. \square

We now introduce a flexible weight diagrams given by a countable tower of 0-arrows whose cone shapes will have a homotopy coherent isomorphism in the triangle over each generating arrow in the diagram.

7.3.10. DEFINITION (iso-towers). Recall the category ω whose objects are natural numbers and whose morphisms are freely generated by maps $\iota_{n, n+1}: n \rightarrow n+1$ for each n .

The **iso-tower** of a diagram $F: \omega^{\text{op}} \rightarrow \mathcal{M}$ in a simplicially enriched and cotensored category \mathcal{M} is the limit weighted by the diagram $W_{\leftarrow}: \omega^{\text{op}} \rightarrow \mathcal{SSet}$ defined by the pushout

$$\begin{array}{ccc} \prod_{n \in \omega} \partial \mathbb{I} \times \omega(-, n) & \xrightarrow{(\text{id}_n, \iota_{n, n+1})} & \prod_{n \in \omega} \omega(-, n) \\ \downarrow & & \downarrow \\ \prod_{n \in \omega} \mathbb{I} \times \omega(-, n) & \xrightarrow{\quad} & W_{\leftarrow} \end{array} \quad (7.3.11)$$

in $\mathcal{SSet}^{\omega^{\text{op}}}$.

By Definition 7.1.3(ii), in an ∞ -cosmos the iso-tower of a diagram

$$F := \quad \dots \xrightarrow{f_{n+2, n+1}} F_{n+1} \xrightarrow{f_{n+1, n}} F_n \xrightarrow{f_{n, n-1}} \dots \xrightarrow{f_{2, 1}} F_1 \xrightarrow{f_{1, 0}} F_0$$

is constructed by the pullback

$$\begin{array}{ccc} \lim_{W_{\leftarrow}} F & \xrightarrow{\phi} & \prod_{n \in \omega} F_n^{\mathbb{I}} \\ \rho \downarrow & \lrcorner & \downarrow \Pi(q_1, q_0) \\ \prod_{n \in \omega} F_n & \xrightarrow{(f_{n+1, n}, \text{id}_{F_n})} & \prod_{n \in \omega} F_n \times F_n \end{array} \quad (7.3.12)$$

The limit cone is generated by a 0-arrow $\rho_n: \lim_{W_{\leftarrow}} F \rightarrow F_n$ for each $n \in \omega$ together with a homotopy coherent isomorphism ϕ_n in each triangle over a generating arrow $F_{n+1} \rightarrow F_n$ in the ω^{op} -indexed diagram.

7.3.13. LEMMA. *Iso-towers are flexible weighted limits and in particular exist in any ∞ -cosmos.*

PROOF. The weight W_{\leftarrow} is a projective cell complex built by attaching one projective 0-cell at each $n \in \omega$ — forming the coproduct appearing in the upper right-hand corner of (7.3.11) — and then by attaching a projective k -cell at each $n \in \omega$ for each non-degenerate k -simplex of \mathbb{I} . Rather than attach each projective k -cell for fixed $n \in \omega$ in sequence, by Remark 7.2.2 these can all be attached at once by taking a single pushout of the “generalized projective cell at n ” defined by the map $\partial \mathbb{I} \times \omega(-, n) \hookrightarrow \mathbb{I} \times \omega(-, n)$. These are the maps appearing as the left-hand vertical of (7.3.11). Now Corollary 7.3.3 or the formula (7.3.12) make it clear that such objects exist in any ∞ -cosmos. \square

7.3.14. LEMMA (iso-towers and inverse limits). *In an ∞ -cosmos \mathcal{K} , the inverse limit of a countable tower of isofibrations is equivalent to the iso-pullback of that tower.*

PROOF. We will rearrange the formula (7.3.12) to construct the iso-tower $\lim_{W_{\leftarrow}} F$ as an inverse limit of a countable tower of isofibrations $P: \omega^{\text{op}} \rightarrow \mathcal{K}$ that is pointwise equivalent to the diagram $F: \omega^{\text{op}} \rightarrow \mathcal{K}$. In the case where the diagram F is also given by a tower of isofibrations

$$\begin{array}{ccc} \lim P & \cong & \dots \xrightarrow{p_{n+2, n+1}} P_{n+1} \xrightarrow{p_{n+1, n}} P_n \xrightarrow{p_{n, n-1}} \dots \xrightarrow{p_{2, 1}} P_1 \xrightarrow{p_{1, 0}} P_0 \\ \downarrow & & \downarrow e_n \quad \downarrow e_n \quad \downarrow e_1 \quad \downarrow e_0 \\ \lim F & \cong & \dots \xrightarrow{f_{n+2, n+1}} F_{n+1} \xrightarrow{f_{n+1, n}} F_n \xrightarrow{f_{n, n-1}} \dots \xrightarrow{f_{2, 1}} F_1 \xrightarrow{f_{1, 0}} F_0 \end{array} \quad (7.3.15)$$

the equivalence invariance of the inverse limit of a diagram of isofibrations will imply that the limits $\lim_{W_{\leftarrow}} F \cong \lim P$ and $\lim F$ are equivalent as claimed.

The ∞ -categories P_n will be defined as conical limits of truncated versions of the diagram (7.3.12). To start define $P_0 := F_0$ and e_0 to be the identity, then define P_1 , $p_{1,0}$, and e_1 via the pullback

$$\begin{array}{ccccc} & & p_{1,0} & & \\ & \nearrow & & \searrow & \\ P_1 & \longrightarrow & F_0^{\mathbb{I}} & \xrightarrow{\sim} & F_0 \\ & \downarrow e_1 & \downarrow q_1 & & \\ & F_1 & \xrightarrow{f_{1,0}} & F_0 & \end{array}$$

Note that $P_1 \cong F_1 \times_{F_0} F_0$ computes the iso-comma objects of the cospan given by id_{F_0} and $f_{1,0}$.

Now define P_2 , $p_{2,1}$, and e_2 using the composite pullback

$$\begin{array}{ccccccc} & & p_{2,1} & & & & \\ & \nearrow & & \searrow & & & \\ P_2 & \longrightarrow & \bullet & \xrightarrow{\sim} & P_1 & \longrightarrow & F_0^{\mathbb{I}} \xrightarrow{\sim} F_0 \\ & \downarrow e_2 & \downarrow & \downarrow e_1 & \downarrow & \downarrow q_1 & \\ & \bullet & \longrightarrow & F_1^{\mathbb{I}} \xrightarrow{\sim} F_1 & \xrightarrow{f_{1,0}} & F_0 & \\ & \downarrow & \downarrow q_1 & & & & \\ & F_2 & \xrightarrow{f_{2,1}} & F_1 & & & \end{array}$$

Continuing inductively, P_n , $p_{n,n-1}$, and e_n are defined by appending the diagram

$$\begin{array}{ccc} F_{n-1}^{\mathbb{I}} & \xrightarrow{\sim} & F_{n-1} \\ \downarrow q_1 & & \\ F_n & \xrightarrow{f_{n,n-1}} & F_{n-1} \end{array}$$

to the limit cone defining P_{n-1} and taking the limit of this composite diagram.

There is one small problem with the construction just given: it defines a diagram (7.3.15) in which each square commutes up to isomorphism — the isomorphism encoded by the map $P_n \rightarrow F_{n-1}^{\mathbb{I}}$ — not on the nose. But because the maps $f_{n+1,n}$ are isofibrations this is no problem. The isomorphism inhabiting the square $e_0 p_{1,0} \cong f_{1,0} e_1$ can be lifted along $f_{1,0}$ to define a new map $e'_1: P_1 \rightarrow F_1$ isomorphic to e_1 ; as observed in the proof of Theorem 1.4.7 this e'_1 is then also an equivalence, so we replace e_1 with e'_1 , and then continue inductively to lift away the isomorphisms in the square $e'_1 p_{2,1} \cong f_{2,1} e_2$.

Since inverse limits of towers of isofibrations are equivalence-invariant, it follows that $\lim P \simeq \lim F$. By construction $\lim P \cong \lim_{W_{\leftarrow}} F$, so it follows that $\lim_{W_{\leftarrow}} F \simeq \lim F$, which is what we wanted to show. \square

Exercises.

7.3.i. EXERCISE. Verify — either directly from Definition 7.2.1 or by applying Theorem 7.2.12 — that conical products are flexible weighted limits.

7.4. More ∞ -cosmoi

Our aim in this section is to introduce further examples of ∞ -cosmoi.

Our first example is a special case of a more general result that will appear in Appendix E that we nonetheless spell out in detail to illustrate the ideas involved in this sort of argument. The walking arrow category $\mathbb{2}$ is an *inverse Reedy category*, where the domain of the non-identity arrow is assigned “degree 1” and the codomain is assigned “degree zero.” This Reedy structure motivates the definitions in the ∞ -cosmos of isofibrations that we now introduce:

7.4.1. PROPOSITION (∞ -cosmoi of isofibrations). *For any ∞ -cosmos \mathcal{K} there is an ∞ -cosmos $\mathcal{K}^{\mathbb{2}}$ whose*

- (i) *objects are isofibrations $p: E \twoheadrightarrow B$ in \mathcal{K}*
- (ii) *functor-spaces, say from $q: F \twoheadrightarrow A$ to $p: E \twoheadrightarrow B$, are defined by pullback*

$$\begin{array}{ccc} \text{Fun}(F \xrightarrow{q} A, E \xrightarrow{p} B) & \longrightarrow & \text{Fun}(F, E) \\ \downarrow & \lrcorner & \downarrow p_* \\ \text{Fun}(A, B) & \xrightarrow{q^*} & \text{Fun}(F, B) \end{array}$$

- (iii) *isofibrations from q to p are commutative squares*

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ q \downarrow & \lrcorner & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

in which the horizontals and the induced map from the initial vertex to the pullback of the cospan are isofibrations in \mathcal{K}

- (iv) *limits are defined pointwise in \mathcal{K}*
- (v) *and in which a map*

$$\begin{array}{ccc} F & \xrightarrow[g]{} & E \\ q \downarrow & & \downarrow p \\ A & \xrightarrow[f]{} & B \end{array}$$

is an equivalence in the ∞ -cosmos $\mathcal{K}^{\mathbb{2}}$ if and only if g and f are equivalences in \mathcal{K} .

Relative to these definitions, the domain, codomain, and identity functors

$$\mathcal{K}^{\mathbb{2}} \begin{array}{c} \xrightarrow{\text{dom}} \\ \xleftarrow{\text{id}} \\ \xrightarrow{\text{cod}} \end{array} \mathcal{K}$$

are all cosmological.

PROOF. The diagram category $\mathcal{K}^{\mathbb{2}}$ inherits its simplicially enriched limits, defined pointwise, from \mathcal{K} . The functor-spaces described in (ii) are the usual ones for an enriched category of diagrams. This verifies 1.2.1(i).

For axiom 1.2.1(ii) note that the product and simplicial cotensor functors carry pointwise isofibrations to isofibrations. The pullback of an isofibration as in (iii) along a commutative square from an

isofibration r to p may be formed in \mathcal{K} . Our task is to show that the induced map t is an isofibration and also that the square from t to r is an isofibration in the sense of (iii):

$$\begin{array}{ccccc}
 G \times F & \xrightarrow{\quad} & F & & \\
 \downarrow t & \searrow & \downarrow q & \searrow z & \\
 C \times A & \xrightarrow{\quad} & A & & \\
 \downarrow r & \searrow & \downarrow p & & \\
 C & \xrightarrow{\quad} & B & &
 \end{array}
 \quad (7.4.2)$$

The map t factors as a pullback of z followed by a pullback of r as displayed above, and is thus an isofibration, as claimed. This observation also verifies that the square from t to r defines an isofibration. A similar argument verifies the Leibniz stability of the isofibrations and that the limit of a tower of isofibration is an isofibration. This proves that \mathcal{K}^2 defines an ∞ -cosmos in such a way so that the domain, codomain, and identity functors are cosmological.

Finally, since pullbacks of isofibrations in \mathcal{QCat} are invariant under equivalences, a pair of equivalences (g, f) induces an equivalence between the functor-spaces defined in (ii). The converse, that an equivalence in \mathcal{K}^2 defines a pair of equivalences in \mathcal{K} follows from the fact that domain and codomain-projection functors are cosmological and Lemma 1.3.2. \square

In close analogy with Proposition 3.5.3 we have a smothering 2-functor that relates the homotopy 2-category of \mathcal{K}^2 to the 2-category of isofibrations, commutative squares, and parallel natural transformations in the homotopy 2-category of \mathcal{K} .

7.4.3. LEMMA. *There is an identity on objects and 1-cells smothering 2-functor $\mathfrak{h}(\mathcal{K}^2) \rightarrow (\mathfrak{h}\mathcal{K})^2$ whose codomain is the 2-category whose*

- *objects are isofibrations in \mathcal{K} ,*
- *1-cells are commutative squares between such,*
- *2-cells are pairs of 2-cells in $\mathfrak{h}\mathcal{K}$*

$$\begin{array}{ccc}
 F & \xrightarrow{g} & E \\
 \Downarrow \alpha & & \\
 q \downarrow & g' & \downarrow p \\
 A & \xrightarrow{f} & B \\
 \Downarrow \beta & & \\
 & f' &
 \end{array}$$

PROOF. Exercise 7.4.i. \square

For any ∞ -cosmos \mathcal{K} and any subcategory of its underlying 1-category — that is for any subset of its objects and subcategory of its 0-arrows — one can form a quasi-categorically enriched subcategory $\mathcal{L} \subset \mathcal{K}$ that contains exactly those objects and 0-arrows and all higher dimensional arrows that they span. We call such subcategories \mathcal{L} **full on positive-dimensional arrows**; note the functor spaces of \mathcal{L} are quasi-categories because all inner horn inclusions are bijective on vertices. We will take particular interest in subcategories that satisfy a further “repleteness” condition.

7.4.4. DEFINITION. Let \mathcal{K} be an ∞ -cosmos. A subcategory $\mathcal{L} \subset \mathcal{K}$ is **replete** in \mathcal{K} if it is full on positive-dimensional arrows and moreover:

- (i) Every ∞ -category in \mathcal{K} that is equivalent to an object in \mathcal{L} lies in \mathcal{L} .
- (ii) Any equivalence in \mathcal{K} between objects in \mathcal{L} lies in \mathcal{L} .
- (iii) Any arrow in \mathcal{K} that is isomorphic in \mathcal{K} to an arrow in \mathcal{L} lies in \mathcal{L} .

7.4.5. LEMMA. Suppose $\mathcal{L} \subset \mathcal{K}$ is a replete subcategory of an ∞ -cosmos. Then any map $p: E \rightarrow B$ in \mathcal{L} that defines an isofibration in \mathcal{K} is a representably-defined isofibration in \mathcal{L} : that is for all $X \in \mathcal{L}$, $p_*: \text{Fun}_{\mathcal{L}}(X, E) \rightarrow \text{Fun}_{\mathcal{L}}(X, B)$ is an isofibration of quasi-categories.

PROOF. Since \mathcal{K} is an ∞ -cosmos, axiom 1.2.1(ii) requires that $p_*: \text{Fun}_{\mathcal{K}}(X, E) \rightarrow \text{Fun}_{\mathcal{K}}(X, B)$ is an isofibration of quasi-categories. Because the inner horn inclusions are bijective on vertices and $\text{Fun}_{\mathcal{L}}(X, E) \hookrightarrow \text{Fun}_{\mathcal{K}}(X, E)$ is full on positive-dimensional arrows, it follows immediately that the restricted map $p_*: \text{Fun}_{\mathcal{L}}(X, E) \rightarrow \text{Fun}_{\mathcal{L}}(X, B)$ lifts against the inner horn inclusions. Thus it remains only to solve lifting problems of the form displayed below-left

$$\begin{array}{ccccc}
 \mathbb{I} & \xrightarrow{e} & \text{Fun}_{\mathcal{L}}(X, E) & \hookrightarrow & \text{Fun}_{\mathcal{K}}(X, E) \\
 \downarrow & & \downarrow p_* & \nearrow \text{dashed} & \downarrow p_* \\
 \mathbb{I} & \xrightarrow{\beta} & \text{Fun}_{\mathcal{L}}(X, B) & \hookrightarrow & \text{Fun}_{\mathcal{K}}(X, B)
 \end{array}$$

The lifting problem defines a 0-arrow $e: X \rightarrow E$ in \mathcal{L} and an isomorphism $\beta: b \cong pe$ in \mathcal{L} . Its solution in \mathcal{K} defines a 0-arrow $e': X \rightarrow E$ in \mathcal{K} so that $pe' = b$ together with an isomorphism $e \cong e'$ in \mathcal{K} . By fullness on positive-dimensional arrows, to show that this lift factors through the inclusion $\text{Fun}_{\mathcal{L}}(X, E) \hookrightarrow \text{Fun}_{\mathcal{K}}(X, E)$, we need only argue that the map e' lies in \mathcal{L} , but this is the case by condition (iii) of Definition 7.4.4. \square

The following result describes a condition under which a replete subcategory $\mathcal{L} \subset \mathcal{K}$ inherits an ∞ -cosmos structure created from \mathcal{K} .

7.4.6. PROPOSITION. Suppose $\mathcal{L} \subset \mathcal{K}$ is a replete subcategory of an ∞ -cosmos. If \mathcal{L} is closed under flexible weighted limits in \mathcal{K} , then \mathcal{L} defines an ∞ -cosmos with isofibrations, equivalences, trivial fibrations and simplicial limits created by the inclusion $\mathcal{L} \hookrightarrow \mathcal{K}$, which then defines a cosmological functor.

When these conditions hold, we refer to \mathcal{L} as a **replete sub ∞ -cosmos** of \mathcal{K} and $\mathcal{L} \hookrightarrow \mathcal{K}$ as a **cosmological embedding**.

PROOF. To say that a replete subcategory $\mathcal{L} \hookrightarrow \mathcal{K}$ is closed under flexible weighted limits means that for any diagram in \mathcal{L} and any limit cone in \mathcal{K} that limit cone lies in \mathcal{L} and satisfies appropriate simplicially-enriched universal property of Definition 7.1.7 in there. We must verify that each of the limits of axiom 1.2.1(i) exist in \mathcal{L} . Immediately, \mathcal{L} has a terminal object, products, and simplicial cotensors, since all of these are flexible weighted limits. By Lemmas 7.3.7 and 7.3.13, \mathcal{L} also admits the construction of iso-comma objects and of iso-towers.

Define the class of isofibrations in \mathcal{L} to be those maps in \mathcal{L} that define isofibrations in \mathcal{K} . By Lemmas 7.3.9 and 7.3.14, pullbacks and limits of towers of isofibrations are equivalent in \mathcal{K} to the iso-commas and iso-towers formed over the same diagrams. Since these latter limit cones lie in \mathcal{L} by hypothesis, so do the equivalence former cones by repleteness of \mathcal{L} in \mathcal{K} .

There is a little more still to verify: namely that pullbacks and limits of towers of isofibrations satisfy the simplicially-enriched universal property as conical limits in \mathcal{L} . In the case of a pullback diagram

$$\begin{array}{ccc} P & \xrightarrow{b} & B \\ \downarrow c & \lrcorner & \downarrow f \\ C & \xrightarrow{g} & A \end{array}$$

in \mathcal{L} we must show that for each $X \in \mathcal{L}$, the functor-space $\mathrm{Fun}_{\mathcal{L}}(X, P)$ is isomorphic to the pullback $\mathrm{Fun}_{\mathcal{L}}(X, C) \times_{\mathrm{Fun}_{\mathcal{L}}(X, A)} \mathrm{Fun}_{\mathcal{L}}(X, B)$ of functor spaces. We have such an isomorphism for functor spaces in \mathcal{K} and on account of the commutative diagram

$$\begin{array}{ccc} \mathrm{Fun}_{\mathcal{L}}(X, P) & \dashrightarrow & \mathrm{Fun}_{\mathcal{L}}(X, C) \times_{\mathrm{Fun}_{\mathcal{L}}(X, A)} \mathrm{Fun}_{\mathcal{L}}(X, B) \\ \downarrow & & \downarrow \\ \mathrm{Fun}_{\mathcal{K}}(X, P) & \xrightarrow{\cong} & \mathrm{Fun}_{\mathcal{K}}(X, C) \times_{\mathrm{Fun}_{\mathcal{K}}(X, A)} \mathrm{Fun}_{\mathcal{K}}(X, B) \end{array}$$

and fullness on positive-dimensional arrows, we need only verify surjectivity of the dotted map on 0-arrows. So consider a cone $(h: X \rightarrow B, k: X \rightarrow C)$ over the pullback diagram in \mathcal{L} . By the universal property of the isocomma $A \times_B E$, there exists a factorization $y: X \rightarrow C \times_B A$ in \mathcal{L} . Composing with the equivalence $C \times_B A \simeq P$, this map is equivalent to the factorization $z: X \xrightarrow{A} P$ of the cone (h, k) through the limit cone (b, c) in \mathcal{K} that exists on account of the strict universal property of the pullback in there. By repleteness, the isomorphism between z and the composite of y with the equivalence suffices to show that z lies in \mathcal{L} . Hence, the functor spaces in \mathcal{L} are isomorphic. A similar argument invoking Lemma 7.3.14 proves that inverse limits of towers of isofibrations define conical limits in \mathcal{L} . This completes the proof of the limit axiom 1.2.1(i).

Since the isofibrations in \mathcal{L} are a subset of the isofibrations in \mathcal{K} and the limit constructions in both contexts coincide, most of the closure properties of 1.2.1(ii) are inherited from the closure properties in \mathcal{K} . The one exception is the requirement that the isofibrations in \mathcal{L} define isofibrations of quasi-categories representably, which was proven for any replete subcategory in Lemma 7.4.5. This proves that \mathcal{L} defines an ∞ -cosmos.

Finally, we argue that the equivalences in \mathcal{L} coincide with those of \mathcal{K} , which will imply that the trivial fibrations in \mathcal{L} coincide with those of \mathcal{K} as well. Condition (ii) of Definition 7.4.4 implies that for any arrow in \mathcal{L} that defines an equivalence in \mathcal{K} , its equivalence inverse and witnessing homotopies of Lemma 1.2.15 lie in \mathcal{L} . Because we have already shown that \mathcal{L} admits cotensors with \mathbb{I} preserved by the inclusion $\mathcal{L} \hookrightarrow \mathcal{K}$, Lemma 1.2.15 implies that this data defines an equivalence in \mathcal{L} . Conversely, any equivalence in \mathcal{L} extends to the data of (1.2.16) and since $\mathcal{L} \hookrightarrow \mathcal{K}$ preserves \mathbb{I} -cotensors, this data defines an equivalence in \mathcal{K} . Thus, by construction, the ∞ -cosmos structure of \mathcal{L} is preserved and reflected by the inclusion $\mathcal{L} \hookrightarrow \mathcal{K}$ as claimed. \square

In practice the repleteness condition of Definition 7.4.4 is satisfied by any subcategory of objects and 0-arrows that is determined by some ∞ -categorical property, so the main task in verifying that a subcategory defines an ∞ -cosmos is verifying the closure under flexible weighted limits.

7.4.7. PROPOSITION. *For any ∞ -cosmos \mathcal{K} , let \mathcal{K}_{\top} denote the quasi-categorically enriched category whose*

- (i) *objects are ∞ -categories in \mathcal{K} that possess a terminal object*

(ii) functor spaces $\text{Fun}_\top(A, B) \subset \text{Fun}(A, B)$ are the sub-quasi-categories whose 0-arrows preserve terminal objects and containing all n -arrows they span

Then the inclusion $\mathcal{K}_\top \hookrightarrow \mathcal{K}$ creates an ∞ -cosmos structure on \mathcal{K}_\top from \mathcal{K} , and moreover for each object of \mathcal{K}_\top defined as a flexible weighted limit of some diagram in \mathcal{K}_\top , its terminal element is created by the 0-arrow legs of the limit cone.

PROOF. We apply Proposition 7.4.6. Lemma 2.2.6 and Proposition 2.1.10 verify the repleteness condition, so it remains only to prove closure under flexible weighted limits, which we do by induction over the tower of isofibrations constructed in Proposition 7.3.19.2, which expresses a flexible weighted limit $\lim_W F$ as the inverse limit of a tower of isofibrations

$$\lim_W F \longrightarrow \cdots \longrightarrow \lim_{W_{k+1}} F \longrightarrow \lim_{W_k} F \longrightarrow \cdots \longrightarrow \lim_{W_0} F \longrightarrow 1$$

each of which is a pullback of products of maps of the form (7.3.2) indexed by the projective cells of the flexible weight W . We'll argue inductively that each ∞ -category in this tower possesses a terminal element that's created by the legs of the tower of isofibrations.

For the base case, note that if $(A_i)_{i \in I}$ is a family of ∞ -categories possessing terminal elements $t_i: 1 \rightarrow A_i$, then the product of the adjunctions $! \dashv t_i$ defines an adjunction

$$\begin{array}{ccc} & ! & \\ \swarrow & & \searrow \\ 1 \cong \prod_{i \in I} 1 & \perp & \prod_{i \in I} A_i \\ \searrow & & \swarrow \\ & (t_i)_{i \in I} \cong \prod_i t_i & \end{array}$$

exhibiting $(t_i)_{i \in I}$ as a terminal element of $\prod_{i \in I} A_i$. By construction, this terminal element is jointly created by the legs of the limit cone. Note that by construction the product-projection functors preserve this terminal element and the map into the product ∞ -category $\prod_{i \in I} A_i$ induced by any family of terminal element preserving functors $(f: X \rightarrow A_i)_{i \in I}$ will preserve terminal elements. This verifies that the subcategory \mathcal{K}_\top is closed under products.

For the inductive step consider a pullback diagram

$$\begin{array}{ccc} \lim_{W_{k+1}} F & \longrightarrow & A^{\Delta[n]} \\ \downarrow & \lrcorner & \downarrow \\ \lim_{W_k} F & \xrightarrow{\ell} & A^{\partial\Delta[n]} \end{array}$$

that arises from the attaching map for a projective n -cell. The inductive hypothesis tells us that $\lim_{W_k} F$ admits a terminal element t_k and for each vertex of $i \in \partial\Delta[n]$, the corresponding component $\ell_i: \lim_{W_k} F \rightarrow A$ of the limit cone preserves it. Since F is a diagram valued in \mathcal{K}_\top and A is an ∞ -category in its image, we know that A must possess a terminal element $t: 1 \rightarrow A$. By Proposition 2.1.7(iii), the constant diagram at t then defines a terminal element in $A^{\partial\Delta[n]}$ and $A^{\Delta[n]}$, which we also denote by t . By terminality, there is a 1-arrow $\alpha: \ell(t_k) \rightarrow t \in A^{\partial\Delta[n]}$ whose components at each $i \in \partial\Delta[n]$ are isomorphisms in A . By Lemma ??, it follows that α is also an isomorphism, which tells us that $\ell(t_k)$ is also a terminal element of $A^{\partial\Delta[n]}$. The same argument demonstrates that terminal elements in simplicial cotensors, in this case by $\partial\Delta[n]$ are jointly created by the 0-arrow components of the limit cone, namely by evaluation on each of the vertices of the cotensoring simplicial set. The proof is completed now by the following lemma. \square

7.4.8. LEMMA. Consider a pullback diagram

$$\begin{array}{ccc} F & \xrightarrow{g} & E \\ q \downarrow & \lrcorner & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

in which the ∞ -categories A , B , and E possess a terminal element and the functors f and p preserve them. Then F possesses a terminal element that is created by the legs of the pullback cone q and g .

PROOF. If $e: 1 \rightarrow E$ and $a: 1 \rightarrow A$ are terminal, then this implies that $f(a) \cong p(e) \in B$. Using the fact that p is an isofibration, there is a lift $e' \cong e$ of this isomorphism along p that then defines another terminal element of E . The pair (a, e') now induces an element t of F that we claim is terminal.

To see this we'll apply Proposition 4.3.10, which proves that t is a terminal element of F if and only if the domain-projection functor $p_0: \text{Hom}_F(F, t) \rightarrow F$ is a trivial fibration. By construction of t , we know that the domain-projection functors for the elements gt , qt , and $pqt = fqt$ are all trivial fibrations and moreover the top and bottom faces of the cube

$$\begin{array}{ccccc} & & \text{Hom}_F(F, t) & \xrightarrow{\quad} & \text{Hom}_E(E, gt) \\ & \swarrow & \lrcorner & \swarrow & \\ \text{Hom}_A(A, qt) & \xrightarrow{p_0} & \text{Hom}_B(B, fqt) & & \\ \downarrow p_0 \wr & & \downarrow & & \downarrow p_0 \wr \\ & & F & \xrightarrow{g} & E \\ & \swarrow q & \lrcorner & \swarrow & \\ A & \xrightarrow{f} & B & & \end{array}$$

are pullbacks. Since homotopy pullbacks are homotopical, the fact that the three maps between the cospan are equivalences implies that the map between their pullbacks is also an equivalence, as required. \square

Applying the result of Proposition 7.4.7 to \mathcal{K}^{co} constructs an ∞ -cosmos \mathcal{K}_{\perp} whose objects are ∞ -categories in \mathcal{K} that possess an initial object and 0-arrows are initial-element-preserving functors. Combining these, we get an ∞ -cosmos for the pointed ∞ -categories of Definition 4.4.1, those that possess a zero element.

7.4.9. PROPOSITION. For any ∞ -cosmos \mathcal{K} , let \mathcal{K}_* denote the quasi-categorically enriched category of pointed ∞ -categories, i.e., ∞ -categories that possess a zero element, and functors that preserve them. Then the inclusion $\mathcal{K}_* \hookrightarrow \mathcal{K}$ creates an ∞ -cosmos structure on \mathcal{K}_{\top} from \mathcal{K} .

PROOF. The natural inclusions define a pullback diagram of quasi-categorically enriched categories

$$\begin{array}{ccc} \mathcal{K}_{\perp, \top} & \hookrightarrow & \mathcal{K}_{\top} \\ \downarrow & \lrcorner & \downarrow \\ \mathcal{K}_{\perp} & \hookrightarrow & \mathcal{K} \end{array}$$

where the objects of $\mathcal{K}_{\perp, \top}$ are ∞ -categories that possess both an initial and terminal element and functors that preserve them separately.

Now repleteness of $\mathcal{K}_{\perp, \top}$ follows from repleteness of \mathcal{K}_{\top} and \mathcal{K}_{\perp} as does closure under flexible weighted limits. Given a diagram in $\mathcal{K}_{\perp, \top}$ admitting a flexible weighted limit in \mathcal{K} that limit cone lies in both \mathcal{K}_{\top} and \mathcal{K}_{\perp} and hence in their intersection. Since the functor spaces of $\mathcal{K}_{\perp, \top}$ are the intersections of the functor spaces of \mathcal{K}_{\top} and \mathcal{K}_{\perp} in \mathcal{K} , the simplicial universal property in those ∞ -cosmoi restricts to the required simplicially-enriched universal property in $\mathcal{K}_{\perp, \top}$.

Now the ∞ -cosmos \mathcal{K}_* of interest is the full subcategory of $\mathcal{K}_{\perp, \top}$ spanned by those ∞ -categories in which the initial and terminal element coincide. To prove that \mathcal{K}_* is an ∞ -cosmos, created by cosmological embedding $\mathcal{K}_* \hookrightarrow \mathcal{K}_{\perp, \top}$ it remains only to show that this subcategory is closed under flexible weighted limits. To that end consider a diagram $F: \mathcal{A} \rightarrow \mathcal{K}_{\perp, \top}$ and a flexible weight $W: \mathcal{A} \rightarrow \mathbf{SSet}$. We have shown that the limit $\lim_W F$ admits an initial element $i: 1 \rightarrow \lim_W F$ and also a terminal element $t: 1 \rightarrow \lim_W F$, each of which is preserved by the 0-arrow legs of the limit cone. The elements i and t are vertices in the underlying quasi-category $\mathbf{Fun}(1, \lim_W F)$, and remain respectively initial and terminal in there. Appealing to the universal property of either, there is a 1-simplex $\alpha: i \rightarrow t \in \mathbf{Fun}(1, \lim_W F)$, representing a natural transformation $\alpha: i \Rightarrow t$ in $\mathbf{h}\mathcal{K}$, and $\lim_W F$ is a pointed ∞ -category if and only if α is invertible.

Invertibility of 1-simplices in quasi-categories can be detected by applying the cosmological functor $(-)^{\natural}: \mathbf{QCat} \rightarrow \mathbf{1-Comp}$ of Example 1.3.7; a 1-simplex in $\mathbf{Fun}(1, \lim_W F)$ is an isomorphism if and only if its image in $\mathbf{Fun}(1, \lim_W F)^{\natural}$ is marked. Corollary 7.3.3 proves that the cosmological functor $\mathbf{Fun}(1, -)^{\natural}: \mathcal{K} \rightarrow \mathbf{1-Comp}$ preserves flexible weighted limits, so

$$\mathbf{Fun}(1, \lim_W F)^{\natural} \cong \lim_W \mathbf{Fun}(1, F-)^{\natural},$$

and thus it remains only to show that a 1-simplex in a flexible weighted limit of a diagram of 1-complicial sets, whose image under each of the legs of the limit cone is marked, is marked in the weighted limit. Indeed the markings for all simplicially enriched limits in $\mathbf{1-Comp}$ are defined in this manner: a 1-simplex is marked if and only if each of its components is marked. So this proves that $\mathcal{K}_* \hookrightarrow \mathcal{K}_{\perp, \top}$ is closed under flexible weighted limits, completing the proof. \square

Applying the result of Proposition 7.4.7 or its dual to the ∞ -cosmos $\mathcal{K}_{/B}$ of isofibrations over $B \in \mathcal{K}$, we obtain two new ∞ -cosmoi of interest.

7.4.10. COROLLARY. *For any ∞ -category B in an ∞ -cosmos \mathcal{K} , the sliced ∞ -cosmos $\mathcal{K}_{/B}$ admits sub ∞ -cosmoi*

$$\mathcal{R}ari(\mathcal{K})_{/B} \hookrightarrow \mathcal{K}_{/B} \longleftarrow \mathcal{L}ari(\mathcal{K})_{/B}$$

whose

- objects are isofibrations over B admitting a right adjoint right inverse or left adjoint right inverse, respectively, and
- 0-arrows are functors over B that commute with the respective right or left adjoints up to fibered isomorphism

with the ∞ -cosmos structures created by the inclusions.

PROOF. These ∞ -cosmoi are defined by $\mathcal{R}ari(\mathcal{K})_{/B} := (\mathcal{K}_{/B})_{\top}$ and $\mathcal{L}ari(\mathcal{K})_{/B} := (\mathcal{K}_{/B})_{\perp}$. \square

Leveraging Corollary 7.4.10, we can establish similar cosmological embeddings

$$\mathcal{R}ari(\mathcal{K}) \hookrightarrow \mathcal{K}^2 \longleftarrow \mathcal{L}ari(\mathcal{K})$$

The quasi-categorically enriched subcategories $\mathcal{R}ari(\mathcal{K})$ and $\mathcal{L}ari(\mathcal{K})$ are replete in \mathcal{K}^2 , so by Proposition 7.4.6 we need only check closure under flexible weighted limits. We argue separately for cotensors, which are easy, and for the conical limits, which are harder. For this, we make use of a general 1-categorical result making use of the fact that the codomain-projection functor $\text{cod}: \mathcal{R}ari(\mathcal{K}) \rightarrow \mathcal{K}$ is a Grothendieck fibration of underlying 1-categories, defined by restricting the Grothendieck fibration $\text{cod}: \mathcal{K}^2 \rightarrow \mathcal{K}$.

7.4.11. LEMMA. *Let $P: \mathcal{E} \rightarrow \mathcal{B}$ be a Grothendieck fibration between 1-categories. Suppose that \mathcal{J} is a small category, that $D: \mathcal{J} \rightarrow \mathcal{E}$ is a diagram, and that*

- (i) *the diagram $PD: \mathcal{J} \rightarrow \mathcal{B}$ has a limit L in \mathcal{B} with limiting cone $\lambda: \Delta L \Rightarrow D$,*
- (ii) *the diagram $\lambda^*D: \mathcal{J} \rightarrow \mathcal{E}_L$*

$$\begin{array}{ccc} \mathcal{J} & \xrightarrow{D} & \mathcal{E} \\ & \searrow \Delta L & \downarrow P \\ & \uparrow \lambda & \mathcal{B} \end{array} = \begin{array}{ccc} \mathcal{J} & \xrightarrow{\lambda^*D} & \mathcal{E} \\ & \uparrow \chi & \downarrow P \\ & \lambda^*D & \mathcal{B} \end{array}$$

*constructed by lifting the cone λ to a cartesian natural transformation $\chi: \lambda^*D \Rightarrow D$ has a limit M in the fibre \mathcal{E}_L with limiting cone $\mu: \Delta M \Rightarrow \lambda^*D$, and*

- (iii) *the limit $\mu: \Delta M \Rightarrow \lambda^*D$ is preserved by the re-indexing functor $u^*: \mathcal{E}_L \rightarrow \mathcal{E}_B$ associated with any arrow $u: B \rightarrow L$ in \mathcal{B} .*

Then the composite cone

$$\Delta M \xRightarrow{\mu} \lambda^*D \xRightarrow{\chi} D$$

displays M as a limit of the diagram D in \mathcal{E} .

PROOF. Any arrow $f: E \rightarrow E'$ in the domain of a Grothendieck fibration $P: \mathcal{E} \rightarrow \mathcal{B}$ factors uniquely up to isomorphism through a “vertical” arrow in the fiber \mathcal{E}_{PE} followed by a “horizontal” cartesian lift of Pf with codomain E' .

Given a cone $\alpha: \Delta E \Rightarrow D$ with summit $E \in \mathcal{E}$ over D , by (i) its image $P\alpha: \Delta PE \Rightarrow PD$ factors uniquely through the limit cone $\lambda: \Delta L \Rightarrow D$ via a map $b: PE \rightarrow L \in \mathcal{B}$. By the universal property of the cartesian lift χ of λ constructed in (ii), it follows that α factors uniquely through χ via a natural transformation $\beta: \Delta E \Rightarrow \lambda^*D$ so that $P\beta = \Delta b$. This arrow factors uniquely up to isomorphism via “vertical” natural transformation $\gamma: \Delta E \rightarrow \alpha^*D \cong b^*\gamma^*D$ followed by a “horizontal” cartesian lift of b . By (iii), the limit cone $\mu: \Delta M \Rightarrow \lambda^*D$ in \mathcal{E}_L pulls back along b to a limit cone in \mathcal{E}_{PE} through which the pullback of β factors via a map $k: E \rightarrow b^*M$. Thus, β itself factors uniquely through μ via the composite of this map $k: E \rightarrow b^*M$ with the cartesian arrow $b^*M \rightarrow M$ lifting $b: PE \rightarrow L$. \square

7.4.12. PROPOSITION. *For any ∞ -cosmos \mathcal{K} , the ∞ -cosmos of isofibrations admits sub ∞ -cosmoi*

$$\mathcal{R}ari(\mathcal{K}) \hookrightarrow \mathcal{K}^2 \longleftarrow \mathcal{L}ari(\mathcal{K})$$

whose

- *objects are isofibrations admitting a right adjoint right inverse or left adjoint right inverse, respectively, and*
- *0-arrows are commutative squares between the right or left adjoints, respectively, whose mates are isomorphisms*

with the ∞ -cosmos structures created by the inclusions.

We refer to a commutative square between right adjoints whose mate is an isomorphism as an **exact square**.

PROOF. The quasi-categorically enriched subcategories $\mathcal{R}ari(\mathcal{K})$ and $\mathcal{L}ari(\mathcal{K})$ are replete in \mathcal{K}^2 , so by Proposition 7.4.6 we need only check that $\mathcal{R}ari(\mathcal{K}) \hookrightarrow \mathcal{K}^2$ is closed under flexible weighted limits; the argument for $\mathcal{L}ari(\mathcal{K}) \hookrightarrow \mathcal{K}^2$ is dual. We argue separately for cotensors and for the conical limits.

If $p: E \twoheadrightarrow B$ is an isofibration admitting a right adjoint right inverse in \mathcal{K} and U is a simplicial set, then the cosmological functor $(-)^U: \mathcal{K} \rightarrow \mathcal{K}$ carries this data to a right adjoint right inverse to $p^U: E^U \twoheadrightarrow B^U$, which proves that the simplicial cotensor in \mathcal{K}^2 of an object in $\mathcal{R}ari(\mathcal{K})$ lies in $\mathcal{R}ari(\mathcal{K})$. The limit cone for the cotensor is given by the canonical map of simplicial sets $U \rightarrow \mathbf{Fun}(E^U \xrightarrow{p^U} B^U, E \xrightarrow{p} B)$ defined on each vertex $u: \mathbf{1} \rightarrow U$ by the commutative square

$$\begin{array}{ccc} E^U & \xrightarrow{u^*} & E \\ p^U \downarrow & & \downarrow p \\ B^U & \xrightarrow{u^*} & B \end{array} \quad (7.4.13)$$

The maps u^* define the components of a simplicial natural transformation from $(-)^U$ to the identity functor and thus the mate of this commutative square is an identity, so the limit cone for the U -cotensor lies in $\mathcal{R}ari(\mathcal{K})$. Finally, to verify the universal property of the cotensor in $\mathcal{R}ari(\mathcal{K})$, we must show that for any commutative square whose domain is an isofibration admitting a right adjoint right inverse

$$\begin{array}{ccc} F & \longrightarrow & E^U \\ \downarrow q & & \downarrow p^U \\ A & \longrightarrow & B^U \end{array}$$

that composes with each of the squares (7.4.13) to an exact square is itself exact. To see this take the mate to define a 1-arrow in $\mathbf{Fun}(A, E^U) \cong \mathbf{Fun}(A, E)^U$ and note that the hypothesis says that the components of this 1-arrow are invertible for each vertex of U . Lemma ?? then tells us that this 1-arrow is invertible as required.

Taking U to be a set, the argument just given proves also that $\mathcal{R}ari(\mathcal{K})$ is closed in \mathcal{K}^2 under products. It remains only to show that it is closed under the remaining conical limits. By pullback stability of fibered adjunctions, the Grothendieck fibration of 1-categories $\mathbf{cod}: \mathcal{K}^2 \rightarrow \mathcal{K}$ restricts to $\mathbf{cod}: \mathcal{R}ari(\mathcal{K}) \rightarrow \mathcal{K}$, so we may appeal to Lemma 7.4.11 to calculate 1-categorical limit cones in $\mathcal{R}ari(\mathcal{K}) \subset \mathcal{K}^2$ as composites of cartesian cells with limit cones of fiberwise diagrams. By Corollary 7.4.10, these fiberwise limits in \mathcal{K}_B of diagrams in $\mathcal{R}ari(\mathcal{K})_B$ lie in $\mathcal{R}ari(\mathcal{K})_B \hookrightarrow \mathcal{R}ari(\mathcal{K})$. Moreover, these 1-categorical limits are preserved by the simplicial cotensor, which by Proposition A.5.6 implies that their universal property enriches to define conical limits. In this way we see that $\mathcal{R}ari(\mathcal{K}) \hookrightarrow \mathcal{K}^2$ is closed under flexible weighted limits and thus defines a cosmological embedding, as claimed. \square

Proposition 7.4.12 allows us to construct further ∞ -cosmoi of interest.

7.4.14. PROPOSITION. For any ∞ -cosmos \mathcal{K} and simplicial set J , there exist sub ∞ -cosmoi

$$\mathcal{K}_{\top, J} \hookrightarrow \mathcal{K} \hookleftarrow \mathcal{K}_{\perp, J}$$

whose

- objects are ∞ -categories in \mathcal{K} that admit all limits of shape J or all colimits of shape J , respectively,
- 0-arrows are the functors that preserve them

with the ∞ -cosmos structures created by the inclusions. Moreover for each object of $\mathcal{K}_{\top, J}$ or $\mathcal{K}_{\perp, J}$ defined as a flexible weighted limit of some diagram in that ∞ -cosmos, its J -shaped limits or colimits are created by the 0-arrow legs of the limit or colimits cones respectively.

PROOF. First note that the quasi-categorically enriched subcategories $\mathcal{K}_{\top, J}$ and $\mathcal{K}_{\perp, J}$ are replete in \mathcal{K} , so by Proposition 7.4.6 we need only confirm that the inclusions are closed under flexible weighted limits. We prove this in the case of colimits, the other case being dual.

For any fixed simplicial set J , there is a cosmological functor $F_J: \mathcal{K} \rightarrow \mathcal{K}^2$ defined on objects by mapping an ∞ -category A to the isofibration $A^{J^\triangleright} \twoheadrightarrow A^J$ in the notation of 4.2.6 and a functor $f: A \rightarrow B$ to the commutative square

$$\begin{array}{ccc} A^{J^\triangleright} & \xrightarrow{f^{J^\triangleright}} & B^{J^\triangleright} \\ \downarrow & & \downarrow \\ A^J & \xrightarrow{f^J} & B^J \end{array}$$

By Corollary 4.3.5, A admits colimits of shape J if and only if this isofibration admits a left adjoint right inverse, and now it is clear that $f: A \rightarrow B$ preserves these colimits if and only if the square displayed above is exact. In summary, the quasi-categorically enriched subcategory $\mathcal{K}_{\perp, J}$ is defined by the pullback

$$\begin{array}{ccc} \mathcal{K}_{\perp, J} & \longrightarrow & \mathcal{Lari}(\mathcal{K}) \\ \downarrow & \lrcorner & \downarrow \\ \mathcal{K} & \xrightarrow{F_J} & \mathcal{K}^2 \end{array}$$

Proposition 7.4.12 proves that $\mathcal{Lari}(\mathcal{K}) \hookrightarrow \mathcal{K}^2$ is closed under flexible weighted limits and $F_J: \mathcal{K} \rightarrow \mathcal{K}^2$ preserves them, so it follows, as in the proof of Lemma 6.1.7, that $\mathcal{K}_{\perp, J}$ is closed in \mathcal{K} under flexible weighted limits. Now Proposition 7.4.6 proves that the inclusion $\mathcal{K}_{\perp, J} \hookrightarrow \mathcal{K}$ creates an ∞ -cosmos structure. \square

7.4.15. PROPOSITION. The ∞ -cosmos of isofibrations admits sub ∞ -cosmoi

$$\mathcal{Cart}(\mathcal{K}) \hookrightarrow \mathcal{K}^2 \hookleftarrow \mathcal{coCart}(\mathcal{K})$$

whose objects are cartesian or cocartesian fibrations, respectively, and whose 0-arrows are cartesian functors, with the ∞ -cosmos structures created by the inclusions. Similarly, for any ∞ -category B in an ∞ -cosmos \mathcal{K} , the sliced ∞ -cosmos $\mathcal{K}_{/B}$ admits sub ∞ -cosmoi

$$\mathcal{Cart}(\mathcal{K})_{/B} \hookrightarrow \mathcal{K}_{/B} \hookleftarrow \mathcal{coCart}(\mathcal{K})_{/B}$$

whose objects are cartesian or cocartesian fibrations over B , respectively, and whose 0-arrows are cartesian functors, with the ∞ -cosmos structures created by the inclusions.

PROOF. The quasi-categorically enriched subcategories $\mathcal{Cart}(\mathcal{K})$ and $\mathcal{coCart}(\mathcal{K})$ are replete in \mathcal{K}^2 by Corollary 5.1.17. By Theorems 5.1.11 and 5.1.19, the quasi-categorically enriched category $\mathcal{Cart}(\mathcal{K})$ is defined by the pullback

$$\begin{array}{ccc} \mathcal{Cart}(\mathcal{K}) & \longrightarrow & \mathcal{Pari}(\mathcal{K}) \\ \downarrow & \lrcorner & \downarrow \\ \mathcal{K}^2 & \xrightarrow{K} & \mathcal{K}^2 \end{array}$$

along the simplicial functor that sends an isofibration $p: E \twoheadrightarrow B$ to the isofibration $k: E^2 \twoheadrightarrow \mathbf{Hom}_B(B, p)$ defined by Remark 5.1.13. The simplicial functor K is constructed out of weighted limits and thus preserves all weighted limits, and the replete subcategory inclusion $\mathcal{Pari}(\mathcal{K}) \hookrightarrow \mathcal{K}^2$ creates flexible weighted limits by Proposition 7.4.12. Hence, as in the proof of Lemma 6.1.7, $\mathcal{Cart}(\mathcal{K})$ is closed in \mathcal{K}^2 under flexible weighted limits, and now Proposition 7.4.6 proves that the inclusion $\mathcal{Cart}(\mathcal{K}) \hookrightarrow \mathcal{K}^2$ creates an ∞ -cosmos structure.

The result for cartesian fibrations with a fixed base can be proven directly by a similar argument or deduced by considering $\mathcal{K}_{/B} \subset \mathcal{K}^2$ as the (non-replete!) subcategory whose n -arrows have id_B as their codomain components. \square

Exercises.

7.4.i. EXERCISE. Prove Lemma 7.4.3.

7.4.ii. EXERCISE. Use an argument similar to that given in the proof of Proposition 7.4.9 to prove that any ∞ -cosmos \mathcal{K} admits a sub ∞ -cosmos $\mathbf{Stab}(\mathcal{K}) \hookrightarrow \mathcal{K}$ whose objects are the stable ∞ -categories of Definition 4.4.5 and whose morphisms are the **exact functors**, which preserve the zero elements and the exact triangles.

7.4.iii. EXERCISE. Consider a functor between isofibrations

$$\begin{array}{ccc} E & \xrightarrow{g} & F \\ \swarrow p & & \searrow q \\ & B & \\ \nwarrow r & & \nearrow s \end{array}$$

in which p admits a right adjoint right inverse r and q admits a right adjoint right inverse s . Prove that if $gr \cong s$ over B , then the mate of the identity $qg = p$ is an isomorphism. This proves that the 0-arrows in the ∞ -cosmos $\mathcal{Pari}(\mathcal{K})_{/B}$ are *exact transformations* between right adjoint right inverse adjunctions.

7.4.iv. EXERCISE. Prove that $\mathcal{Lari}(\mathcal{K}) \cong \mathcal{Pari}(\mathcal{K}^{\mathrm{co}})^{\mathrm{co}}$.

7.4.v. EXERCISE. Use Exercise 1.2.iv to show that if $\mathcal{L} \hookrightarrow \mathcal{K}$ is a replete sub ∞ -cosmos, then an object $A \in \mathcal{L}$ is discrete if and only if A is discrete as an object of \mathcal{K} .

7.5. Weak 2-limits revisited

To wrap up this chapter on weighted limits, we briefly switch the base of enrichment from simplicial sets to categories and reconsider the weak 2-limits introduced in Chapter 3. We give a general

definition that unifies the weak 2-limits introduced in special cases there and prove their essential uniqueness in a uniform manner.

Before turning our attention to weak 2-limits we describe the explicit construction of the weighted limit of any \mathbf{Cat} -valued diagram. Let \mathcal{A} be a small 2-category and consider any pair of 2-functors $F, W: \mathcal{A} \Rightarrow \mathbf{Cat}$, the first regarded as the diagram and the second as the weight.

7.5.1. LEMMA (on the construction of weighted limits in \mathbf{Cat}). *For any diagram $F: \mathcal{A} \rightarrow \mathbf{Cat}$ and weight $W: \mathcal{A} \rightarrow \mathbf{Cat}$, the weighted limit $\lim_W F \in \mathbf{Cat}$ exists, defined to be the category whose*

- *objects are 2-natural transformations $\alpha: W \Rightarrow F$ and*
- *morphisms are modifications.*

PROOF. By Definition 7.1.7, the W -weighted limit of F is a category $\lim_W F \in \mathbf{Cat}$ characterized by a natural isomorphism of categories

$$\mathbf{Cat}(X, \lim_W F) \cong \mathbf{Cat}^{\mathcal{A}}(W, \mathbf{Cat}(X, F-))$$

for any category X . The 2-functor $\mathbf{Cat}(\mathbf{1}, -): \mathbf{Cat} \rightarrow \mathbf{Cat}$ is the identity, so taking $X = \mathbf{1}$ this tells us that

$$\lim_W F \cong \mathbf{Cat}^{\mathcal{A}}(W, F),$$

the category of 2-natural transformations and modifications from W to F . □

7.5.2. DEFINITION (weak 2-limits in a 2-category). Consider a 2-functor $F: \mathcal{A} \rightarrow \mathbf{C}$ indexed by a small 2-category \mathcal{A} and a weight $W: \mathcal{A} \rightarrow \mathbf{Cat}$. A W -cone with summit $P \in \mathbf{C}$

$$W \xRightarrow{\lambda} \mathbf{C}(P, F-)$$

displays P as a weak 2-limit of F if and only if for all $X \in \mathbf{C}$ the functor induced by composition with λ

$$\mathbf{C}(X, P) \xrightarrow{\lambda_*} \lim_W \mathbf{C}(X, F-)$$

to the W -weighted limit of the diagram $\mathbf{C}(X, F-): \mathcal{A} \rightarrow \mathbf{Cat}$ is smothering, in the sense of Definition 3.1.2.

The weak universal property encoded by a smothering functor is sufficiently strong to characterize the limit objects up to equivalence in the ambient 2-category:

7.5.3. PROPOSITION (uniqueness of weak 2-limits). *For any fixed diagram and fixed weight, any pair of weak 2-limits are equivalent via an equivalence that commutes with the legs of the limit cones.*

PROOF. If

$$W \xRightarrow{\lambda} \mathbf{C}(P, F-) \quad \text{and} \quad W \xRightarrow{\lambda'} \mathbf{C}(P', F-)$$

both define weak 2-limit W -weighted cones over a 2-functor $F: \mathcal{A} \rightarrow \mathbf{C}$, then for any $X \in \mathbf{C}$, we have a pair of smothering functors

$$\mathbf{C}(X, P) \xrightarrow{\lambda_*} \lim_W \mathbf{C}(X, F-) \xleftarrow{\lambda'_*} \mathbf{C}(X, P')$$

Taking $X = P$, the identity $\text{id}_P \in \mathbf{C}(P, P)$ maps to the cone $\lambda \in \lim_W \mathbf{C}(P, F-)$, which then lifts along the right-hand smothering functor to define a 1-cell $u: P \rightarrow P'$; a 1-cell $v: P' \rightarrow P$ is defined similarly as the lift of $\lambda' \in \lim_W \mathbf{C}(P', F-)$ along λ_* . By construction, both u and v commute with the legs of the limit cones λ and λ' .

Now λ_* carries the composite $vu \in C(P, P)$ to the cone $W \Rightarrow C(P, F-)$ whose component at $a \in \mathcal{A}$ is the composite

$$P \xrightarrow{u} P' \xrightarrow{v} P \xrightarrow{\lambda_a} Fa$$

$$\searrow \lambda_a \quad \swarrow \lambda'_a$$

which equals simply the cone leg λ_a . Thus id_P and vu lie in the same fiber of the smothering functor λ_* and so by Lemma 3.1.3 must be isomorphic via an isomorphism that whiskers to identities along the legs of the limit cone. Similarly, $uv \cong \text{id}_{P'}$, proving that $P \simeq P'$ as claimed. \square

Exercises.

7.5.i. EXERCISE. An **inserters** is a limit of a diagram indexed by the parallel pair category $\bullet \rightrightarrows \bullet$ weighted by the weight

$$\mathbb{1} \xrightleftharpoons[1]{0} 2 \in \text{Cat}$$

Prove that the homotopy 2-category of an ∞ -cosmos has weak inserters of any parallel pair of functors $f, g: A \rightrightarrows B$ constructed by the pullback

$$\begin{array}{ccc} \text{Ins}(f, g) & \longrightarrow & B^2 \\ \downarrow & \lrcorner & \downarrow (p_1, p_0) \\ A & \xrightarrow{(g, f)} & B \times B \end{array}$$

Homotopy coherent adjunctions and monads

Bar and cobar resolutions are ubiquitous in modern homotopy theory, defining for instances various completions of spaces and spectra [11] and free resolutions such as given in Definition 6.2.1. Formally, these bar or cobar constructions are associated to the monad or comonad of an adjunction

$$A \begin{array}{c} \xleftarrow{f} \\ \perp \\ \xrightarrow{u} \end{array} B \qquad \eta: \text{id}_B \Rightarrow uf, \epsilon: fu \Rightarrow \text{id}_A$$

between ∞ -categories. The monad and comonad resolutions associated to an adjunction are dual. By the triangle equalities, the unit and counit maps give rise to a coaugmented cosimplicial object in $\mathbf{hFun}(B, B)$, the “monad resolution”

$$\mathrm{id}_B \longrightarrow \eta \longrightarrow uf \begin{array}{c} \xrightarrow{\eta uf} \\ \xleftarrow{u\epsilon f} \\ \xrightarrow{uf\eta} \end{array} ufuf \begin{array}{c} \xrightarrow{\quad} \\ \xleftarrow{\quad} \\ \xrightarrow{\quad} \end{array} ufufuf \quad \dots \quad (8.0.1)$$

an augmented simplicial object in $\mathbf{hFun}(A, A)$, the “comonad resolution”

$$\text{id}_A \leftarrow \epsilon \text{ --- } fu \begin{array}{c} \xleftarrow{\epsilon fu} \\ \xrightarrow{f\eta u} \\ \xleftarrow{fu\epsilon} \end{array} fu fu \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \\ \xleftarrow{\quad} \\ \xrightarrow{\quad} \end{array} fu fu fu \quad \dots \quad (8.0.2)$$

and augmented simplicial objects in $\mathbf{hFun}(A, B)$ and $\mathbf{hFun}(B, A)$ admitting forwards and backwards contracting homotopies

$$\begin{array}{ccccccc}
 u & \begin{array}{c} \xrightarrow{\eta u} \\ \xleftarrow{u \epsilon} \end{array} & ufu & \begin{array}{c} \xrightarrow{\eta ufu} \\ \xleftarrow{u \epsilon fu} \\ \xrightarrow{uf \eta u} \\ \xleftarrow{ufu \epsilon} \end{array} & ufu fu & \begin{array}{c} \xrightarrow{\hspace{1cm}} \\ \xleftarrow{\hspace{1cm}} \\ \xrightarrow{\hspace{1cm}} \\ \xleftarrow{\hspace{1cm}} \end{array} & ufu fu fu & \dots \\
 f & \begin{array}{c} \xrightarrow{\epsilon f} \\ \xleftarrow{f \eta} \end{array} & fuf & \begin{array}{c} \xrightarrow{\epsilon fuf} \\ \xleftarrow{f \eta uf} \\ \xrightarrow{fu \epsilon f} \\ \xleftarrow{fuf \eta} \end{array} & fuf uf & \begin{array}{c} \xrightarrow{\hspace{1cm}} \\ \xleftarrow{\hspace{1cm}} \\ \xrightarrow{\hspace{1cm}} \\ \xleftarrow{\hspace{1cm}} \end{array} & fuf uf uf & \dots
 \end{array} \tag{8.0.3}$$

A classical categorical observation tells a richer story, relating the four resolutions displayed above. There is a strict 2-category \mathcal{Adj} containing two objects and an adjunction between them — the free 2-category containing an adjunction — and collectively these four diagrams display the image of a 2-functor whose domain is \mathcal{Adj} [53]. More precisely, each diagram is the image of one of the four hom-categories of this two object 2-category: a 2-functor $\mathcal{Adj} \rightarrow \mathbf{hK}$ extending the adjunction $f \dashv u$ is defined by a pair of objects $A, B \in \mathbf{hK}$, the monad and comonad resolutions in the functor categories $\mathbf{hFun}(B, B)$ and $\mathbf{hFun}(A, A)$, and the dual pair of split augmented simplicial objects in $\mathbf{hFun}(A, B)$ and $\mathbf{hFun}(B, A)$. The fact that these resolutions assemble into a 2-functor says that, e.g., that the image of

the comonad resolution under u is an augmented simplicial object in $\mathbf{hFun}(A, B)$ that admits “extra degeneracies.”

In this chapter, we will prove that any adjunction in the homotopy 2-category of an ∞ -cosmos — that is, any adjunction between ∞ -categories — can be lifted to a *homotopy coherent adjunction* in the ∞ -cosmos. The data of a homotopy coherent adjunction is indexed by a simplicial computad that is uncannily closely related to the free adjunction $\mathcal{A}dj$. In fact, we define the *free homotopy coherent adjunction* to be the 2-category $\mathcal{A}dj$ regarded as a simplicial category by identifying its hom-categories with their nerves. Section 8.1 is spent justifying this definition by introducing a graphical calculus that allows us to precisely understand homotopy coherent adjunction data and prove that $\mathcal{A}dj$ is a simplicial computad.

In a homotopy coherent adjunction, the resolutions (8.0.1), (8.0.2), and (8.0.3) lift to homotopy coherent diagrams

$$\Delta_+ \rightarrow \mathbf{Fun}(B, B), \quad \Delta_+^{\mathrm{op}} \rightarrow \mathbf{Fun}(A, A), \quad \Delta_{\top} \rightarrow \mathbf{Fun}(A, B), \quad \Delta_{\perp} \rightarrow \mathbf{Fun}(B, A)$$

indexed by the 1-categories introduced in Definition 2.3.9 and valued in the functor quasi-categories of the ∞ -cosmos. In the case of the split augmented simplicial objects, the contracting homotopies, also called “splittings” or “extra degeneracies,” are given by the bottom and top η ’s respectively. Applying Proposition 2.3.11, it follows that the geometric realization or homotopy invariant realization of the simplicial objects spanned by maps in the image of fuf and ufu are simplicial homotopy equivalent to f and u . Dual results apply to the (homotopy invariant) totalization of the cosimplicial object spanned by these same objects; in this case the “extra codegeneracies” are given by the top and bottom ϵ ’s.

The main theorem of this chapter proves that homotopy coherent adjunctions are abundant: indeed *any* adjunction of ∞ -categories extends to a homotopy coherent adjunction. Homotopy coherent adjunctions extending a subcomputad of generating adjunction data are not unique on the nose. However, whenever the subcomputad of generating adjunction is “parental” — loosely, generating from the universal property of either the right adjoint or the left adjoint exclusively — then extensions to a full homotopy coherent adjunction define the vertices of a contractible Kan complex, proving appropriately generated extensions are “homotopically unique.”

All of the results in this chapter apply to any adjunction defined in (the homotopy 2-category of) a quasi-categorically enriched category \mathcal{K} . Yet since we’ll typically apply these results to ∞ -cosmoi, we retain the usual notation $\mathbf{Fun}(A, B)$ for the hom quasi-categories of \mathcal{K} to trigger the correct intuition in these contexts.

8.1. The free homotopy coherent adjunction

In this section, we present a strict 2-category $\mathcal{A}dj$ introduced by Schanuel and Street under the name “the free adjunction” [53], which has the universal property that it is the free 2-category containing an adjunction. Immediately after introducing this classical object, we take the unorthodox step of reconsidering it as a simplicial category via a mechanism that we shall describe. We develop a new presentation of $\mathcal{A}dj$ by introducing a graphical calculus that allows us to prove the surprising fact that this simplicial category is a simplicial computad. This justifies referring to it as the *free homotopy coherent adjunction*. The remainder of this chapter will explore the consequences of this definition.

8.1.1. DEFINITION (the free adjunction). Let $\mathcal{A}dj$ denote the 2-category with two objects $+$ and $-$ and the four hom-categories

$$\mathcal{A}dj(+, +) := \Delta_+, \quad \mathcal{A}dj(-, -) := \Delta_+^{\text{op}}, \quad \mathcal{A}dj(-, +) := \Delta_{\top}, \quad \mathcal{A}dj(+, -) := \Delta_{\perp}$$

displayed in the following cartoon:

$$\Delta_+ \curvearrowright + \begin{array}{c} \xrightarrow{\Delta_{\perp} \cong \Delta_{\top}^{\text{op}}} \\ \perp \\ \xleftarrow{\Delta_{\top} \cong \Delta_{\perp}^{\text{op}}} \end{array} - \curvearrowright \Delta_+^{\text{op}}$$

Here $\Delta_{\top}, \Delta_{\perp} \subset \Delta \subset \Delta_+$ are the subcategories of order-preserving maps that preserve the top or bottom elements, respectively, in each ordinal, as described in Definition 2.3.9. Their intersection

$$\Delta_{\perp, \top} := \Delta_{\perp} \cap \Delta_{\top} \cong \Delta_+^{\text{op}}$$

is the subcategory of order-preserving maps that preserve both the top and bottom elements in each ordinal. This identifies Δ_+^{op} with the subcategory $\Delta_{\perp, \top} \subset \Delta_+$ of “intervals,” as is elaborated upon in Digression 8.1.8.

The horizontal composition maps in $\mathcal{A}dj$ are defined in $\mathcal{A}dj(-, -)^{\text{op}} \cong \mathcal{A}dj(+, +) \cong \Delta_+$ by the ordinal sum operation:

$$\begin{array}{ccc} \Delta_+ \times \Delta_+ & \xrightarrow{\oplus} & \Delta_+ \\ [n], [m] & \longmapsto & [n + m + 1] \\ \alpha, \beta \downarrow & \mapsto & \downarrow \alpha \oplus \beta \\ [n'], [m'] & \longmapsto & [n' + m' + 1] \end{array} \quad \alpha \oplus \beta(i) := \begin{cases} \alpha(i) & i \leq n \\ \beta(i - n - 1) + n' + 1 & i > n \end{cases}$$

The object $[-1] \in \Delta_+$ serves as the identity for ordinal sum, and thus represents the identity 1-cells on $-$ and $+$ in $\mathcal{A}dj$. Ordinal sum restricts to the subcategories $\Delta_{\perp}, \Delta_{\top} \subset \Delta_+$ to give bifunctors

$$\begin{array}{ccc} \Delta_+ \times \Delta_{\top} & \xrightarrow{\oplus} & \Delta_{\top} \\ \Downarrow & & \Downarrow \\ \mathcal{A}dj(+, +) \times \mathcal{A}dj(-, +) & \xrightarrow{\circ} & \mathcal{A}dj(-, +) \end{array} \quad \begin{array}{ccc} \Delta_{\perp} \times \Delta_+ & \xrightarrow{\oplus} & \Delta_{\perp} \\ \Downarrow & & \Downarrow \\ \mathcal{A}dj(+, -) \times \mathcal{A}dj(+, +) & \xrightarrow{\circ} & \mathcal{A}dj(+, -) \end{array}$$

defining these horizontal composition operations that we'll later come to think of as “actions” of $\mathcal{A}dj(+, +)$ on the left and right of $\mathcal{A}dj(-, +)$ and $\mathcal{A}dj(+, -)$. The opposites of these functors defines the action of $\mathcal{A}dj(-, -)$ on the right and left of $\mathcal{A}dj(-, +)$ and $\mathcal{A}dj(+, -)$.

8.1.2. LEMMA. *The 2-category $\mathcal{A}dj$ contains a distinguished adjunction*

$$+ \begin{array}{c} \xrightarrow{[0]} \\ \perp \\ \xleftarrow{[0]} \end{array} -$$

with unit $! : [-1] \rightarrow [0] \in \Delta_+ \cong \mathcal{A}dj(+, +)$ and counit given by the same map in $\Delta_+^{\text{op}} \cong \mathcal{A}dj(-, -)$.

PROOF. We must verify the triangle equalities in $\mathcal{A}dj(-, +)$ and $\mathcal{A}dj(+, -)$; these categories are opposites and the calculation in each case is dual, so we focus on the case of $\mathcal{A}dj(-, +)$. The whiskered composite of the unit $! : [-1] \rightarrow [0] \in \mathcal{A}dj(+, +)$ with the right adjoint $[0] \in \mathcal{A}dj(-, +)$ is the map $\delta^0 : [0] \rightarrow [1] \in \mathcal{A}dj(-, +)$, which is indeed top-element preserving. The whiskered composite of the counit in $\mathcal{A}dj(-, -)$ with the right adjoint in $\mathcal{A}dj(-, +)$ is defined by whiskering the opposite map

$! : [-1] \rightarrow [0] \in \mathcal{Adj}(+, +) \cong \mathcal{Adj}(-, -)^{\text{op}}$ with $[0] \in \mathcal{Adj}(+, -) \cong \mathcal{Adj}(-, +)^{\text{op}}$. This composite is the map $\delta^1 : [0] \rightarrow [1] \in \mathcal{Adj}(+, -) \cong \mathcal{Adj}(-, +)^{\text{op}}$, which is indeed top-element preserving. Under the isomorphism $\mathcal{Adj}(-, +) \cong \mathcal{Adj}(+, -)^{\text{op}}$, this corresponds to the map $\sigma^0 : [1] \rightarrow [0] \in \mathcal{Adj}(-, +)$. Now the composite $\sigma^0 \cdot \delta^0 : [0] \rightarrow [0] \in \mathcal{Adj}(-, +)$ is the identity as required. \square

The 2-categorical universal property of \mathcal{Adj} — that 2-functors $\mathcal{Adj} \rightarrow \mathcal{C}$ correspond to adjunctions in the 2-category \mathcal{C} — is stated without proof in [53]. We will take a roundabout route to verifying it in Proposition 8.1.13 that uses the simplicial computads of Chapter 6.

Throughout this text we have found it convenient to identify 1-categories with their nerves, which define simplicial sets. The 1-categories can be characterized as those simplicial sets that admit unique extensions along any inner horn inclusion or spine inclusion, or as those 2-coskeletal simplicial sets that admit unique extensions along inner horn or spine inclusions in dimensions 2 and 3; see Remark 1.1.5. Similarly, in developing homotopy coherent category theory it will be convenient to identify 2-categories with the simplicial categories obtained by identifying each of the hom-categories with its nerve — a categorification of the previous construction. As a corollary of the characterization of nerves of 1-categories, we obtain a characterization of the simplicially enriched categories that arise in this way.

8.1.3. LEMMA (2-categories as simplicial categories). *A 2-category \mathcal{A} may be regarded as a quasi-categorically enriched category whose*

- *objects are the objects of \mathcal{A}*
- *0-arrows in $\mathcal{A}(x, y)$ are the 1-cells of \mathcal{A} from x to y*
- *1-arrows in $\mathcal{A}(x, y)$ from f to g are the 2-cells of \mathcal{A} of the form $x \begin{array}{c} \xrightarrow{f} \\ \Downarrow \\ \xrightarrow{g} \end{array} y$*
- *and in which there exists a 2-arrow σ in $\mathcal{A}(x, y)$ whose faces $\sigma^i := \sigma \cdot \delta^i$ are 1-arrows in $\mathcal{A}(x, y)$*

$$\begin{array}{ccc} \begin{array}{ccc} & g & \\ \sigma^2 \nearrow & \sigma & \searrow \sigma^0 \\ f & \xrightarrow{\sigma^1} & h \end{array} & \rightsquigarrow & \begin{array}{ccc} & f & \\ x & \begin{array}{c} \xrightarrow{f} \\ \Downarrow \sigma^2 \\ \xrightarrow{g} \end{array} & y \\ & \Downarrow \sigma^0 & \\ & h & \end{array} & = & \begin{array}{ccc} & f & \\ x & \begin{array}{c} \xrightarrow{f} \\ \Downarrow \sigma^1 \\ \xrightarrow{h} \end{array} & y \end{array} \end{array}$$

if and only if σ^1 is the vertical composite $\sigma^0 \cdot \sigma^2$

with the higher-dimensional arrows determined by the property that each of the hom-spaces is 2-coskeletal. Conversely, a simplicially-enriched category \mathcal{A} is isomorphic to a 2-category if and only if each of its hom-spaces are 2-coskeletal simplicial sets that admit unique extensions along the spine inclusions in dimensions 2 and 3. \square

We now give the first of two presentations of the free homotopy coherent adjunction. Since we use the same notation for 1-categories and their nerves, we also adopt the same notation for a 2-category and its corresponding simplicial category under the embedding of Lemma 8.1.3.

8.1.4. DEFINITION (the free homotopy coherent adjunction, as a 2-category). The **free homotopy coherent adjunction** to be the free adjunction \mathcal{Adj} , regarded as a simplicial category. Explicitly \mathcal{Adj} has two objects $+$ and $-$ and the four hom quasi-categories defined by

$$\mathcal{Adj}(+, +) := \Delta_+, \quad \mathcal{Adj}(-, -) := \Delta_+^{\text{op}}, \quad \mathcal{Adj}(-, +) := \Delta_+, \quad \mathcal{Adj}(+, -) := \Delta_-$$

with the composition maps defined in 8.1.1.

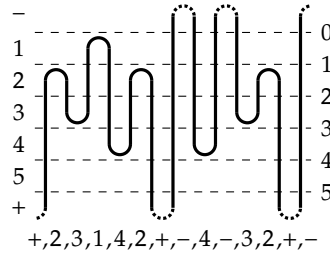
This presentation of the free homotopy coherent adjunction is not particularly enlightening. Via Lemma 8.1.3 and Definition 8.1.1 we could in principle describe the n -arrows in $\mathcal{A}dj$ but it's tricky to get a real feel for them. We will now reintroduce this simplicial category in a different guise that achieves just this. Before doing so, note:

8.1.5. OBSERVATION. To specify a simplicial category, thought of as an identity-on-objects simplicial object in $\mathcal{C}at$, it suffices to specify:

- a set of objects
- for each $n \geq 0$, a set of n -arrows whose domains and codomains are among the specified object set,
- a right action of the morphisms in Δ on this graded set of arrows that preserves domains and codomains,
- a “horizontal” composition operation for the n -arrows with compatible (co)domains that preserves the simplicial action.

We will now reintroduce $\mathcal{A}dj$ following this outline, by exhibiting its graded set of n -arrows between the objects $+$ and $-$.

8.1.6. DEFINITION (strictly undulating squiggles). Define a graded set of arrows between objects $-$ and $+$ whose n -arrows are strictly undulating squiggles on $n + 1$ lines, such as displayed below in the case $n = 5$:



The lines are labeled $0, 1, \dots, n$ and the gaps between them are labeled $-, 1, \dots, n, +$. A squiggle must start, on the right-hand side, and end, on the left-hand side, in either the gap $-$ or $+$. The right-hand starting gap becomes the domain of the squiggle and the left-hand ending gap becomes its codomain, these conventions chosen to follow the usual composition order. Each turning point of the squiggle must lie entirely within a single gap. The qualifier “strict undulation” refers to the requirement that adjacent turning points should be distinct and that they should oscillate up and down as we proceed from right to left.

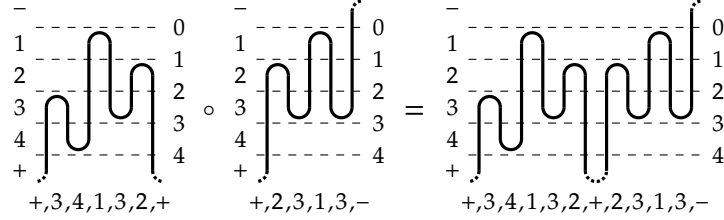
Formally, the data of a **strictly undulating squiggle** on $n + 1$ lines can be encoded by a string $\underline{a} = (a_0, a_1, \dots, a_{r-1}, a_r)$ of letters in the set $\{-, 1, 2, \dots, n, +\}$ corresponding to the gaps in which each successive turning point occurs, whose **width** is the integer $w(\underline{a}) := r$, subject to the following conditions:

- The **domain** $a_{w(\underline{a})}$ and **codomain** a_0 of \underline{a} are both in $\{-, +\}$.
- If $a_0 = -$ then for all $0 \leq i < w(\underline{a})$ we have $a_i < a_{i+1}$ whenever i is even and $a_i > a_{i+1}$ whenever i is odd, and if $a_0 = +$ then for all $0 \leq i < w(\underline{a})$ we have $a_i > a_{i+1}$ whenever i is even and $a_i < a_{i+1}$ whenever i is odd.

8.1.7. LEMMA. *The graded set of strictly undulating squiggles admits a right action of the morphisms in Δ that preserves domains and codomains and a “horizontal” composition operation for arrows in the same degree with*

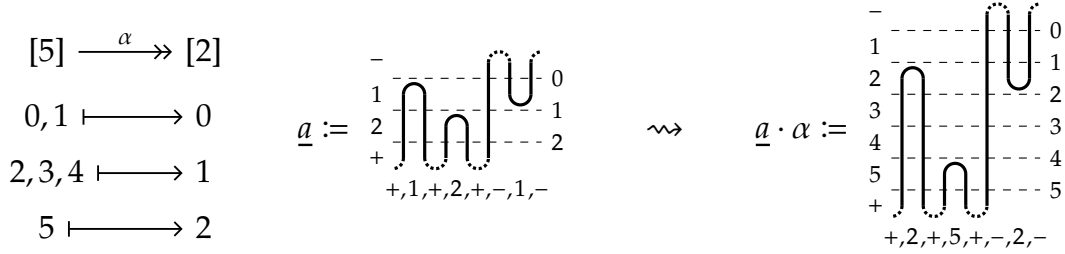
compatible (co)domains that preserves the simplicial action. Relative to the horizontal composition, an n -arrow is atomic if and only if there are no instances of $+$ or $-$ occurring in its interior. While the faces of an atomic arrow need not be atomic, the degeneracies of an atomic arrow always are.

PROOF. The horizontal composition of n -arrows is given by horizontal juxtaposition of strictly undulating squiggles on $n + 1$ lines, which produces a well-formed squiggle just when the codomain of the right-hand squiggle matches the domain of the left-hand squiggle:



This operation is clearly associative. Moreover, any strictly undulating squiggle admits a unique decomposition into squiggles that do not contain $+$ or $-$ in their interior sequences of gaps, which proves that any squiggle $\underline{a} = (a_0, a_1, \dots, a_{r-1}, a_r)$ with the property that $a_1, \dots, a_{r-1} \in \{1, \dots, n\}$ is atomic.

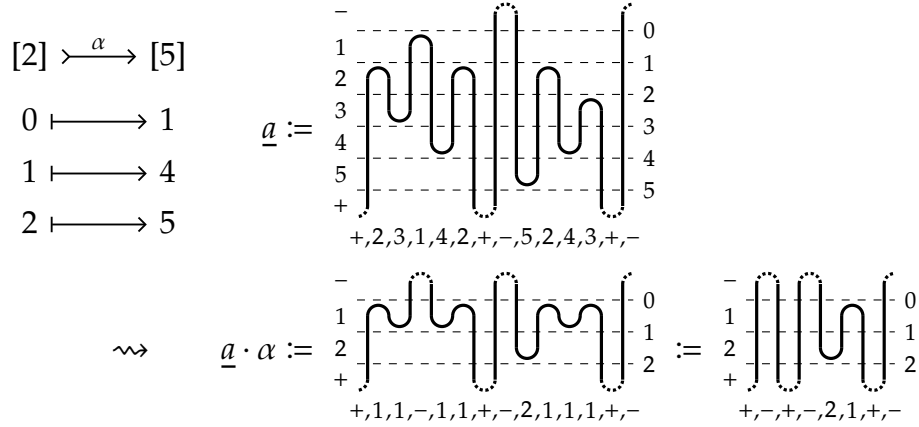
The right action of the simplicial operators on strictly undulating squiggles is best described in two cases. If $\alpha: [m] \rightarrow [n]$ is an epimorphism, then a strictly undulating squiggle on lines $0, \dots, n$ becomes a strictly undulating squiggle on lines $0, \dots, m$ by replacing each line labeled $i \in [n]$ with lines labeled by each element of the fiber $\alpha^{-1}(i)$ and then “pulling these lines apart” to create new gaps:



Note that “pulling apart lines” does not create instances of $+$ or $-$ in the interior sequence of gaps, so the action by degeneracy operators preserves atomic arrows.

If $\alpha: [m] \rightarrow [n]$ is a monomorphism, then a strictly undulating squiggle on lines $0, \dots, n$ becomes a strictly undulating squiggle on lines $0, \dots, m$ by removing the lines labelled by elements $i \in [n]$ not in the image of α and renumbering the lines that are in the image in sequence. The original squiggle will still undulate between the new lines, but may not do so “strictly” — it is possible for the squiggle to turn around multiple times in the same gap — but this is easily corrected by “pulling the string

taut”:



Note that in both of these cases, the actions by epimorphisms and monomorphisms preserve domains and codomains of squiggles and respect horizontal concatenations.

Now in general, a simplicial operator $\alpha: [m] \rightarrow [n]$ can be factored uniquely in Δ as an epimorphism followed by a monomorphism, so it acts on a strictly undulating squiggle on $n + 1$ lines by first “removing lines and pulling taut” and then by “duplicating lines and pulling apart.” \square

We leave the formalization of these geometric descriptions of the actions of the simplicial operators on strictly undulating squiggles presented as sequences satisfying the axioms of Definition 8.1.6(i) and (ii) to Exercise 8.1.iii, with the hint that a combinatorial description of this action can easily be defined using the “interval representation” of Δ^{op} .

8.1.8. DIGRESSION (the interval representation). There is a faithful **interval representation** of the category Δ_+^{op} as a subcategory of Δ in the form of a functor

$$\begin{array}{ccc}
 \Delta_+^{\text{op}} & \xhookrightarrow{\text{ir}} & \Delta \\
 [n-1] \longmapsto [n] & & \\
 \delta^i \downarrow & \mapsto & \uparrow \sigma^i \\
 [n] \longmapsto [n+1] & & \\
 \sigma^i \uparrow & \mapsto & \downarrow \delta^{i+1} \\
 [n+1] \longmapsto [n+2] & &
 \end{array}$$

whose image is the subcategory $\Delta_{\perp, \top} := \Delta_{\perp} \cap \Delta_{\top} \subset \Delta$ of simplicial operators that preserve both the top and bottom elements in each ordinal.

If we think of the elements of $[n]$ as labelling the lines in the graphical representation of an n -arrow, then the elements of $\text{ir}[n] := [n + 1]$ label the gaps, with the bottom element 0 relabeled as $-$ and the top element $n + 1$ relabeled as $+$. If the elementary face operators δ^i and elementary degeneracy operators σ^i act by removing and duplicating the lines in a squiggle diagram, then the functors $\text{ir} \delta^i$ and $\text{ir} \sigma^i$ describe the corresponding actions on the gaps.

The graphical description of its n -arrows of $\mathcal{A}dj$ clearly exhibits a simplicial computad structure on a simplicial category we now more formally introduce following the outline of Observation 8.1.5:

8.1.9. DEFINITION (the free homotopy coherent adjunction, as a simplicial computad). The **free homotopy coherent adjunction** $\mathcal{A}dj$ is the simplicial computad with

- two objects $+$ and $-$,
- whose n -arrows are strictly undulating squiggles on $n + 1$ lines of Definition 8.1.6, oriented from right to left, with the right-hand starting position defining the domain object and the left-hand ending position defining the codomain object,
- with the simplicial operators acting as described in Lemma 8.1.7, and
- with horizontal composition defined by horizontal juxtaposition of squiggle diagrams,

which means that the atomic n -arrows are those squiggles each of whose interior undulations occurs between the lines 0 and n .

We now reconcile our two descriptions of the free homotopy coherent adjunction, comparing Definition 8.1.9 with Definition 8.1.4. Zaganidis discovered a similar proof in his PhD thesis [65, §2.3.3] that improves upon some aspects of the authors' original argument.

8.1.10. PROPOSITION. *The simplicial computad \mathcal{Adj} is isomorphic to the 2-category \mathcal{Adj} .*

PROOF. We explain how the n -arrows in each of the four homs of the simplicial category \mathcal{Adj} correspond to sequences of n composable arrows in the corresponding hom-categories Δ_+ , Δ_\perp , Δ_\top , and $\Delta_{\perp,\top}$ of the 2-category \mathcal{Adj} . Here it is most convenient to think of Δ_\perp , Δ_\top , and $\Delta_{\perp,\top}$ as subcategories of Δ , the latter via the interval representation of Digression 8.1.8.

To easily visualize the isomorphism, shade the region under a strictly undulating squiggle on $n + 1$ lines to define a topological space S embedded in the plane. In the case of a squiggle from $-$ to $-$, this shaded region includes both the left and right boundary regions of the squiggle diagram. For each $i \in [n]$, the connected components of the intersection S_i of the shaded region with the region above the labelled i define a finite linearly ordered set, ordered from left to right by the order in which the intervals defined as the intersection of each component with the line i appear on that line. These ordinals define the objects in the composable sequence of arrows in Δ_+ or one of its subcategory $\Delta_{\perp,\top}$, Δ_\perp , or Δ_\top corresponding to the squiggle diagram.¹ Formally, the ordinal representing the i th object in the sequence of n arrows counts the number of “maximal convex subsequences” of the sequence $\underline{a} = (a_0, \dots, a_{w(\underline{a})})$ that encodes the squiggle; a **maximal convex subsequence** is a maximal sequence of consecutive entries a_j satisfying the condition $a_j \leq i$.

The intersections of the shaded region S with the regions above the lines $i = 0, \dots, n$ define a nested sequence of subspaces

$$S_0 \hookrightarrow S_1 \hookrightarrow \dots \hookrightarrow S_{n-1} \hookrightarrow S_n.$$

Taking path components yields a composable sequence

$$\pi_0 S_0 \rightarrow \pi_0 S_1 \rightarrow \dots \rightarrow \pi_0 S_{n-1} \rightarrow \pi_0 S_n.$$

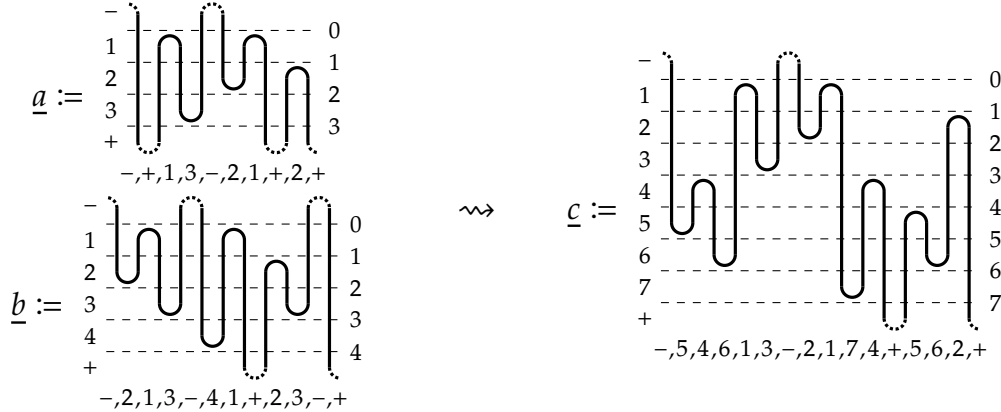
As explained above, each of the sets $\pi_0 S_i$ is linearly ordered, from left to right, by the positions in which each component of S_i intersects the line labeled i and the functions induced by the inclusions are order-preserving. This defines the composable sequence of arrows in Δ_+ , Δ_\perp , Δ_\top , or $\Delta_{\perp,\top}$ corresponding to a strictly undulating squiggle on $n + 1$ -lines.

For instance, suppose the shaded region under the squiggle diagram intersects the line labelled i in $m + 1$ components, corresponding to the ordinal $[m]$ and similarly suppose the shaded region

¹In the case of a squiggle from $+$ to $+$, it is possible that the squiggle diagram does not intersect the line labeled 0, in which case the subspace S_0 is empty; if this is the case, the squiggle may also fail to cross the next several lines. In each of the other three hom-categories, the ordinals defined by taking the connected components of the intersection of each line with the shaded region are non-empty because either the left or right boundary of the squiggle diagram is also shaded.

under the squiggle diagram intersects the line labelled $i + 1$ in $k + 1$ components, corresponding to the ordinal $[k]$. We identify the corresponding simplicial operator $\alpha: [m] \rightarrow [k]$ by taking the fiber over $t \in [k]$ to be the subset of shaded regions $s \in [m]$ above the i th line that belong to the same connected component as t in the shaded region above the line $i + 1$. Formally, the element $t \in [k]$ represents a maximal convex subsequence of $\underline{a} = (a_0, \dots, a_{w(\underline{a})})$ comprised of those $a_j \leq i + 1$. This convex subsequence is partitioned into possibly smaller maximally convex subsequences satisfying the more restrictive condition $a_j \leq i$ and the elements $s \in [m]$ indexing these subsequences form the fiber of α over t . Note that if the domain of the squiggle is $-$, then the top element of each ordinal is necessarily preserved because the right-hand boundary of the squiggle diagram defines a connected shaded region; similarly, if the codomain of the squiggle is $-$, then the bottom element of each ordinal is preserved. This constructs a map from the simplicial computad \mathcal{Adj} of Definition 8.1.9 to the 2-category \mathcal{Adj} of Definition 8.1.4.

The converse map can be constructed by iterating a splicing operation that we now introduce. This splicing operation proves that each of the hom-spaces of the simplicial computad \mathcal{Adj} satisfies a “strict Segal condition” that says that the set of $n + m$ -arrows is isomorphic to the set of pairs of n -arrows and m -arrows whose last and first vertices coincide. In more detail, if \underline{a} and \underline{b} are strictly undulating squiggles on $n + 1$ and $m + 1$ lines that lie in the same hom-space with the property that the n th vertex of \underline{a} coincides with the 0th vertex of \underline{b} , then these squiggle diagrams can be uniquely spliced to form a strictly undulating squiggle \underline{c} on $n + m + 1$ lines whose face spanned by the vertices $0, \dots, n$ is \underline{a} and whose face spanned by the vertices $n, \dots, m + n$ is \underline{b} .



This splicing operation is defined graphically by separating the squiggle diagrams for \underline{a} and for \underline{b} into an ordered sequence of components by cutting the squiggle \underline{a} each time it enters or leaves the gap marked “+,” removing the dotted arcs at the bottom of the squiggle diagram, and cutting the squiggle \underline{b} each time it enters or leaves the gap marked “-,” removing the dotted arcs at the top of the depicted squiggle diagram. This requires two cuts for each occurrence of “+” or “-” in the interior of \underline{a} or \underline{b} respectively and one cut for each occurrence of “+” or “-” as the source or target of \underline{a} or \underline{b} respectively. The condition that the n th vertex of \underline{a} coincides with the 0th vertex of \underline{b} ensures that the numbers of cuts made to \underline{a} (the number of times \underline{a} intersects the n th line) and \underline{b} (the number of times \underline{b} intersects the 0th line) are the same. Now form \underline{c} by sewing together these squiggle components in order to form the crossings of the line labeled “ n .”

By iterating the splicing operation, we can construct a strictly undulating squiggle on $n + 1$ lines from a sequence of n composable arrows once we know how to encode a single 1-arrow of \mathcal{Adj} as a strictly undulating squiggle on 2 lines. We give full details in the case of a 1-arrow from $+$ to $+$. A

simplicial operator $\alpha: [m] \rightarrow [k]$ defines a strictly undulating squiggle on 2 lines from $+$ to $+$ by a sequence \underline{a} with “ $-$ ” occurring $m + 1$ times (each occurrence of which corresponds to an intersection of the shaded region and the 0th line) and “ $+$ ” occurring $k + 2$ times (each consecutive pair bounding an intersection of the shaded region and the 1st line). The strings between each consecutive pair of $+$ s correspond to the elements $i \in [k]$. If the fiber over i is empty, the sequence is “ $+1+$.” If the fiber contains a single element, the sequence is “ $+ - 1 - +$,” and if the fiber contains $s > 1$ elements, the sequence is “ $+ - (1-)^{s-1} +$.” \square

Note that the planar orientation of a strictly undulating squiggle diagram makes the numerical labels for the lines, gaps, and the sequence of undulation points redundant. Going forward, we typically omit them.

8.1.11. EXAMPLE (adjunction data in $\mathcal{A}dj$). For later use we name some of the low-dimensional non-degenerate atomic arrows in $\mathcal{A}dj$. There exist just two atomic 0-arrows, which we call

$$\underline{f} := \begin{array}{c} \downarrow \\ \text{---} \\ \downarrow \end{array} \quad \text{and} \quad \underline{u} := \begin{array}{c} \uparrow \\ \text{---} \\ \uparrow \end{array}.$$

Since $\mathcal{A}dj$ is a simplicial computad, all of its other 0-arrows may be obtained as a unique alternating composite of these two, for example:

$$\underline{f}\underline{u}\underline{f}\underline{u}\underline{f} := \begin{array}{c} \downarrow \uparrow \downarrow \uparrow \downarrow \\ \text{---} \end{array}.$$

There are exactly two non-degenerate atomic 1-arrows in $\mathcal{A}dj$, these being:

$$\underline{\eta} := \begin{array}{c} \text{---} \\ \downarrow \uparrow \\ \text{---} \end{array} \quad \text{and} \quad \underline{\epsilon} := \begin{array}{c} \downarrow \uparrow \\ \text{---} \end{array}.$$

Again, since $\mathcal{A}dj$ is a simplicial computad, all of its other 1-arrows are uniquely expressible as horizontal composites of the 1-arrows $\underline{\eta}$ and $\underline{\epsilon}$ with degenerated 1-arrows obtained from \underline{f} and \underline{u} , such as for example

$$\underline{u}\underline{f}\underline{\eta} := \begin{array}{c} \downarrow \uparrow \downarrow \uparrow \\ \text{---} \end{array} \quad \text{and} \quad \underline{\epsilon}\underline{\epsilon} := \begin{array}{c} \downarrow \uparrow \downarrow \uparrow \\ \text{---} \end{array}.$$

There exist two non-degenerate atomic 2-arrows with minimal width, whose faces are easily computed:

$$\begin{array}{llll} \underline{\alpha} := \begin{array}{c} \downarrow \uparrow \downarrow \\ \text{---} \end{array} & \underline{\alpha} \cdot \delta^2 := \underline{f}\underline{\eta} := \begin{array}{c} \downarrow \uparrow \downarrow \uparrow \\ \text{---} \end{array} & \underline{\alpha} \cdot \delta^1 := \underline{f} := \begin{array}{c} \downarrow \\ \text{---} \\ \downarrow \end{array} & \underline{\alpha} \cdot \delta^0 := \underline{\epsilon}\underline{f} := \begin{array}{c} \downarrow \uparrow \\ \text{---} \end{array} \\ \underline{\beta} := \begin{array}{c} \uparrow \downarrow \uparrow \\ \text{---} \end{array} & \underline{\beta} \cdot \delta^2 := \underline{\eta}\underline{u} := \begin{array}{c} \text{---} \\ \downarrow \uparrow \\ \text{---} \end{array} & \underline{\beta} \cdot \delta^1 := \underline{u} := \begin{array}{c} \uparrow \\ \text{---} \\ \uparrow \end{array} & \underline{\beta} \cdot \delta^0 := \underline{u}\underline{\epsilon} := \begin{array}{c} \uparrow \downarrow \\ \text{---} \end{array} \end{array}$$

For each width $w \geq 3$, there exist exactly two non-degenerate atomic 2-arrows, the description of which we leave to Exercise 8.1.v. There are countably many atomic non-degenerate n -arrows in each dimension $n \geq 2$, which we shall partially enumerate in the proof of Proposition 8.2.11.

In the “homotopy 2-category” of the simplicial category $\mathcal{A}dj$, which is isomorphic to the 2-category $\mathcal{A}dj$, the atomic 2-arrows $\underline{\alpha}$ and $\underline{\beta}$ witness the triangle equalities, proving that this 2-category contains an adjunction $(\underline{f}, \underline{u}, \underline{\eta}: \text{id}_+ \Rightarrow \underline{u}\underline{f}, \underline{\epsilon}: \underline{f}\underline{u} \Rightarrow \text{id}_-)$.

8.1.12. LEMMA. *The simplicial computad $\mathcal{A}dj$ contains a distinguished adjunction*

$$\begin{array}{ccc} & \underline{f} & \\ \curvearrowright & & \curvearrowleft \\ + & \perp & - \\ \curvearrowleft & & \curvearrowright \\ & \underline{u} & \end{array}$$

with unit $\underline{\eta}: \text{id}_+ \rightarrow \underline{u}\underline{f} \in \mathcal{A}dj(+, +)$ and counit $\underline{\epsilon}: \underline{f}\underline{u} \rightarrow \text{id}_- \in \mathcal{A}dj(-, -)$.

PROOF. By Proposition 8.1.10 this follows from Lemma 8.1.2 though the reader may prefer to prove this result directly. \square

We can now prove the universal property of the free adjunction $\mathcal{A}dj$ claimed by Schanuel and Street.

8.1.13. PROPOSITION. *For any 2-category \mathcal{C} , 2-functors $\mathcal{A}dj \rightarrow \mathcal{C}$ correspond to adjunctions in the 2-category \mathcal{C} .*

PROOF. Lemma 8.1.2 identifies an adjunction in $\mathcal{A}dj$ that we denote in the notation of Lemma 8.1.12 by $(\underline{f}, \underline{u}, \underline{\eta}: \text{id}_+ \Rightarrow \underline{u}\underline{f}, \underline{\epsilon}: \underline{f}\underline{u} \Rightarrow \text{id}_-)$. A 2-functor $\mathcal{A}dj \rightarrow \mathcal{C}$ carries this data to an adjunction in the 2-category \mathcal{C} .

Conversely, we suppose that \mathcal{C} is equipped with an adjunction $(f, u, \eta: \text{id}_B \Rightarrow uf, \epsilon: fu \Rightarrow \text{id}_A)$. To construct a 2-functor $\mathcal{A}dj \rightarrow \mathcal{C}$ it suffices, because the embedding $2\text{-Cat} \hookrightarrow \mathcal{S}\mathcal{S}\text{et-Cat}$ is fully faithful, to consider both 2-categories as simplicial categories via Lemma 8.1.3 and instead define a simplicial functor $\mathcal{A}dj \rightarrow \mathcal{C}$; see Exercise 8.1.i. Now since $\mathcal{A}dj$ is a simplicial computad and the homs of \mathcal{C} are 2-coskeletal, it suffices to define a simplicial functor $\text{sk}_2 \mathcal{A}dj \rightarrow \mathcal{C}$ from the subcomputad of $\mathcal{A}dj$ generated by its atomic 0-, 1-, and 2-arrows. This functor is given by the mapping

- $+ \mapsto B$ and $- \mapsto A$ on objects,
- $\underline{f} \mapsto f$ and $\underline{u} \mapsto u$ on atomic 0-arrows,
- $\underline{\eta} \mapsto \eta$ and $\underline{\epsilon} \mapsto \epsilon$ on atomic non-degenerate 1-arrows,

and for each of the atomic non-degenerate 2-arrows of Exercise 8.1.v we must, by Lemma 8.1.3, verify that the 2-cells in \mathcal{C} defined by their boundaries compose vertically as indicated.

For $\underline{\alpha}$ and $\underline{\beta}$, the unique non-degenerate atomic 2-arrows of minimal width 3, the required composition relations are

$$\epsilon f \cdot f \eta = \text{id}_f \quad \text{and} \quad u \epsilon \cdot \eta u = \text{id}_u,$$

which hold by the triangle equalities for the adjunction in \mathcal{C} . For the atomic 2-arrows of odd width $2r + 1$, the required composition relations are the “higher order triangle equalities”

$$\epsilon^r f \cdot f \eta^r = \text{id}_f \quad \text{and} \quad u \epsilon^r \cdot \eta^r u = \text{id}_u,$$

which can easily be seen to hold by depicting the left-hand expressions as pasting diagrams.² For the atomic 2-arrows of even width $2r$, the required composites are closely related “higher order triangle equalities”

$$\epsilon^{r+1} \cdot f \eta^r u = \epsilon \quad \text{and} \quad u \epsilon^r \cdot \eta^{r+1} = \eta,$$

which again can easily be seen to hold by depicting the left-hand expressions as pasting diagrams. \square

²Here η^r refers to the horizontal composite of r copies of the unit and the “ \cdot ” expresses a vertical composite of a whiskered copy of this with a whiskered copy of ϵ^r , the horizontal composite of r -copies of the counit. The 1-cell codomain of the former and 1-cell domain of the latter fit together like a cartoon depiction of a closed mouth of pointy teeth.

Motivated by this result and the fact that the simplicial category \mathcal{Adj} is a simplicial computad, we use it to define a notion of *homotopy coherent adjunction* in any quasi-categorically enriched category, and in particular in any ∞ -cosmos.

8.1.14. DEFINITION. A **homotopy coherent adjunction** in a quasi-categorically enriched category \mathcal{K} is a simplicial functor $\mathcal{Adj} \rightarrow \mathcal{K}$. Explicitly, it picks out:

- a pair of objects $A, B \in \mathcal{K}$
- together with four homotopy coherent diagrams

$$\Delta_+ \rightarrow \text{Fun}(B, B), \quad \Delta_+^{\text{op}} \rightarrow \text{Fun}(A, A), \quad \Delta_\top \rightarrow \text{Fun}(A, B), \quad \Delta_\perp \rightarrow \text{Fun}(B, A) \quad (8.1.15)$$

that are functorial with respect to the composition action of \mathcal{Adj} .

The 0- and 1-dimensional data of these diagrams has the form displayed in (8.0.1), (8.0.2), and (8.0.3). We interpret the homotopy coherent diagrams (8.1.15) as defining homotopy coherent versions of the bar and cobar resolutions of the adjunction $(f \dashv u, \eta, \epsilon)$.

Exercises.

8.1.i. EXERCISE. Prove that the embedding $2\text{-Cat} \hookrightarrow \mathcal{S}\text{Set-Cat}$ defined by Lemma 8.1.3 is fully faithful: prove that simplicial functors $\mathcal{A} \rightarrow \mathcal{B}$ between 2-categories define 2-functors.

8.1.ii. EXERCISE. Use Lemma 8.1.3 to prove that the homotopy coherent ω -simplex $\mathfrak{C}\Delta[\omega]$ is a 2-category.³

8.1.iii. EXERCISE. Describe the action of a general simplicial operator $\alpha: [m] \rightarrow [n]$ on a strictly undulating squiggle on $n + 1$ lines represented by a sequence $\underline{a} = (a_0, a_1, \dots, a_{r-1}, a_r)$ of “gaps” $a_i \in \{-, 1, \dots, n, +\}$.

8.1.iv. EXERCISE. Give a graphical interpretation of the dualities

$$\mathcal{Adj}(-, -) \cong \mathcal{Adj}(+, +)^{\text{op}} \quad \text{and} \quad \mathcal{Adj}(-, +) \cong \mathcal{Adj}(+, -)^{\text{op}}$$

of Definition 8.1.4.

8.1.v. EXERCISE.

(i) Describe the non-degenerate atomic 2-arrows of \mathcal{Adj} and compute their faces and compare your results with the composition relations appearing in the last paragraph of the proof of Proposition 8.1.13.

(ii) Describe the degenerate atomic 2-arrows of \mathcal{Adj} and “compute” their faces.

8.1.vi. EXERCISE. Use the graphical calculus presented in Definition 8.1.9 to verify the following observation of Karol Szumilo: the simplicial category \mathcal{Adj} is isomorphic to the Dwyer-Kan hammock localization [17] of the category consisting of two objects $+$ and $-$ and a single non-identity arrow $+\rightrightarrows -$ that is a weak equivalence.

8.1.vii. EXERCISE. For any homotopy coherent adjunction as in Definition 8.1.14, define internal versions of monad resolution, the comonad resolution, the bar resolution, and the comonad resolution

$$B \xrightarrow{(uf)^\bullet} B^{\Delta_+}, \quad A \xrightarrow{(fu)^\bullet} A^{\Delta_+^{\text{op}}}, \quad A \xrightarrow{\text{bar}} B^{\Delta_\top}, \quad B \xrightarrow{\text{cobar}} A^{\Delta_\perp},$$

³In light of Lemma 8.1.3, Theorem 6.4 of [46] proves more generally that the simplicial computads defined as free resolutions of strict 1-categories are always 2-categories.

and explore the relationships between these functors.⁴

8.2. Homotopy coherent adjunction data

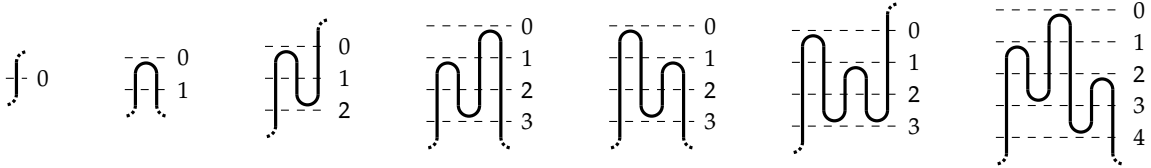
Any homotopy coherent adjunction in an ∞ -cosmos or general quasi-categorically enriched category has an underlying adjunction in its homotopy 2-category. Remarkably, this low-dimensional adjunction data may always be extended to give a full homotopy coherent adjunction by repeated invoking the universal property of the unit, as expressed in Proposition 8.3.2. In this section, we filter the free homotopy coherent adjunction $\mathcal{A}dj$ by a sequence of “parental” subcomputads, which must contain, for each atomic n -arrow with codomain “ $-$,” its “fillable parent,” the atomic $n + 1$ -arrow with codomain “ $+$ ” obtained by whiskering with \underline{u} and the “precomposing” with $\underline{\eta}$.

In §8.3 we then use this filtration to prove that any adjunction in an ∞ -cosmos — or more precisely any diagram indexed by a parental subcomputad — extends to a homotopy coherent adjunction. Our proof is essentially constructive, enumerating the choices necessary to make each stage of the extension. In §8.4, we give precise characterizations of the homotopical uniqueness of such extensions, proving that the appropriate spaces of extensions are contractible Kan complexes. Via the 2-categorical self-duality of $\mathcal{A}dj$ described in Remark 8.2.12, there is a dual proof that instead exploits the universal property of the counit, the main steps of which are alluded to in the exercises.

Our proof that any adjunction extends to a homotopy coherent adjunction inductively specifies the data in the image of a homotopy coherent adjunction by choosing fillers for horns corresponding to “fillable” arrows.

8.2.1. DEFINITION. An arrow \underline{b} of $\mathcal{A}dj$ is **fillable** if

- it is non-degenerate and atomic,
- its codomain $b_0 = +$, and
- $b_i \neq b_1$ for $i > 1$.



Write $\text{Fill}_n \subset \text{Atom}_n$ for the subset of fillable n -arrows of the subset of atomic and non-degenerate n -arrows.

8.2.2. DEFINITION (distinguished faces of fillable arrows). On account of the graphical calculus, we refer to $h(\underline{b}) := b_1 - 1$, an integer in $\{0, \dots, n - 1\}$ that labels the line immediately above the position of the left-most turn-around, as the **height** of the fillable arrow \underline{b} .⁵ The fillability of \underline{b} implies that no “tautening” is required in computing the distinguished codimension-one face $\underline{b} \cdot \delta^{h(\underline{b})}$, which then is non-degenerate and has the same width as \underline{b} . Further analysis of this face differs by case:

$$\begin{array}{ccc} A & \xrightarrow{\text{bar}} & B^{\Delta_{\tau}} \\ u \downarrow & & \downarrow \text{res} \\ B & \xrightarrow{(uf)^{\bullet}} & B^{\Delta_{+}} \end{array}$$

⁴For instance, there is a commutative diagram

⁵The unique fillable 0-arrow \underline{u} behaves somewhat differently, but nonetheless it is linguistically convenient to include it among the fillable arrows.

- **case $h(\underline{b}) > 0$:** The face $\underline{b} \cdot \delta^{h(\underline{b})}$ is non-degenerate and atomic, but it is not fillable, since non-degeneracy implies that there is some $i > 1$ with $b_i = h(\underline{b})$, whence the entries of $\underline{b} \cdot \delta^{h(\underline{b})}$ at 1 and i both equal $h(\underline{b})$.
- **case $h(\underline{b}) = 0$:** The face $\underline{b} \cdot \delta^{h(\underline{b})}$ decomposes as $\underline{u} \cdot \underline{a}$, where \underline{a} is non-degenerate, atomic, has width one less than the width of \underline{b} , and has codomain $-$.

We write

$$\underline{b}^\circ := \begin{cases} \underline{b} \cdot \delta^{h(\underline{b})} & h(\underline{b}) > 0 \\ \underline{a} & h(\underline{b}) = 0. \end{cases}$$

for the non-degenerate atomic $h(\underline{b})$ th face in the positive height case and for the non-degenerate atomic factor of the 0th face \underline{ua} in the height 0 case and refer to the atomic $n - 1$ -arrow defined in either case as the **distinguished face** of the fillable arrow.

We now argue that any non-degenerate and atomic n -arrow of \mathcal{Adj} that is *not* fillable arises as the distinguished face of a unique fillable $n + 1$ -arrow in the form of the first case just described when its codomain is $+$ and in the form of the second case just described when its codomain is $-$.

8.2.3. LEMMA (identifying fillable parents).

- (i) If \underline{b} is a non-degenerate and atomic n -arrow of \mathcal{Adj} with codomain $+$ that is not fillable then it is the codimension-one face of exactly two fillable $(n + 1)$ -arrows with the same width, both of which has \underline{b} as its b_1 th face: one which has height b_1 that we refer to as its **fillable parent** and denote by \underline{b}^+ and the other which has height $b_1 - 1$.
- (ii) If \underline{a} is a non-degenerate and atomic n -arrow of \mathcal{Adj} with codomain $-$, then the composite arrow \underline{ua} is a codimension-one face of exactly one fillable $(n + 1)$ -arrow, which we call the **fillable parent** of \underline{a} and denote by \underline{a}^+ . The fillable parent \underline{a}^+ has width one greater than the width of \underline{a} , has height 0, and has \underline{ua} as its 0th face.

Together, these cases define a “fillable parent/distinguished face” bijection

$$\text{Atom}_n \setminus \text{Fill}_n \xrightleftharpoons[\text{(-)}^\circ]{\text{(-)}^+} \text{Atom}_{n+1}$$

between fillable $n + 1$ -arrows and non-degenerate atomic n -arrows which are not fillable.

PROOF. For 8.2, if \underline{b} is a non-degenerate atomic n -arrow with domain $+$ that is not fillable, then it must be the case that $b_i = b_1$ for some $i > 1$. This arrow is then a codimension-one face of the two atomic $n + 1$ -arrows that are formed by inserting an extra line into the gap labeled b_1 separate the entry b_1 from the other turn-arounds that occur in the same gap; the $n + 1$ -arrows obtained in this way will then clearly have \underline{b} as their b_1 th face. There are exactly two ways to do this, as illustrated below:

$$\underline{b} := \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} 0 \\ 1 \\ 2 \end{array} \rightsquigarrow \underline{b}^+ := \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \end{array} \quad \text{or} \quad \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \end{array}$$

For (ii), given a non-degenerate atomic n -arrow \underline{a} with codomain $-$, there is a unique way to make \underline{ua} into the face of an atomic $n + 1$ -arrow with domain $+$ whose width is only one greater: by adding

an extra line in the upper-most space above the squiggle diagram.

$$\underline{a} := \begin{array}{c} \text{---} 0 \\ \text{---} 1 \\ \text{---} 2 \\ \text{---} \end{array} \rightsquigarrow \underline{ua} := \begin{array}{c} \text{---} 0 \\ \text{---} 1 \\ \text{---} 2 \\ \text{---} \end{array} \rightsquigarrow \underline{a}^+ := \begin{array}{c} \text{---} 0 \\ \text{---} 1 \\ \text{---} 2 \\ \text{---} 3 \\ \text{---} \end{array} \quad \square$$

8.2.4. DEFINITION. A subcomputad \mathcal{A} of \mathcal{Adj} is **parental** if it contains at least one non-identity arrow and satisfies the condition:

- if \underline{c} is a non-degenerate atomic arrow in \mathcal{A} , then either it is fillable or its fillable parent \underline{c}^+ is also in \mathcal{A} .

The condition implies that any parental subcomputad $\mathcal{A} \subset \mathcal{Adj}$ contains at least one fillable arrow. The last vertex of any fillable arrow has the form \underline{ua} for some 0-arrow \underline{a} , so it follows that the 0-arrow \underline{u} is contained in any parental subcomputad.

Recall from Definition 6.1.8, that any collection of arrows S in a computad generates a minimal subcomputad \overline{S} .

8.2.5. EXAMPLE (notable parental subcomputads).

- The unique fillable 0-arrow \underline{u} generates the **minimal parental subcomputad** $\overline{\{\underline{u}\}} \subset \mathcal{Adj}$ containing only \underline{u} and its degenerate copies.
- The unit 1-arrow $\underline{\eta}$ is fillable and the subcomputad $\overline{\{\underline{\eta}\}} \subset \mathcal{Adj}$ it generates has \underline{u} , \underline{f} , and $\underline{\eta}$ as its only non-degenerate atomic arrows. Of these, \underline{u} and $\underline{\eta}$ are parental and $\underline{\eta}$ is the fillable parent of \underline{f} , so this subcomputad is parental.
- The triangle identity witness $\underline{\beta}$ of Example 8.1.11 is fillable and the subcomputad $\overline{\{\underline{\beta}\}} \subset \mathcal{Adj}$ it generates has \underline{u} , \underline{f} , $\underline{\eta}$, $\underline{\epsilon}$, and $\underline{\beta}$ as its only non-degenerate atomic arrows. Since $\underline{\beta}$ is the fillable parent of $\underline{\epsilon}$, this subcomputad is parental.
- The pair of fillable 3-arrows

$$\underline{\omega} := \begin{array}{c} \text{---} \text{---} \text{---} \\ \text{---} \text{---} \text{---} \\ \text{---} \text{---} \text{---} \\ \text{---} \end{array} \quad \text{and} \quad \underline{\tau} := \begin{array}{c} \text{---} \text{---} \text{---} \\ \text{---} \text{---} \text{---} \\ \text{---} \text{---} \text{---} \\ \text{---} \end{array}$$

generate a subcomputad $\overline{\{\underline{\omega}, \underline{\tau}\}} \subset \mathcal{Adj}$ that has \underline{u} , \underline{f} , $\underline{\eta}$, $\underline{\epsilon}$, both triangle identity witnesses $\underline{\beta}$ and $\underline{\alpha}$ of Example 8.1.11, and $\underline{v} := \underline{\omega} \cdot \delta^1 = \underline{\tau} \cdot \delta^1$ as its only non-degenerate atomic arrows. Since $\underline{\omega}$ is the fillable parent of $\underline{\alpha}$ and $\underline{\tau}$ is the fillable parent of

$$\underline{v} := \begin{array}{c} \text{---} \text{---} \text{---} \\ \text{---} \text{---} \text{---} \\ \text{---} \text{---} \text{---} \\ \text{---} \end{array}$$

this subcomputad is parental.

- \mathcal{Adj} is trivially a parental subcomputad of itself.

8.2.6. NON-EXAMPLE.

- The subcomputad $\overline{\{\underline{\epsilon}\}}$ has \underline{u} , \underline{f} , and $\underline{\epsilon}$ as its only non-degenerate atomic arrows. Since both \underline{f} and $\underline{\epsilon}$ are missing their fillable parents, this subcomputad is not parental.

- The subcomputad $\overline{\{\underline{\eta}, \underline{\epsilon}\}}$ that has \underline{u} , \underline{f} , $\underline{\eta}$, and $\underline{\epsilon}$ as its only non-degenerate atomic arrows still fails to be parental since the fillable parent of $\underline{\epsilon}$ is missing.
- The subcomputad $\overline{\{\underline{\beta}, \underline{\alpha}\}}$ that has \underline{u} , \underline{f} , $\underline{\eta}$, $\underline{\epsilon}$, and both triangle identity witnesses $\underline{\beta}$ and $\underline{\alpha}$ as its atomic non-degenerate arrows is not parental since the fillable parent $\underline{\omega}$ of $\underline{\alpha}$ is missing.

These examples establish a chain of parental subcomputad inclusions

$$\overline{\{\underline{u}\}} \subset \overline{\{\underline{\eta}\}} \subset \overline{\{\underline{\beta}\}} \subset \overline{\{\underline{\omega}, \underline{\tau}\}} \subset \mathcal{Adj}.$$

Our aim in the remainder of this section is to filter a general parental subcomputad inclusion $\mathcal{A} \subset \mathcal{A}'$ as a countable tower of parental subcomputad inclusions, with each sequential inclusion presented as the pushout of an explicit simplicial subcomputad inclusion. The subcomputad inclusions $2[\Lambda^k[n]] \hookrightarrow 2[\Delta[n]]$ from Example 6.1.5 will feature, where $\Lambda^k[n]$ is an inner horn. A second family of inclusions will also be needed, which we now introduce.

8.2.7. DEFINITION. For any simplicial set U , let $\mathfrak{Z}[U]$ denote the simplicial category whose three non-trivial homs are displayed in the following cartoon:

$$\begin{array}{ccc} & - & \\ U \nearrow & & \searrow \mathbb{1} \\ \tau & \xrightarrow{\mathbb{1} \star U} & + \end{array}$$

That is $\mathfrak{Z}[U]$ has objects “ τ ”, “ $-$ ”, and “ $+$ ” and non-trivial hom-sets

$$\mathfrak{Z}[U](\tau, -) := U, \quad \mathfrak{Z}[U](-, +) := \mathbb{1}, \quad \mathfrak{Z}[U](\tau, +) := \mathbb{1} \star U,$$

and whose only non-trivial composition operation is defined by the canonical inclusion

$$\begin{array}{ccc} \mathfrak{Z}[U](-, +) \times \mathfrak{Z}[U](\tau, -) & \hookrightarrow & \mathfrak{Z}[U](\tau, +) \\ \Downarrow & & \Downarrow \\ U & \hookrightarrow & \mathbb{1} \star U \end{array}$$

Here we define the endo hom-spaces to contain only the respective identities and the remaining hom-spaces to be empty.

8.2.8. LEMMA. A simplicial functor $\mathfrak{Z}[U] \rightarrow \mathcal{K}$ is uniquely determined by the data:

- a pair of 0-arrows $u: A \rightarrow B$ and $b: X \rightarrow B$
- a cone with summit U over the cospan

$$\begin{array}{ccc} U & \dashrightarrow & {}^b/\mathrm{Fun}(X, B) \\ \downarrow & & \downarrow \pi \\ \mathrm{Fun}(X, A) & \xrightarrow{u_*} & \mathrm{Fun}(X, B) \end{array}$$

or equivalently a map $U \rightarrow {}^b/u_*$ whose codomain is its pullback.

PROOF. The objects X , A , and B are the images of τ , $-$, and $+$ respectively. The map $u: A \rightarrow B$ is the image of the unique 0-arrow from $-$ to $+$. Simplicial functoriality then demands the specification

of the vertical maps below making the square commute

$$\begin{array}{ccc} U & \xrightarrow{\quad} & \mathbb{1} \star U \\ \downarrow & & \downarrow \\ \text{Fun}(X, A) & \xrightarrow{u_*} & \text{Fun}(X, B) \end{array}$$

By the join \dashv slice adjunction of Proposition 4.2.5, the simplicial map $\mathbb{1} \star U \rightarrow \text{Fun}(X, B)$ may be defined by specifying a 0-arrow $b: X \rightarrow B$, the image of the cone point of $\mathbb{1} \star U$, together with a map $U \rightarrow {}^b\text{Fun}(X, B)$. Now the above commutative square transposes to the one of the statement. \square

Similarly a simplicial functor $2[U] \rightarrow \mathcal{K}$ is uniquely determined by the data $U \rightarrow \text{Fun}(X, A)$ of a simplicial map valued in one of the functor spaces of \mathcal{K} . In particular, simplicial functors $2[\Delta[n]] \rightarrow \mathcal{K}$ correspond to n -arrows in \mathcal{K} . \square

8.2.9. NOTATION.

- For each fillable n -arrow \underline{b} of positive height, let $F_{\underline{b}}: 2[\Delta[n]] \rightarrow \mathcal{Adj}$ be the simplicial functor classified by the n -arrow \underline{b} of \mathcal{Adj} .
- For each fillable n -arrow \underline{b} of height 0, let $F_{\underline{b}}: 3[\Delta[n-1]] \rightarrow \mathcal{Adj}$ be the simplicial functor defined on objects by $- \mapsto -, + \mapsto +$, and $\top \mapsto b_{w(\underline{b})}$, the domain of \underline{b} , and on the three non-trivial homs by

$$3[\Delta[n-1]](\top, -) \cong \Delta[n-1] \xrightarrow{\underline{b}^\circ} \mathcal{Adj}(b_{w(\underline{b})}, -) \quad 3[\Delta[n-1]](-, +) \cong \Delta[0] \xrightarrow{u} \mathcal{Adj}(-, +)$$

$$3[\Delta[n-1]](\top, +) \cong \Delta[n] \xrightarrow{\underline{b}} \mathcal{Adj}(b_{w(\underline{b})}, +)$$

8.2.10. LEMMA (extending parental subcomputads). *Suppose $\mathcal{A} \subset \mathcal{Adj}$ is a parental subcomputad and \underline{b} is a fillable n -arrow of height k that is not a member of \mathcal{A} but whose faces $\underline{b} \cdot \delta^i$ are in \mathcal{A} for all $i \neq k$. Then the subcomputad $\mathcal{A}' := \overline{\{\mathcal{A}, \underline{b}\}}$ generated by \mathcal{A} and \underline{b} is defined by the pushout on the left below in the case $k > 0$ and on the right below in the case $k = 0$*

$$\begin{array}{ccc} 2[\Lambda^k[n]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A} \\ \downarrow & \lrcorner & \downarrow \\ 2[\Delta[n]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A}' \end{array} \quad \begin{array}{ccc} 3[\partial\Delta[n-1]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A} \\ \downarrow & \lrcorner & \downarrow \\ 3[\Delta[n-1]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A}' \end{array}$$

and in both cases \mathcal{A}' is again a parental subcomputad.

PROOF. Because \underline{b} is the fillable parent of its distinguished face \underline{b}° , this non-degenerate, atomic, non-fillable $(n-1)$ -arrow cannot be a member of the parental subcomputad \mathcal{A} . Since the other faces of \underline{b} are assumed to belong to \mathcal{A} , \underline{b} and \underline{b}° are the only two atomic arrows that are in \mathcal{A}' but not in \mathcal{A} . Since the first is fillable and the second has the first as its fillable parent, it is clear that the subcomputad \mathcal{A}' is again parental.

To verify the claimed pushouts, we consider what is required to extend a simplicial functor $F: \mathcal{A} \rightarrow \mathcal{K}$ to a simplicial functor $F: \mathcal{A}' \rightarrow \mathcal{K}$. In the positive height case, all that is needed for such an extension is an n -arrow f in \mathcal{K} with the property that $f \cdot \delta^i = F(\underline{b} \cdot \delta^i)$ for all $i \neq k$, which may be specified

by a simplicial functor $f: 2[\Delta[n]] \rightarrow \mathcal{K}$ that makes the following square commute:

$$\begin{array}{ccc} 2[\Lambda^k[n]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A} \\ \downarrow & & \downarrow F \\ 2[\Delta[n]] & \dashrightarrow_f & \mathcal{K} \end{array}$$

If the height of \underline{b} is zero, then both its 0th face $\underline{b} \cdot \delta^0 = \underline{u} \cdot \underline{a}$ and its atomic non-degenerate factor \underline{a} are missing from \mathcal{A} . So to extend a simplicial functor $F: \mathcal{A} \rightarrow \mathcal{K}$ to a simplicial functor $F: \mathcal{A}' \rightarrow \mathcal{K}$ requires an $(n-1)$ arrow g and an n -arrow f in \mathcal{K} so that $g \cdot \delta^i = F(\underline{a} \cdot \delta^i)$ for all $i \in [n-1]$ and $f \cdot \delta^i = F(\underline{b} \cdot \delta^i)$ for all $i \neq 0 \in [n]$, so that $f \cdot \delta^0 = F\underline{u} \cdot g$. By Lemma 8.2.8 this data may be specified by a simplicial functor $f: 3[\Delta[n-1]] \rightarrow \mathcal{K}$ that makes the following square commute:

$$\begin{array}{ccc} 3[\partial\Delta[n-1]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A} \\ \downarrow & & \downarrow F \\ 3[\Delta[n-1]] & \dashrightarrow_f & \mathcal{K} \end{array}$$

□

8.2.11. PROPOSITION. Any inclusion $\mathcal{A} \hookrightarrow \mathcal{A}'$ of parental subcomputads of \mathcal{Adj} may be filtered as a countable tower of parental subcomputad inclusions

$$\mathcal{A} = \mathcal{A}_0 \hookrightarrow \mathcal{A}_1 \hookrightarrow \dots \hookrightarrow \bigcup_{i \geq 0} \mathcal{A}_i = \mathcal{A}'$$

in such a way that for each $i \geq 1$ there is a finite non-empty set S_i of fillable arrows that are not themselves contained in but which have all faces except the distinguished one contained in \mathcal{A}_{i-1} so that the parental subcomputad \mathcal{A}_i is generated by $\mathcal{A}_{i-1} \cup S_i$. Hence, the inclusion $\mathcal{A} \hookrightarrow \mathcal{A}'$ may be expressed as a countable composite of inclusions which are constructed by pushouts of the form

$$\begin{array}{ccc} \left(\coprod_{\substack{\underline{b} \in S_i \\ h(\underline{b}) > 0}} 2[\Lambda^{h(\underline{b})}[\dim(\underline{b})]] \right) \sqcup \left(\coprod_{\substack{\underline{b} \in S_i \\ h(\underline{b}) = 0}} 3[\partial\Delta[\dim(\underline{b})]] \right) & \xrightarrow{\langle F_{\underline{b}} \rangle_{\underline{b} \in S_i}} & \mathcal{A}_{i-1} \\ \downarrow & & \downarrow \\ \left(\coprod_{\substack{\underline{b} \in S_i \\ h(\underline{b}) > 0}} 2[\Delta[\dim(\underline{b})]] \right) \sqcup \left(\coprod_{\substack{\underline{b} \in S_i \\ h(\underline{b}) = 0}} 3[\Delta[\dim(\underline{b})]] \right) & \xrightarrow[\langle F_{\underline{b}} \rangle_{\underline{b} \in S_i}]{r} & \mathcal{A}_i \end{array}$$

PROOF. Let S denote the set of fillable arrows in \mathcal{A}' which are not in \mathcal{A} and let $S_{w,n,k}$ denote the subset of arrows with width w , dimension n , and height k . Note that any non-degenerate arrow of \mathcal{Adj} must have dimension strictly less than its width, and there are only finitely many non-degenerate arrows of any given width. The height is strictly less than the dimension so each set $S_{w,n,k}$ is finite and if non-empty we must have $k < n < w$. Now we order the triples (w,n,k) that index non-empty subsets of fillable arrows lexicographically by increasing width, increasing dimension, and decreasing height and let $S_i := S_{w_i, n_i, k_i}$ denote subset of fillable arrows in the i th triple in this ordering for $i \geq 1$.

Let \mathcal{A}_i be the subcomputad of \mathcal{Adj} generated by $\mathcal{A} \cup (\bigcup_{j=1}^i S_i)$. By construction this family filters the inclusion of \mathcal{A} into $\mathcal{A}' = \mathcal{A} \cup (\bigcup_i S_i)$.

We complete the proof by induction on the index starting from the parental subcomputad $\mathcal{A}_0 = \mathcal{A}$. For the inductive step, we must verify that all but the distinguished face of each $\underline{b} \in S_i := S_{w_i, n_i, k_i}$ lie in \mathcal{A}_{i-1} . By iterating Lemma 8.2.10, it will follow that \mathcal{A}_i is again parental.

By construction \mathcal{A}_{i-1} is the smallest subcomputad of \mathcal{Adj} which contains \mathcal{A} and all of the fillable arrows of \mathcal{A}' which have:

- width less than w_i or
- width w_i and dimension less than n_i or
- width w_i , dimension n_i , and height greater than k_i .

Each fillable arrow $\underline{b} \in S_i$ has width w_i , dimension n_i , and height k_i . We must show that its faces $\underline{b} \cdot \delta^j$ lie in \mathcal{A}_{i-1} for each $j \neq k_i$, which we verify by a tedious but straightforward case analysis.

case $j \neq k_i + 1$: If $j \neq k_i + 1$ then since $j \neq k_i$ the line numbered j is not one of the ones separating the gap b_1 from the other entries of \underline{b} , which means that this entry will not be eliminated when computing the j th face. Consider the unique factorization

$$\underline{b} \cdot \delta^j = (\underline{b}^1 \cdot \alpha_1) \circ \cdots \circ (\underline{b}^r \cdot \alpha_r)$$

of the face $\underline{b} \cdot \delta^j$ into non-degenerate and atomic arrows of \mathcal{A}' acted upon by degeneracy operators. By the analysis just given, \underline{b}^1 is fillable with width at most w_i , height k_i or $k_i - 1$ depending on whether $j > k_i + 1$ or $j < k_i$, and dimension less than n_i . Thus \underline{b}^1 is contained in \mathcal{A}_{i-1} by the hypothesis that this subcomputad contains all fillable arrows of width at most w_i and dimension less than n_i . Since b_1 has width at least 2, the other atomic factors have width less than or equal to $w_i - 2$. Thus each of these is either a fillable arrow with width at most $w_i - 2$, which means that it is in \mathcal{A}_{i-1} , or its fillable parent in \mathcal{A}' has width at most $w_i - 1$, which means that this fillable parent is also in \mathcal{A}_{i-1} . As $\underline{b} \cdot \delta^j$ is a composite of degenerate images of arrows in \mathcal{A}_{i-1} it too lies in \mathcal{A}_{i-1} .

case $j = k_i + 1$: Since $\underline{b} \notin \mathcal{A}_{i-1}$ and all parental subcomputads contain the unique fillable 0-arrow \underline{u} , we know that $\underline{b} \neq \underline{u}$ and so has width at least 2 and dimension at least 1. The only fillable arrow of width 2 is $\underline{\eta}$ which has depth 0 and face $\underline{\eta} \cdot \delta^1 = \text{id}_+$, which certainly lies in \mathcal{A}_{i-1} , so we can safely assume that the width of \underline{b} is at least 3 which forces the height k_i to be at most $n_i - 2$; otherwise \underline{b} would not be atomic. Thus j is at most $n_i - 1$, which tells us that $\underline{b} \cdot \delta^j$ is again atomic. Now we have two subcases:

- **case $b_2 = b_1 + 1$:** In this case, the line $j = k_1 + 1 = b_1$ separates the gaps b_1 and b_2 , so the face $\underline{b} \cdot \delta^j$ will have width at least two less than the width of \underline{b} . This face may also be degenerate but in any case the fillable parent of the non-degenerate arrow that it represents has width less than w_i and so this face is present in \mathcal{A}_{i-1} .
- **case $b_2 > b_1 + 1$:** In this case, the line $j = k_1 + 1 = b_1$ separates the gap b_1 from the gap immediately below it, which contains neither b_0 nor b_2 . So the face $\underline{b} \cdot \delta^j$ has width w_i and is non-degenerate. Because \underline{b} is non-degenerate, there is some $s > 2$ so that $b_s = b_1 + 1$, so $\underline{b} \cdot \delta^j$ is not fillable. Now Lemma 8.2.3 tells us that its fillable parent has width w_i , dimension n_i , and height $k_i + 1$. Thus, this fillable parent lies in \mathcal{A}_{i-1} by our hypothesis that \mathcal{A}_{i-1} contains all fillable arrows of \mathcal{A}' of width w_i , dimension n_i , and height greater than k_i , so $\underline{b} \cdot \delta^j$ must also be in there, as desired.

□

8.2.12. REMARK (a dual form). In the 2-category $\mathcal{A}dj^{\text{co}}$, the 0-arrow \underline{u} is left adjoint to the 0-arrow \underline{f} , with unit $\underline{\epsilon}$ and counit $\underline{\eta}$. The 2-functor $\mathcal{A}dj \rightarrow \mathcal{A}dj^{\text{co}}$ that classifies this adjunction is an isomorphism. Via this duality, we could have introduced a variant notion of “fillable n -arrow” (a subset of those n -arrows with codomain $-$) and “parental subcomputad” of $\mathcal{A}dj$ so that every parental subcomputad contained the 0-arrow \underline{f} . Dualizing the argument of Example 8.2.5, the subcomputads $\overline{\{f\}} \subset \overline{\{\epsilon\}} \subset \overline{\{\alpha\}}$ would all be parental, but the subcomputads of Example 8.2.5 would no longer be so.

Exercises.

8.2.i. EXERCISE. Give a graphical description of the dual fillable n -arrows discussed in Remark 8.2.12.

8.3. Building homotopy coherent adjunctions

We now employ Proposition 8.2.11 to prove that every adjunction in an ∞ -cosmos \mathcal{K} extends to a homotopy coherent adjunction $\mathcal{A}dj \rightarrow \mathcal{K}$ which carries the canonical adjunction in $\mathcal{A}dj$ to the chosen adjunction in \mathcal{K} . The data used to present an adjunction in a quasi-categorically enriched category \mathcal{K} in the sense of Definition 2.1.1 — a pair of ∞ -categories A and B , a pair of 0-arrows $u \in \text{Fun}(A, B)$ and $f \in \text{Fun}(B, A)$, a pair of 1-arrows $\eta: \text{id}_B \rightarrow uf \in \text{Fun}(B, B)$ and $\epsilon: fu \rightarrow \text{id}_A \in \text{Fun}(A, A)$, and witnesses to the triangle equalities given by a pair of 2-arrows

$$\begin{array}{ccc} & ufu & \\ \eta u \nearrow & \beta & \searrow u\epsilon \\ u & \xlongequal{\quad} & u \end{array} \in \text{Fun}(A, B) \qquad \begin{array}{ccc} & fuf & \\ f\eta \nearrow & \alpha & \searrow \epsilon f \\ f & \xlongequal{\quad} & f \end{array} \in \text{Fun}(B, A)$$

— determines a simplicial functor $T: \overline{\{\beta, \alpha\}} \rightarrow \mathcal{K}$ whose domain is the subcomputad of $\mathcal{A}dj$ generated by the triangle identity 2-arrows. This functor then is defined by mapping $-$ to A and $+$ to B and acting on the non-degenerate and atomic arrows in the way suggested by their syntax: $T(\underline{u}) := u$, $T(\underline{f}) := f$, $T(\underline{\eta}) := \eta$, $T(\underline{\epsilon}) := \epsilon$, $T(\underline{\beta}) := \beta$, and $T(\underline{\alpha}) := \alpha$. In Theorem 8.3.4, we prove that it is always possible to extend the data $(f \dashv u, \eta, \epsilon)$ to a homotopy coherent adjunction $\mathcal{A}dj \rightarrow \mathcal{K}$, but unless β and α satisfy a coherence condition that will be described, doing so might require making a different choice for one of these triangle equality witnesses.

By Proposition 8.2.11, extensions along parental subcomputad inclusions may be built inductively from two types of extension problem, one of which involves attaching fillable arrows with positive height and the other of which involves attaching fillable arrows of height zero. We prove that both simplicial subcomputad extension problems can be solved relatively against any simplicial functor $P: \mathcal{K} \rightarrow \mathcal{L}$ between quasi-categorically enriched categories that defines a “local isofibration,” meaning that the action of P on functor spaces is by isofibrations. This relative lifting result will be used in the proof of the homotopical uniqueness of such extensions in §8.4.

8.3.1. LEMMA. *Let $P: \mathcal{K} \rightarrow \mathcal{L}$ be a simplicial functor that defines a local isofibration of quasi-categories. Then any lifting problem against the directed suspension of an inner horn inclusion*

$$\begin{array}{ccc} 2[\Lambda^k[n]] & \longrightarrow & \mathcal{K} \\ \downarrow & \nearrow \text{dashed} & \downarrow P \\ 2[\Delta[n]] & \longrightarrow & \mathcal{L} \end{array}$$

has a solution.

PROOF. The lifting problem of the statement is equivalent to asking for a lift of the inner horn inclusion

$$\begin{array}{ccc} \Lambda^k[n] & \longrightarrow & \text{Fun}(A, B) \\ \downarrow & \nearrow & \downarrow \\ \Delta[n] & \longrightarrow & \text{Fun}(PA, PB) \end{array}$$

against the action of P on some functor spaces of \mathcal{K} and \mathcal{L} . By hypothesis this action is an isofibration of quasi-categories and so the claimed lift exists. \square

8.3.2. PROPOSITION (the relative universal property of the unit). *If \mathcal{K} has an adjunction $(f \dashv u, \eta)$, $P: \mathcal{K} \rightarrow \mathcal{L}$ is a local isofibration of quasi-categorically enriched categories, and if $T: \mathfrak{Z}[\partial\Delta[n]] \rightarrow \mathcal{K}$ is defined to carry the unique 0-arrow $- \rightarrow +$ to $u: A \rightarrow B$, the cone point of $\mathbb{1} \star \partial\Delta[n] \cong \Lambda^0[n]$ to $b: X \rightarrow B$ and the 1-arrow from 0 to 1 in $\Lambda^0[n]$ to $\eta b: b \rightarrow ufb$ for some $n \geq 1$, then any lifting problem*

$$\begin{array}{ccc} \mathfrak{Z}[\partial\Delta[n]] & \xrightarrow{T} & \mathcal{K} \\ \downarrow & \nearrow & \downarrow P \\ \mathfrak{Z}[\Delta[n]] & \longrightarrow & \mathcal{L} \end{array}$$

has a solution.

PROOF. By Lemma 8.2.8, the lifting problem of the statement translates to a lifting problem of the following form

$$\begin{array}{ccc} \partial\Delta[n] & \xrightarrow{t} & b/u_* \\ \downarrow & \nearrow & \downarrow \\ \Delta[n] & \longrightarrow & P b / P u_* \end{array}$$

where the upper horizontal map carries the initial vertex $0 \in \partial\Delta[n]$ to the object $\eta b \in b/u_*$, which is initial in there by Proposition 4.1.4 applied to the adjunction between functor spaces

$$\begin{array}{ccc} & f_* & \\ \text{Fun}(X, B) & \xrightarrow{\quad} & \text{Fun}(X, A) \\ & u_* & \end{array}$$

and Appendix C, which proves that Joyal's slices are fibered equivalent to comma quasi-categories. The right-hand vertical is an isofibration that preserves this initial element, since it carries it to a component of the unit for the adjunction $(Pf \dashv Pu, P\eta)$ in \mathcal{L} . Lemma ?? proven in Appendix F now proves that the desired lift exists. \square

Our theorems about extensions to homotopy coherent adjunctions will follow as special cases of the following relative extension and lifting result for parental subcomputads containing the unit of an adjunction.

8.3.3. THEOREM. *Suppose $\overline{\{\eta\}} \subset \mathcal{A} \subset \mathcal{A}' \subset \mathcal{A}dj$ are parental subcomputads. Then if $P: \mathcal{K} \rightarrow \mathcal{L}$ is a local isofibration between quasi-categorically enriched categories and if \mathcal{K} has an adjunction $(f \dashv u, \eta)$ then*

we may solve any lifting problem

$$\begin{array}{ccc} \mathcal{A} & \xrightarrow{T} & \mathcal{K} \\ \downarrow & \nearrow & \downarrow P \\ \mathcal{A}' & \longrightarrow & \mathcal{L} \end{array}$$

so long as $T(\underline{f}) = f$, $T(\underline{u}) = u$, and $T(\underline{\eta}) = \eta$.

PROOF. By Proposition 8.2.11 the inclusion $\mathcal{A} \hookrightarrow \mathcal{A}'$ can be filled as a sequential composite of pushouts of coproducts of maps of two basic forms, so it suffices to demonstrate that we may solve lifting problems of the following two forms

$$\begin{array}{ccc} 2[\Lambda^k[n]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A} \xrightarrow{T} \mathcal{K} \\ \downarrow & \nearrow \tau & \downarrow P \\ 2[\Delta[n]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A}' \longrightarrow \mathcal{L} \end{array} \qquad \begin{array}{ccc} 3[\partial\Delta[n-1]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A} \xrightarrow{T} \mathcal{K} \\ \downarrow & \nearrow \tau & \downarrow P \\ 3[\Delta[n-1]] & \xrightarrow{F_{\underline{b}}} & \mathcal{A}' \longrightarrow \mathcal{L} \end{array}$$

for some fillable n -arrow $\underline{b} \in \mathcal{Adj}$, of positive height in the left-hand case and of height zero in the right-hand case. In the case of the left-hand lifting problem, such lifts exist immediately from Lemma 8.3.1.

In the case of the right-hand lifting problem, we must verify that the hypotheses of Proposition 8.3.2 are satisfied, which amounts to verifying that for any fillable n -arrow \underline{b} of height zero, the functor $F_{\underline{b}}: 3[\Delta[n-1]] \rightarrow \mathcal{Adj}$ defined in Notation 8.2.9 in relevant part by the map

$$3[\Delta[n-1]](\top, +) \cong \Delta[n] \xrightarrow{\underline{b}} \mathcal{Adj}(b_{w(\underline{b})}, +)$$

carries the 1-arrow from 0 to 1 in $\Delta[n]$ to a component of the unit in $\mathcal{A} \subset \mathcal{Adj}$. This is easily verified using the graphical calculus. The image of the 1-arrow from 0 to 1 under the map $\underline{b}: \Delta[n] \rightarrow \mathcal{Adj}(b_{w(\underline{b})}, +)$ is simply the initial edge of \underline{b} , which may be computed by removing all of the other lines from the strictly undulating squiggle diagram. By the specifications of a fillable arrow with height 0, there are only two possibilities, depending on whether the domain of \underline{b} is $+$ or $-$, as illustrated by the following diagrams:

$$\begin{array}{ccc} \underline{b} := \int_0^4 & \rightsquigarrow & \underline{b}^{\delta^{0,1}} := \int_1^0 = \int_1^0 \\ \underline{b} := \int_0^4 & \rightsquigarrow & \underline{b}^{\delta^{0,1}} := \int_1^0 = \int_1^0 \end{array}$$

Thus we see that $\underline{b} \cdot \delta^{0,1} = \underline{\eta}u$ or $\underline{b} \cdot \delta^{0,1} = \underline{\eta}$, both of which satisfy the conditions required for Proposition 8.3.2 to provide the desired lift. \square

8.3.4. THEOREM (homotopy coherent adjunctions). If \mathcal{K} is a quasi-categorically enriched category containing an adjunction $(f \dashv u, \eta, \epsilon, \beta, \alpha)$:

- (i) There exists a simplicial functor $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ for which $\mathbb{A}(u) = u$, $\mathbb{A}(f) = f$, and $\mathbb{A}(\eta) = \eta$.
- (ii) There exists a simplicial functor $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ for which $\mathbb{A}(u) = u$, $\mathbb{A}(f) = f$, $\mathbb{A}(\eta) = \eta$, $\mathbb{A}(\epsilon) = \epsilon$, and $\mathbb{A}(\beta) = \beta$.
- (iii) If there exist a pair of 3-arrows ω and τ in \mathcal{K}

$$\omega := \text{id}_B \quad \begin{array}{ccc} & \nearrow \eta & \\ & \downarrow \eta & \\ & \searrow \eta \cdot \eta & \\ & \downarrow u f \eta & \\ & \searrow u \epsilon f & \\ & \downarrow u f u f & \end{array} \quad \begin{array}{ccc} & \nearrow \eta & \\ & \downarrow \eta & \\ & \searrow \eta \cdot \eta & \\ & \downarrow u f \eta & \\ & \searrow u \epsilon f & \\ & \downarrow u f u f & \end{array}$$

$$\tau := \text{id}_B \quad \begin{array}{ccc} & \nearrow \eta & \\ & \downarrow \eta & \\ & \searrow \eta \cdot \eta & \\ & \downarrow \eta u f & \\ & \searrow u \epsilon f & \\ & \downarrow u f u f & \end{array} \quad \begin{array}{ccc} & \nearrow \eta & \\ & \downarrow \eta & \\ & \searrow \eta \cdot \eta & \\ & \downarrow \eta u f & \\ & \searrow u \epsilon f & \\ & \downarrow u f u f & \end{array}$$

witnessing the coherence relations $\omega \delta^0 = u \alpha$, $\tau \delta^0 = \beta f$, $\omega \delta^1 = \tau \delta^1$, $\omega \delta^2 = \tau \delta^2 = \eta \sigma^1$, with the 3rd faces of these simplices defined by the pair of 2-arrows given by the horizontal composite

$$\Delta[1] \times \Delta[1] \xrightarrow{\eta \times \eta} \text{Fun}(B, B) \times \text{Fun}(B, B) \xrightarrow{\circ} \text{Fun}(B, B)$$

then there exists a simplicial functor $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ for which $\mathbb{A}(u) = u$, $\mathbb{A}(f) = f$, $\mathbb{A}(\eta) = \eta$, $\mathbb{A}(\epsilon) = \epsilon$, $\mathbb{A}(\beta) = \beta$, $\mathbb{A}(\alpha) = \alpha$, $\mathbb{A}(\omega) = \omega$, and $\mathbb{A}(\tau) = \tau$.

Coherence conditions of the form stated in ((iii)) appear in the definition of a biadjoint pair in a strongly bicategorically enriched category in [62, 1.3.8].

Exercises.

8.3.i. EXERCISE. Unpack Proposition 8.3.2 in the case $n = 1$ and $n = 2$.

8.3.ii. EXERCISE. Use Remark 8.2.12 to formulate the dual of Theorem 8.3.4, describing homotopy coherent adjunctions generated by a given counit.

8.4. Homotopical uniqueness of homotopy coherent adjunctions

The homotopy 2-category of an ∞ -cosmos can be regarded as a simplicial category of the form described in Lemma 8.1.3, in which context it is equipped with a canonical quotient functor $Q: \mathcal{K} \rightarrow \mathfrak{h}\mathcal{K}$ of simplicial categories. Formally, Q is a component of the counit of the adjunction described in Digression 1.4.2. It follows easily from the characterization of 2-categories in Lemma 8.1.3 that Q is a local isofibration.

By Proposition 8.1.13, any adjunction in the homotopy 2-category of an ∞ -cosmos is represented by a unique simplicial functor $T: \mathcal{A}dj \rightarrow \mathfrak{h}\mathcal{K}$. To say that a homotopy coherent adjunction $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ lifts the adjunction in the homotopy 2-category means that \mathbb{A} is a lift of T along Q . Theorem 8.3.4 proves that a lift of any adjunction in the homotopy 2-category $\mathfrak{h}\mathcal{K}$ can be constructed by specifying a lift $T: \underline{\beta} \rightarrow \mathcal{K}$ of $T: \mathcal{A}dj \rightarrow \mathfrak{h}\mathcal{K}$ — this amounting to a choice of 1-arrows representing the unit

and counit and a 2-arrow witnessing one of the triangle equalities — and then extending along the parental subcomputad inclusion to define the homotopy coherent adjunction \mathbb{A} .

$$\begin{array}{ccc} \overline{\{\beta\}} & \xrightarrow{T} & \mathcal{K} \\ \downarrow & \nearrow \mathbb{A} & \downarrow Q \\ \mathcal{A}dj & \xrightarrow{T} & \mathfrak{h}\mathcal{K} \end{array}$$

Note that the commutativity of the top left triangle implies the commutativity of the bottom right one, so instead of thinking of \mathbb{A} as a *lift* of $T: \mathcal{A}dj \rightarrow \mathfrak{h}\mathcal{K}$ to a homotopy coherent adjunction, we can equally think of \mathbb{A} as an *extension* of $T: \overline{\{\beta\}} \rightarrow \mathcal{K}$ to a homotopy coherent adjunction.

In this section, we will define the space of extensions of given adjunction data to a homotopy coherent adjunction. Our main theorem in this section is that if the base diagram to be extended is indexed by a parental subcomputad, then the space of lifts is a contractible Kan complex.

The first step is to construct a (possibly large) simplicial hom-space between two simplicial categories.

8.4.1. DEFINITION. Define the cotensor \mathcal{L}^U of a simplicial category \mathcal{L} with a simplicial set U to be the simplicial category with $\text{obj } \mathcal{L}^U := \text{obj } \mathcal{L}$ and hom-spaces

$$\mathcal{L}^U(X, Y) := \mathcal{L}(X, Y)^U.$$

Any simplicial set U defines a comonoid $(U, !: U \rightarrow \mathbb{1}, \Delta: U \rightarrow U \times U)$ with respect to the cartesian product and diagonal maps, so the endofunctor $(-)^U: \mathcal{S}Set\text{-}Cat \rightarrow \mathcal{S}Set\text{-}Cat$ is a monad whose unit and multiplication are defined by restricting along these maps.

For simplicial categories \mathcal{K} and \mathcal{L} , let $\text{lcon}(\mathcal{K}, \mathcal{L})$ denote the large simplicial sets defined by the natural isomorphism

$$\text{lcon}(\mathcal{K}, \mathcal{L})^U \cong \text{lcon}(\mathcal{K}, \mathcal{L}^U) \quad \text{i.e.,} \quad \text{lcon}(\mathcal{K}, \mathcal{L})_n := \text{lcon}(\mathcal{K}, \mathcal{L}^{\Delta[n]}).$$

The composition map

$$\text{lcon}(\mathcal{L}, \mathcal{M}) \times \text{lcon}(\mathcal{K}, \mathcal{L}) \xrightarrow{\circ} \text{lcon}(\mathcal{K}, \mathcal{M})$$

is given by defining the composite of a pair of n -arrows $F: \mathcal{K} \rightarrow \mathcal{L}^{\Delta[n]}$ and $G: \mathcal{L} \rightarrow \mathcal{M}^{\Delta[n]}$ to be the Kleisli composite n -arrow

$$\mathcal{K} \xrightarrow{F} \mathcal{L}^{\Delta[n]} \xrightarrow{G^{\Delta[n]}} (\mathcal{M}^{\Delta[n]})^{\Delta[n]} \cong \mathcal{M}^{\Delta[n] \times \Delta[n]} \xrightarrow{\Delta^*} \mathcal{M}^{\Delta[n]}$$

8.4.2. REMARK. The vertices of $\text{lcon}(\mathcal{K}, \mathcal{L})$ are simplicial functors $\mathcal{K} \rightarrow \mathcal{L}$. The name “icon” is chosen because the 1-simplices are analogous to the “identity component oplax natural transformations” in 2-category theory as defined by Lack [34]. In particular, each 1-simplex $\mathcal{K} \rightarrow \mathcal{L}^{\Delta[1]}$ or n -simplex $\mathcal{K} \rightarrow \mathcal{L}^{\Delta[n]}$ spans simplicial functors $\mathcal{K} \rightarrow \mathcal{L}$ that agree on objects.

8.4.3. LEMMA. If $P: \mathcal{K} \twoheadrightarrow \mathcal{L}$ is a local isofibration between quasi-categorically enriched categories and $I: \mathcal{A} \hookrightarrow \mathcal{B}$ is a simplicial subcomputad inclusion, then if either P is bijective on objects or I is injective on objects then the Leibniz map

$$\widehat{\text{lcon}}(I, P): \text{lcon}(\mathcal{B}, \mathcal{K}) \twoheadrightarrow \text{lcon}(\mathcal{A}, \mathcal{K}) \times_{\text{lcon}(\mathcal{A}, \mathcal{L})} \text{lcon}(\mathcal{B}, \mathcal{L})$$

is an isofibration between quasi-categories.

PROOF. A lifting problem of simplicial sets as below-left transposes into a lifting problem of simplicial categories below-right:

$$\begin{array}{ccc}
 U & \longrightarrow & \mathbf{Icon}(\mathcal{B}, \mathcal{K}) \\
 \downarrow i & \nearrow & \downarrow \widehat{\mathbf{Icon}(I, P)} \\
 V & \longrightarrow & \mathbf{Icon}(\mathcal{A}, \mathcal{K}) \times_{\mathbf{Icon}(\mathcal{A}, \mathcal{L})} \mathbf{Icon}(\mathcal{B}, \mathcal{L})
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathcal{A} & \longrightarrow & \mathcal{K}^V \\
 \downarrow I & \nearrow & \downarrow \{i, P\} \\
 \mathcal{B} & \longrightarrow & \mathcal{K}^U \times_{\mathcal{L}^U} \mathcal{L}^V
 \end{array}$$

When P is surjective on objects, so is the simplicial functor $\{i, P\}$ and in general the action on homs is given by the Leibniz map

$$\{i, P\}: \mathbf{Fun}(X, Y)^V \rightarrow \mathbf{Fun}(X, Y)^U \times_{\mathbf{Fun}(PX, PY)^U} \mathbf{Fun}(PX, PY)^V,$$

which is a trivial fibration whenever $U \hookrightarrow V$ is an inner horn inclusion or is the inclusion $\mathbf{1} \hookrightarrow \mathbf{I}$.

By Definition 6.1.11 to solve the right-hand lifting problem, it suffices to solve the two lifting problems

$$\begin{array}{ccc}
 \emptyset & \longrightarrow & \mathcal{K}^V \\
 \downarrow & \nearrow & \downarrow \{i, P\} \\
 \mathbf{1} & \longrightarrow & \mathcal{K}^U \times_{\mathcal{L}^U} \mathcal{L}^V
 \end{array}
 \qquad
 \begin{array}{ccc}
 2[\partial\Delta[n]] & \longrightarrow & \mathcal{K}^V \\
 \downarrow & \nearrow & \downarrow \{i, P\} \\
 2[\Delta[n]] & \longrightarrow & \mathcal{K}^U \times_{\mathcal{L}^U} \mathcal{L}^V
 \end{array}$$

where the left-hand lifting problem is not needed if I is bijective on objects. The right-hand lifting problem can be solved because $\{i, P\}$ is a local trivial fibration and the left-hand lifting problem can be solved whenever P is surjective on objects. \square

8.4.4. COROLLARY. If \mathcal{K} is a quasi-categorically enriched category, if \mathcal{A} is a simplicial computad, and if $I: \mathcal{A} \hookrightarrow \mathcal{B}$ is a simplicial subcomputad inclusion, then

$$\mathbf{Icon}(I, \mathcal{K}): \mathbf{Icon}(\mathcal{B}, \mathcal{K}) \rightarrow \mathbf{Icon}(\mathcal{A}, \mathcal{K})$$

is an isofibration between quasi-categories. \square

8.4.5. LEMMA. Suppose $P: \mathcal{K} \rightarrow \mathcal{L}$ is a simplicial functor between quasi-categories that is locally conservative in the sense that each $\mathbf{Fun}(A, B) \rightarrow \mathbf{Fun}(PA, PB)$ reflects isomorphisms. Then if \mathcal{A} is a simplicial computad and $\mathcal{A} \hookrightarrow \mathcal{B}$ is a bijective-on-objects simplicial subcomputad inclusion, then the Leibniz map

$$\widehat{\mathbf{Icon}(I, P)}: \mathbf{Icon}(\mathcal{B}, \mathcal{K}) \rightarrow \mathbf{Icon}(\mathcal{A}, \mathcal{K}) \times_{\mathbf{Icon}(\mathcal{A}, \mathcal{L})} \mathbf{Icon}(\mathcal{B}, \mathcal{L})$$

is a conservative functor of quasi-categories.

PROOF. In the language of marked simplicial sets, we must show that any lifting problem below-left has a solution

$$\begin{array}{ccc}
 2 & \longrightarrow & \mathbf{Icon}(\mathcal{B}, \mathcal{K}) \\
 \downarrow & \nearrow & \downarrow \widehat{\mathbf{Icon}(I, P)} \\
 2^\# & \longrightarrow & \mathbf{Icon}(\mathcal{A}, \mathcal{K}) \times_{\mathbf{Icon}(\mathcal{A}, \mathcal{L})} \mathbf{Icon}(\mathcal{B}, \mathcal{L})
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathcal{A} & \longrightarrow & \mathcal{K}^{2^\#} \\
 \downarrow & \nearrow & \downarrow \\
 \mathcal{B} & \longrightarrow & \mathcal{K}^2 \times_{\mathcal{L}^2} \mathcal{L}^{2^\#}
 \end{array}$$

where 2^\sharp represents invertible 1-arrows. By adjunction, this transposes to the lifting problem above-right. As in the proof of Lemma 8.4.3, it suffices to consider the case where $\mathcal{A} \hookrightarrow \mathcal{B}$ is $2[\partial[\Delta[n]]] \hookrightarrow 2[\Delta[n]]$ for some $n \geq 0$, in which case the lifting problem of simplicial categories reduces to one of simplicial sets

$$\begin{array}{ccc}
 \partial\Delta[n] & \xrightarrow{\quad} & \text{Fun}(A, B)^{2^\sharp} \\
 \downarrow & \nearrow \text{dashed} & \downarrow \\
 \Delta[n] & \xrightarrow{\quad} & \text{Fun}(A, B)^2 \times_{\text{Fun}(PA, PB)^2} \text{Fun}(PA, PB)^{2^\sharp}
 \end{array}
 \quad \rightsquigarrow \quad
 \begin{array}{ccc}
 (\partial\Delta[n] \times 2^\sharp) \cup (\Delta[n] \times 2) & \xrightarrow{\quad} & \text{Fun}(A, B) \\
 \downarrow & \nearrow \text{dashed} & \downarrow \\
 \Delta[n] \times 2^\sharp & \xrightarrow{\quad} & \text{Fun}(PA, PB)
 \end{array}$$

The marked simplicial sets on the left have the same underlying sets, differing only in their markings, so by the hypothesis that $\text{Fun}(A, B) \rightarrow \text{Fun}(PA, PB)$ is conservative, the result follows. \square

8.4.6. DEFINITION. The **space of homotopy coherent adjunctions** in a quasi-categorically enriched category \mathcal{K} is

$$\text{cohadj}(\mathcal{K}) := \text{Icon}(\mathcal{A}dj, \mathcal{K}).$$

8.4.7. PROPOSITION. *The space of homotopy coherent adjunctions in \mathcal{K} is a Kan complex, possibly a large one.*

PROOF. Since $\mathcal{A}dj$ is a simplicial computad, Corollary 8.4.4 implies that $\text{cohadj}(\mathcal{K})$ is a quasi-category. By Corollary 1.1.15, we need only show that all of its arrows are isomorphism. Since a 1-arrow in a functor space of \mathcal{K} is an isomorphism if and only if it represents an invertible 2-cell in $\mathfrak{h}\mathcal{K}$, the quotient simplicial functor $Q: \mathcal{K} \rightarrow \mathfrak{h}\mathcal{K}$ is locally conservative, and by Lemma 8.4.5, it suffices to show that $\text{cohadj}(\mathfrak{h}\mathcal{K})$ is a Kan complex.

From Proposition 8.1.13 we can extract an explicit description of $\text{cohadj}(\mathfrak{h}\mathcal{K})$ that reveals that it is actually isomorphic the nerve of a 1-category: its

- objects are adjunctions $(f \dashv u, \eta, \epsilon)$ in $\mathfrak{h}\mathcal{K}$
- arrows $(\phi, \psi): (f \dashv u, \eta, \epsilon) \rightarrow (f' \dashv u', \eta', \epsilon')$ consist of a pair of 2-cells $\phi: f \Rightarrow f'$ and $\psi: u \Rightarrow u'$ so that $\epsilon' \cdot (\phi\psi) = \epsilon$ and $\eta' = (\psi\phi) \cdot \eta$, and
- identities and composition are given componentwise.

The isomorphisms in $\text{cohadj}(\mathfrak{h}\mathcal{K})$ are those pairs (ϕ, ψ) whose components ϕ and ψ are both invertible. From the defining equations $\epsilon' \cdot (\phi\psi) = \epsilon$ and $\eta' = (\psi\phi) \cdot \eta$ it follows that the mate of ψ is an inverse to ϕ and the mate of ϕ is an inverse to ψ , so every arrow is in fact an isomorphism. \square

8.4.8. PROPOSITION (homotopical uniqueness of parental subcomputad extensions). *Suppose $\{\eta\} \subset \mathcal{A} \subset \mathcal{A}' \subset \mathcal{A}dj$ are parental subcomputads. Suppose $T: \mathcal{A} \rightarrow \mathcal{K}$ is a simplicial functor so that $T(\underline{f}) = f$, $T(\underline{u}) = u$, and $T(\underline{\eta}) = \eta$ define an adjunction in \mathcal{K} . Then the fiber of the isofibration*

$$\text{Icon}(\mathcal{A}', \mathcal{K}) \twoheadrightarrow \text{Icon}(\mathcal{A}, \mathcal{K})$$

over T is a contractible Kan complex.

PROOF. The fibers over T are those simplicial functors $T: \mathcal{A}' \rightarrow \mathcal{K}$ extending $T: \mathcal{A} \rightarrow \mathcal{K}$. By Theorem 8.3.3, this fiber is non-empty. We must show for any inclusion $U \hookrightarrow V$ of simplicial sets,

the lifting problem

$$\begin{array}{ccccc} U & \longrightarrow & E_T & \longrightarrow & \text{Icon}(\mathcal{A}', \mathcal{K}) \\ \downarrow i & \nearrow & \downarrow & \lrcorner & \downarrow \\ V & \longrightarrow & \mathbb{1} & \xrightarrow{T} & \text{Icon}(\mathcal{A}, \mathcal{K}) \end{array}$$

has a solution. Transposing, we obtain a lifting problem of simplicial categories

$$\begin{array}{ccccc} \mathcal{A} & \xrightarrow{T} & \mathcal{K} & \xrightarrow{\mathcal{K}^!} & \mathcal{K}^V \\ \downarrow & \nearrow & & & \downarrow \\ \mathcal{A}' & \longrightarrow & & & \mathcal{K}^U \end{array}$$

against the local isofibration $\mathcal{K}^V \twoheadrightarrow \mathcal{K}^U$. The simplicial functor $\mathcal{K}^!: \mathcal{K} \rightarrow \mathcal{K}^V$, like all simplicial functors, preserves the adjunction $(f \dashv u, \eta)$ in \mathcal{K} , so Theorem 8.3.3 applies to provide a solution. \square

Taking $\mathcal{A}' = \mathcal{A}dj$, Proposition 8.4.8 tells us that the space of homotopy coherent adjunctions extending a simplicial functor $\mathcal{A} \rightarrow \mathcal{K}$ indexed by a parental subcomputad whose image specifies the unit of an adjunction is a contractible Kan complex. This proves that such extensions are “homotopically unique.” We conclude this section with more refined presentations of this kind of result for two instances of basic adjunction data of interest.

8.4.9. DEFINITION (the space of units). Simplicial functors $\overline{\{\eta\}} \rightarrow \mathcal{K}$ correspond bijectively to the choice of a pair of 0-arrows $f \in \text{Fun}(B, A)$, $u \in \text{Fun}(A, B)$, together with a 1-arrow $\eta: \text{id}_B \rightarrow uf \in \text{Fun}(B, B)$. We refer to the simplicial subset $\text{unit}(\mathcal{K}) \subset \text{Icon}(\overline{\{\eta\}}, \mathcal{K})$ of those triples (f, u, η) that specify the unit of an adjunction and those 1-simplices that define isomorphisms between them as the **space of units**, and denote its objects by $(f \dashv u, \eta)$. Since $\text{Icon}(\overline{\{\eta\}}, \mathcal{K})$ is a quasi-category, $\text{unit}(\mathcal{K})$ is a Kan complex.

8.4.10. LEMMA. *There is an isomorphism of quasi-categories*

$$\text{Icon}(\overline{\{\eta\}}, \mathcal{K}) \cong \coprod_{A, B \in \mathcal{K}} \text{Hom}_{\text{Fun}(B, B)}(\text{id}_B, \circ) \quad \begin{array}{ccc} & \text{Hom}_{\text{Fun}(B, B)}(\text{id}_B, \circ) & \\ p_1 \swarrow & & \searrow p_0 \\ \text{Fun}(A, B) \times \text{Fun}(B, A) & \xleftarrow{\phi} & \mathbb{1} \\ \circ \searrow & & \swarrow \circ \\ & \text{Fun}(B, B) & \end{array}$$

PROOF. Exercise 8.4.ii. \square

8.4.11. THEOREM (uniqueness of homotopy coherent extensions of a unit).

- (i) *The space E_η of homotopy coherent adjunctions extending the counit η is a contractible Kan complex.*
- (ii) *The forgetful functor $p_U: \text{cohadj}(\mathcal{K}) \rightrightarrows \text{unit}(\mathcal{K})$ is a trivial fibration of Kan complexes.*

PROOF. Both statements follow from specializing Proposition 8.4.8 to the parental subcomputad $\overline{\{\eta\}} \subset \mathcal{A}dj$. If $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ is a homotopy coherent adjunction, its restriction to $\overline{\{\eta\}} \rightarrow \mathcal{K}$ defines

an object of $\text{unit}(\mathcal{K}) \subset \text{lcon}(\{\overline{\eta}\}, \mathcal{K})$. The fiber of the isofibration $p_U: \text{cohadj}(\mathcal{K}) \rightrightarrows \text{unit}(\mathcal{K})$ over $(f \dashv u, \eta)$ coincides with the fiber considered in Proposition 8.4.8 and is thus a contractible Kan complex.

By Corollary 8.4.4, the map $p_U: \text{cohadj}(\mathcal{K}) \rightrightarrows \text{unit}(\mathcal{K})$ is an isofibration between Kan complexes, and is thus a Kan fibration. By Proposition ?? any Kan fibration between Kan complexes with contractible fibers is a trivial fibration, proving (ii). \square

8.4.12. DEFINITION (the space of right adjoints). Simplicial functors $\{\overline{u}\} \rightarrow \mathcal{K}$ correspond bijectively to the choice of a 0-arrow u in \mathcal{K} . Indeed:

$$\text{lcon}(\{\overline{u}\}, \mathcal{K}) \cong \coprod_{A, B \in \mathcal{K}} \text{Fun}(A, B).$$

We refer to the simplicial subset $\text{rightadj}(\mathcal{K}) \subset \text{lcon}(\{\overline{u}\}, \mathcal{K})$ of those 0-arrows that possess a left adjoint and the isomorphisms between them as the **space of right adjoints**. As a quasi-category whose 1-arrows are all isomorphisms, $\text{rightadj}(\mathcal{K})$ is a Kan complex.

The isofibration $\text{lcon}(\{\overline{\eta}\}, \mathcal{K}) \rightarrow \text{lcon}(\{\overline{u}\}, \mathcal{K})$ restricts to define an isofibration $q_R: \text{unit}(\mathcal{K}) \rightarrow \text{rightadj}(\mathcal{K})$ of Kan complexes.

8.4.13. PROPOSITION. *The isofibration $q_R: \text{unit}(\mathcal{K}) \rightarrow \text{rightadj}(\mathcal{K})$ is a trivial fibration of Kan complexes.*

PROOF. Since both $\text{unit}(\mathcal{K})$ and $\text{rightadj}(\mathcal{K})$ are Kan complexes, automatically q_R is a Kan fibration. By Proposition ??, we need only show that its fibers are contractible. The fiber of q_R over $u: A \rightarrow B$ is isomorphic to the sub-quasi-category of the fiber of the isofibration $\text{lcon}(\{\overline{\eta}\}, \mathcal{K}) \rightarrow \text{lcon}(\{\overline{u}\}, \mathcal{K})$ over u whose objects are pairs (f, η) which have the property that f is a left adjoint to the fixed 0-arrow u with unit represented by η and whose 1-simplices are all invertible. By Lemma 8.4.10, this isofibration is isomorphic to the coproduct of the family of projections

$$\coprod_{A, B \in \mathcal{K}} \text{Hom}_{\text{Fun}(B, B)}(\text{id}_B, \circ) \xrightarrow{p_1} \text{Fun}(A, B) \times \text{Fun}(B, A) \xrightarrow{\pi} \text{Fun}(A, B)$$

whose fiber over u is isomorphic to $\text{Hom}_{\text{Fun}(B, B)}(\text{id}_B, u_*)$.

Applying Proposition 4.1.4 to the adjunction between functor spaces

$$\begin{array}{ccc} & f_* & \\ \text{Fun}(B, B) & \perp & \text{Fun}(B, A) \\ & u_* & \end{array}$$

and the element $\text{id}_B \in \text{Fun}(B, B)$ reveals that (f, η) is a initial in $\text{Hom}_{\text{Fun}(B, B)}(\text{id}_B, u_*)$. So the fiber of q_R over u is isomorphic to the sub-quasi-category of $\text{Hom}_{\text{Fun}(B, B)}(\text{id}_B, u_*)$ spanned by its initial elements and as such is a contractible Kan complex.⁶ \square

8.4.14. THEOREM (uniqueness of homotopy coherent extensions of a right adjoint).

⁶In any quasi-category in which every element is initial, all 1-arrows are isomorphisms, since the initial elements are also initial in its homotopy category, which must then be a groupoid. This proves that the quasi-category spanned by initial elements is in fact a Kan complex. Any adjunction between Kan complexes is an adjoint equivalence, so in particular the right adjoint $! : A \rightrightarrows \mathbb{1}$ defines an equivalence, and hence a trivial fibration.

- (i) The space E_u of homotopy coherent adjunctions with right adjoint u is a contractible Kan complex.
- (ii) The forgetful functor $p_R: \mathbf{cohadj}(\mathcal{K}) \rightrightarrows \mathbf{rightadj}(\mathcal{K})$ is a trivial fibration of Kan complexes.

PROOF. The space E_u is defined as the fiber of the composite fibration

$$p_R: \mathbf{cohadj}(\mathcal{K}) \xrightarrow[\sim]{p_U} \mathbf{unit}(\mathcal{K}) \xrightarrow[\sim]{q_R} \mathbf{rightadj}(\mathcal{K})$$

By Theorem 8.4.11 and Proposition 8.4.13, both maps are trivial fibrations of Kan complexes, hence so is the composite and thus its fiber is a contractible Kan complex. \square

Exercises.

8.4.i. EXERCISE. State and prove a relative version of Proposition 8.4.8, establishing the homotopical uniqueness of solutions to lifting problems of parental subcomputad inclusions against local isofibrations of quasi-categorically enriched categories.

8.4.ii. EXERCISE. Prove Lemma 8.4.10.

The formal theory of homotopy coherent monads

9.1. Homotopy coherent monads

The free homotopy coherent monad is defined as a full subcategory $\mathcal{Mnd} \hookrightarrow \mathcal{Adj}$ on the object $+$. Via this definition, it inherits a graphical calculus from the graphical calculus established for \mathcal{Adj} in §8.1.

9.1.1. DEFINITION (the free homotopy coherent monad). The **free homotopy coherent monad** \mathcal{Mnd} is the full subcategory of the free homotopy coherent adjunction \mathcal{Adj} on the object $+$. Proposition 8.1.10 gives us two definitions of \mathcal{Mnd} :

- It is the 2-category regarded as a simplicial category with one object, with the hom-category Δ_+ , and with horizontal composition given by ordinal sum $\oplus: \Delta_+ \times \Delta_+ \rightarrow \Delta_+$.
- It is the simplicial category with one object whose n -arrows are strictly undulating squiggles on $(n + 1)$ -lines that start and end in the gap labeled $+$.

9.1.2. LEMMA. *The simplicial category \mathcal{Mnd} is a simplicial computad, though $\mathcal{Mnd} \hookrightarrow \mathcal{Adj}$ is not a simplicial subcomputad inclusion.*

PROOF. Horizontal composition in \mathcal{Mnd} is given by horizontal juxtaposition of squiggle diagrams that start and end at $+$. Thus, an n -arrow is atomic if and only if it has no instances of $+$ in its interior. This proves that \mathcal{Mnd} is a simplicial computad, but note that \mathcal{Mnd} includes atomic arrows such as

$$\underline{t} := \underline{uf} := \begin{array}{c} - \\ + \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \quad \text{and} \quad \underline{\mu} := \underline{uef} := \begin{array}{c} - \\ + \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \quad (9.1.3)$$

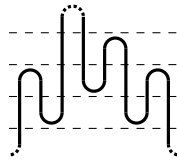
that do have $-$ in their interiors and thus fail to be atomic in \mathcal{Adj} . □

Employing the graphical calculus, we discover another characterization of the atomic n -arrows of \mathcal{Mnd} in reference to the atomic 0-arrow \underline{t} defined in (9.1.3):

9.1.4. LEMMA. *An n -arrow in \mathcal{Mnd} is atomic if and only if its final vertex is \underline{t} .*

In particular, \underline{t} is the unique atomic 0-arrow.

PROOF. The n -arrows are strictly undulating squiggles on $(n + 1)$ -lines that start and end at the space labeled $+$; these are atomic if and only if there are no instances of $+$ in their interiors.



This condition implies that if all the lines are removed except the bottom one, a process that computes the final vertex of the n -simplex, the resulting squiggle looks like a single hump over one line, which is the graphical representation of the 0-arrow \underline{t} . \square

9.1.5. DEFINITION. A **monad** in a 2-category is given by:

- an object B ,
- an endofunctor $t: B \rightarrow B$,
- and a pair of 2-cells $\eta: \text{id}_B \Rightarrow t$ and $\mu: t^2 \Rightarrow t$

so that the “unit” and “associativity” pasting equalities hold:

$$\begin{array}{c} \begin{array}{c} B \\ \downarrow \eta \quad \uparrow t \\ B \xrightarrow{t} B \end{array} = \begin{array}{c} B \\ \downarrow t \\ B \end{array} = \begin{array}{c} B \\ \downarrow \mu \quad \uparrow t \\ B \xrightarrow{t} B \end{array} \quad \begin{array}{c} B \xrightarrow{t} B \\ \downarrow t \quad \downarrow \mu \\ B \xrightarrow{t} B \end{array} = \begin{array}{c} B \xrightarrow{t} B \\ \downarrow \mu \quad \downarrow t \\ B \xrightarrow{t} B \end{array} \end{array}$$

When these conditions are satisfied, we say that (t, η, μ) defines a monad on B .

9.1.6. LEMMA. *The atomic arrows*

$$\underline{t} := \int \! \! \! \int, \quad \underline{\eta} := \int \! \! \! \int, \quad \text{and} \quad \underline{\mu} := \underline{u\epsilon f} := \int \! \! \! \int \! \! \! \int$$

define a monad $(\underline{t}, \underline{\eta}, \underline{\mu})$ on $+$ in the 2-category \mathcal{Mnd} .

PROOF. The unit pasting identities of Definition 9.1.5 are witnessed by the atomic 2-arrows

$$\underline{u\alpha} := \int \! \! \! \int \quad \text{and} \quad \underline{\beta f} := \int \! \! \! \int.$$

The pair of atomic 2-arrows

$$\int \! \! \! \int \quad \text{and} \quad \int \! \! \! \int$$

demonstrate that the left hand side and right-hand side of the associativity pasting equality have a common composite, namely the common first face

$$\int \! \! \! \int \! \! \! \int$$

\square

As a 2-category \mathcal{Mnd} has a familiar universal property. Lawvere’s characterization of $(\Delta_+, \oplus, [-1])$ as the free strict monoidal category containing a monoid $([0], !: [-1] \rightarrow [0], \sigma^0: [1] \rightarrow [0])$ tells us that \mathcal{Mnd} is the free 2-category containing a monad [35]:

9.1.7. PROPOSITION. *For any 2-category \mathcal{C} , 2-functors $\mathcal{Mnd} \rightarrow \mathcal{C}$ correspond to monads in \mathcal{C} .* \square

These considerations motivate the following definition:

9.1.8. DEFINITION (homotopy coherent monad). A **homotopy coherent monad** in a quasi-categorically enriched category \mathcal{K} is a simplicial functor $\mathbb{T}: \mathcal{Mnd} \rightarrow \mathcal{K}$. Explicitly, a homotopy coherent monad consists of

- an object $B \in \mathcal{K}$ and
- a homotopy coherent diagram $\mathbb{T}: \Delta_+ \rightarrow \text{Fun}(B, B)$ that we refer to as the **monad resolution** of \mathbb{T}

so that the diagram

$$\begin{array}{ccc} \Delta_+ \times \Delta_+ & \xrightarrow{\mathbb{T} \times \mathbb{T}} & \text{Fun}(B, B) \times \text{Fun}(B, B) \\ \oplus \downarrow & & \downarrow \circ \\ \Delta_+ & \xrightarrow{\mathbb{T}} & \text{Fun}(B, B) \end{array}$$

commutes. This simplicial functoriality condition implies that the generating 0- and 1-arrows of the monad resolution have the following form:

$$\text{id}_B \xrightarrow{\eta} t \begin{array}{c} \xrightarrow{\eta t} \\ \xleftarrow{\mu} \\ \xrightarrow{t\eta} \end{array} tt \begin{array}{c} \xrightarrow{\eta tt} \\ \xleftarrow{\mu t} \\ \xleftarrow{t\mu} \\ \xrightarrow{tt\eta} \end{array} ttt \cdots \in \text{Fun}(B, B) \quad (9.1.9)$$

where (t, η, μ) denotes the image of the monad $(\underline{t}, \underline{\eta}, \underline{\mu})$ of Lemma 9.1.6 under $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$. We refer to the 0-arrow $t: B \rightarrow B$ as the **functor part** of the homotopy coherent monad \mathbb{T} and refer to the 1-arrows η and μ as the **unit** and **associativity** maps.

Note that for any generalized element $b: X \rightarrow B$, the monad resolution (9.1.9) restricts to define a monad resolution

$$b \xrightarrow{\eta b} tb \begin{array}{c} \xrightarrow{\eta tb} \\ \xleftarrow{\mu b} \\ \xrightarrow{t\eta b} \end{array} ttb \begin{array}{c} \xrightarrow{\eta ttb} \\ \xleftarrow{\mu tb} \\ \xleftarrow{t\mu b} \\ \xrightarrow{tt\eta b} \end{array} tttb \cdots \in \text{Fun}(X, B) \quad (9.1.10)$$

9.1.11. EXAMPLE (free monoid monad). Let \mathcal{M} be a Kan-complex (or topologically) enriched category equipped with an enriched monoidal structure $- \otimes -: \mathcal{M} \times \mathcal{M} \rightarrow \mathcal{M}$ that admits countable conical coproducts that are preserved by the monoidal product separately in each variable. Then there exists a simplicially enriched endofunctor $T: \mathcal{M} \rightarrow \mathcal{M}$ defined on objects by

$$T(X) := \coprod_{n \geq 0} X^{\otimes n}$$

equipped with simplicial natural transformations $\eta: \text{id}_{\mathcal{M}} \Rightarrow T$ and $\mu: T^2 \Rightarrow T$ defined by including at the degree-one component and “distributing” the coproduct

$$T^2(X) \cong \coprod_{n \geq 0} \left(\coprod_{m \geq 0} X^{\otimes m} \right)^{\otimes n}.$$

The monad resolution of this simplicially enriched monad defines a simplicial functor $\Delta_+ \times \mathcal{M} \rightarrow \mathcal{M}$, regarding Δ_+ as a simplicial category whose hom-spaces are sets. Applying the homotopy coherent nerve, $\mathfrak{N}: \mathcal{K}an\text{-}\mathcal{S}Set \rightarrow \mathcal{Q}Cat$, this simplicially enriched monad defines the left action $\Delta_+ \times \mathfrak{N}\mathcal{M} \rightarrow \mathfrak{N}\mathcal{M}$ of a homotopy coherent monad in $\mathcal{Q}Cat$ on $\mathfrak{N}\mathcal{M}$.

More generally, any topologically enriched monad on a topologically enriched category defines a homotopy coherent monad on its homotopy coherent nerve.

Any homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ defines a monad in the homotopy 2-category, simply by composing with the canonical quotient functor discussed at the beginning of §8.4 and applying Proposition 9.1.7:

$$\mathcal{M}nd \xrightarrow{\mathbb{T}} \mathcal{K} \xrightarrow{Q} \mathfrak{h}\mathcal{K}$$

However “monads up to homotopy” — that is, monads in the homotopy 2-category of an ∞ -cosmos — cannot necessarily be made homotopy coherent.

9.1.12. **NON-EXAMPLE** (a monad in the homotopy 2-category that is not homotopy coherent). Stasheff identifies homotopy associative H -spaces that do not extend to A_∞ -spaces; that is, monoids up to homotopy cannot necessarily be rectified into homotopy coherent monoids. Let

$$(M, \eta: * \rightarrow M, \eta: M \times M \rightarrow M)$$

denote such an up-to-homotopy monoid. This structure defines a monad up to homotopy on the (large) quasi-category of spaces by applying the homotopy coherent nerve to the endofunctor $M \times -: \mathcal{K}an \rightarrow \mathcal{K}an$ and natural transformations induced by η and ϵ . This monad in $\mathfrak{h}QC\mathcal{C}at$ cannot be made homotopy coherent.

Exercises.

9.1.i. **EXERCISE.**

- (i) Show that $\mathcal{M}nd$ contains a unique atomic 1-arrow $\underline{\mu}_n: \underline{t}^n \rightarrow \underline{t}$ for each $n \geq 0$, $\underline{\mu}_1 = \text{id}_{\underline{t}}$ being degenerate, but each of the other $\underline{\mu}_n$ being non-degenerate.
- (ii) Identify the images of these atomic 1-arrows in the monad resolution (9.1.9).
- (iii) Given an interpretation for the 1-arrow $\underline{\mu}_n$ that acknowledges the role played by $\underline{\mu}_3$ in the proof of Lemma 9.1.6.

9.2. Homotopy coherent algebras and the monadic adjunction

Homotopy coherent monads can be defined in any quasi-categorically (or merely simplicially) enriched category but we are particularly interested in homotopy coherent monads valued in ∞ -cosmoi because the flexible weighted limits guaranteed by Corollary 7.3.3 permit us to construct the *monadic adjunction*, which relates the ∞ -category on which the monad acts to the ∞ -category of *algebras*.

The universal property of the monadic adjunction associated to a homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ is very easy to describe, though some more work will be required to demonstrate that any ∞ -cosmos \mathcal{K} admits such a construction. The monadic adjunction is the terminal adjunction extending the homotopy coherent monad, which means that it is given by the right Kan extension along the inclusion

$$\begin{array}{ccc} & \mathcal{A}dj & \\ \nearrow & \downarrow \cong & \searrow \mathbb{A}^T \\ \mathcal{M}nd & \xrightarrow{\mathbb{T}} & \mathcal{K} \end{array}$$

Since $\mathcal{M}nd \hookrightarrow \mathcal{A}dj$ is fully faithful, the value of the right Kan extension at $+$ $\in \mathcal{M}nd$ is isomorphic to $B := \mathbb{T}(+)$. By Example 7.1.19, the value of the right Kan extension at $- \in \mathcal{M}nd$ is computed as the

limit of $\mathbb{T}: \mathcal{Mnd} \rightarrow \mathcal{K}$ weighted by the restriction of the covariant representable of \mathcal{Adj} at $-$ along $\mathcal{Mnd} \hookrightarrow \mathcal{Adj}$, which is how we will now define the weight W_- for the ∞ -category of algebras.

9.2.1. OBSERVATION (weights on \mathcal{Mnd}). A **weight on \mathcal{Mnd}** is a simplicial functor $W: \mathcal{Mnd} \rightarrow \mathcal{SSet}$. Explicitly, to specify a weight on \mathcal{Mnd} is equivalent to specifying

- a simplicial set $W := W(+)$
- equipped with a left action of the simplicial monoid¹ $(\Delta_+, \oplus, [-1])$

$$\Delta_+ \times W \xrightarrow{\cdot} W \quad \text{so that} \quad \begin{array}{ccc} \Delta_+ \times \Delta_+ \times W & \xrightarrow{\text{id} \times \cdot} & \Delta_+ \times W \\ \oplus \times \text{id} \downarrow & & \downarrow \cdot \\ \Delta_+ \times W & \xrightarrow{\cdot} & W \end{array} \quad \begin{array}{ccc} W & \xrightarrow{[-1] \times \text{id}} & \Delta_+ \times W \\ & \searrow & \downarrow \cdot \\ & & W \end{array}$$

Frequently, the simplicial set W happens to be a quasi-category, in which case the weight W on \mathcal{Mnd} is precisely a homotopy coherent monad on the quasi-category W .

Relative to the encoding of weights on \mathcal{Mnd} as simplicial sets with a left Δ_+ -action, a map $f: V \rightarrow W \in \mathcal{SSet}^{\mathcal{Mnd}}$ is given by a map $f: V \rightarrow W$ of simplicial sets that is Δ_+ -equivariant in the sense that the diagram

$$\begin{array}{ccc} V & \xrightarrow{f} & W \\ [-1] \times \text{id} \downarrow & & \downarrow [-1] \times \text{id} \\ \Delta_+ \times V & \xrightarrow{\text{id} \times f} & \Delta_+ \times W \\ \cdot \downarrow & & \downarrow \cdot \\ V & \xrightarrow{f} & W \end{array}$$

commutes.

9.2.2. LEMMA. Let $W: \mathcal{Mnd} \rightarrow \mathcal{SSet}$ be a weight on \mathcal{Mnd} and let $T: \mathcal{Mnd} \rightarrow \mathcal{K}$ be a homotopy coherent monad on $B \in \mathcal{K}$. Then a W -shaped cone over \mathbb{T} with summit X is specified by a simplicial map $\gamma: W \rightarrow \text{Fun}(X, B)$ which makes the square

$$\begin{array}{ccc} \Delta_+ \times W & \xrightarrow{\mathbb{T} \times \gamma} & \text{Fun}(B, B) \times \text{Fun}(X, B) \\ \cdot \downarrow & & \downarrow \circ \\ W & \xrightarrow{\gamma} & \text{Fun}(X, B) \end{array}$$

PROOF. By Observation 9.2.1, a simplicial natural transformation $\gamma: W \rightarrow \text{Fun}(X, \mathbb{T}-)$ is given by its unique component $\gamma: W \rightarrow \text{Fun}(X, B)$ subject to the equivariance condition:

$$\begin{array}{ccc} \Delta_+ \times W & \xrightarrow{\text{id} \times \gamma} & \Delta_+ \times \text{Fun}(X, B) \\ \cdot \downarrow & & \downarrow \cdot \\ W & \xrightarrow{\gamma} & \text{Fun}(X, B) \end{array}$$

¹The strict monoidal category $(\Delta_+, \oplus, [-1])$ is a monoid in $(\mathcal{SSet}, \times, \mathbb{1})$. Applying the nerve functor, $(\Delta_+, \oplus, [-1])$ also defines a monoid in $(\mathcal{SSet}, \times, \mathbb{1})$.

The right-hand action map is the transpose of the action map of the composite simplicial functor $\text{Fun}(X, \mathbb{T}-): \mathcal{Mnd} \rightarrow \mathcal{QCat}$, this being

$$\Delta_+ \xrightarrow{\mathbb{T}} \text{Fun}(B, B) \xrightarrow{\text{Fun}(X, -)} \text{Fun}(\text{Fun}(X, B), \text{Fun}(X, B))$$

which transposes to

$$\Delta_+ \times \text{Fun}(X, B) \xrightarrow{\mathbb{T} \times \text{id}} \text{Fun}(B, B) \times \text{Fun}(X, B) \xrightarrow{\circ} \text{Fun}(X, B).$$

Now the equivariance square coincides with the commutative square of the statement. \square

9.2.3. EXAMPLE (notable weights on \mathcal{Mnd}). We fix notation for a few notable weights on \mathcal{Mnd} .

- (i) Write $W_+ : \mathcal{Mnd} \rightarrow \mathcal{SSet}$ for the unique represented functor on \mathcal{Mnd} , which is given by the quasi-category $\Delta_+ = \mathcal{Mnd}(+, +) = \mathcal{Adj}(+, +)$ acted upon the left by itself via the ordinal sum map

$$\Delta_+ \times \Delta_+ \xrightarrow{\oplus} \Delta_+$$

- (ii) Write $W_- : \mathcal{Mnd} \rightarrow \mathcal{SSet}$ for the restriction of the covariant representable functor $\mathcal{Adj} \rightarrow \mathcal{SSet}$ on $-$ along $\mathcal{Mnd} \hookrightarrow \mathcal{Adj}$. This weight is presented by the quasi-category $\Delta_- = \mathcal{Adj}(-, +)$ acted upon the left by Δ_+ by the ordinal sum map

$$\Delta_+ \times \Delta_- \xrightarrow{\oplus} \Delta_-$$

which defines the horizontal composition in \mathcal{Adj} in Definition 8.1.1.

There is a natural inclusion

$$\begin{array}{ccc} \Delta_+ & \xrightarrow{-\oplus[0]} & \Delta_- \\ \Downarrow & & \Downarrow \\ \mathcal{Adj}(+, +) & \xrightarrow{-\circ \underline{u}} & \mathcal{Adj}(-, +) \end{array}$$

that “freely adjoins a top element in each ordinal” or, in the graphical calculus of Definition 8.1.9, “precomposes a strictly undulating squiggle with $\underline{u} := (+, -)$.” This commutes with the left Δ_+ -actions and so defines an inclusion of weights $W_+ \hookrightarrow W_-$ by Observation 9.2.1.²

Since W_+ is the representable weight it is automatically flexible. By the first axiom of Definition 7.1.3 the W_+ -weighted limit of a homotopy coherent monad \mathbb{T} recovers the ∞ -category $\lim_{W_+} \mathbb{T} \cong B$ on which \mathbb{T} acts.

9.2.4. LEMMA. *The inclusion $W_+ \hookrightarrow W_-$ is a projective cell complex in $\mathcal{SSet}^{\mathcal{Mnd}}$ built by attaching projective n -cells $\partial \Delta[n] \times W_+ \hookrightarrow \Delta[n] \times W_+$ in dimensions $n > 0$. In particular, W_- is a flexible weight.*

PROOF. We apply Theorem 7.2.12 and prove that $W_+ \hookrightarrow W_-$ is a projective cell complex by verifying that $\text{coll}(W_+) \hookrightarrow \text{coll}(W_-)$ is a relative simplicial computad. Since W_+ is flexible, it follows then that W_- is too. The collage $\text{coll}(W_-)$ can be identified with the non-full simplicial subcategory of \mathcal{Adj} containing two objects $-$ (aka \top) and $+$ and the hom-spaces $\mathcal{Adj}(-, +)$ and $\mathcal{Adj}(+, +)$ but with the hom-space from $-$ to $-$ trivial and the hom-space from $+$ to $-$ empty. Via the graphical calculus of Definition 8.1.9, we see that $\text{coll}(W_-)$ is a simplicial category whose n -arrows are strictly undulating squiggles from $-$ to $+$ or from $+$ to $+$ with composition defined by concatenation at $+$. Its *atomic* n -arrows are then those that have no instances of $+$ in their interiors.

²A “right adjoint” to the inclusion $W_+ \hookrightarrow W_-$ will be described in the proof of Proposition 9.2.11.

Similarly, $\text{coll}(W_+)$ is the simplicial category with two objects \top and $+$ and with the hom-spaces from \top to $+$ and from $+$ to $+$ both defined to be $\mathcal{A}dj(+, +)$, with the hom space from \top to \top trivial and the hom-space from $+$ to \top empty. This is also a simplicial computad in which the only atomic arrow from \top to $+$ is the identity 0-arrow corresponding to $[-1] \in \mathcal{A}dj(+, +) = \Delta_+$; as before, the atomic arrows from $+$ to $+$ are the strictly undulating squiggles which have no instances of $+$ in their interiors. To provide intuition for this simplicial computad structure on $\text{coll}(W_+)$, recall that since the representable W_+ defines a projective cell complex $\emptyset \hookrightarrow W_+$ built by attaching a single projective 0-cell at $+$, the proof of Theorem 7.2.12 tells us that the simplicial subcomputad inclusion $\mathbb{1} + \mathcal{M}nd \hookrightarrow \text{coll}(W_+)$ is defined by adjoining a single atomic 0-arrow from \top to $+$ to the simplicial computad $\mathbb{1} + \mathcal{M}nd$.

The inclusion $\text{coll}(W_+) \hookrightarrow \text{coll}(W_-)$ is bijective on the common subcategory $\mathbb{1} + \mathcal{M}nd$ and defined by sending each n -arrow from \top to $+$ in $\text{coll}(W_+)$, represented as a squiggle from $+$ to $+$, to the squiggle from $-$ to $+$ defined by precomposing with \underline{u} . This function carries the unique atomic 0-arrow from \top to $+$ in $\text{coll}(W_+)$ to \underline{u} , which is the unique atomic 0-arrow in $\text{coll}(W_-)$ from \top to $+$. Now Theorem 7.2.12 proves that $W_+ \hookrightarrow W_-$ is a projective cell complex. Furthermore, since $\text{coll}(W_+) \hookrightarrow \text{coll}(W_-)$ is surjective on atomic 0-arrows, only projective cells of positive dimension are needed to present $W_+ \hookrightarrow W_-$ as a sequential composite of pushouts of projective n -cells $\partial\Delta[n] \times W_+ \hookrightarrow \Delta[n] \times W_+$. \square

Now let \mathcal{K} be an ∞ -cosmos.

9.2.5. DEFINITION. The ∞ -category of \mathbb{T} -algebras for a homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ in an ∞ -cosmos \mathcal{K} is the flexible weighted limit $\lim_{W_-} \mathbb{T}$. When \mathbb{T} acts on the ∞ -category B via the monad resolution (9.1.9) with functor part $t: B \rightarrow B$, we write

$$\text{Alg}_{\mathbb{T}}(B) := \lim_{W_-} \mathbb{T}$$

for the ∞ -category of algebras. By Proposition 7.3.1(ii), the projective cell complex $W_+ \hookrightarrow W_-$ induces an isofibration

$$\lim_{W_-} \mathbb{T} \twoheadrightarrow \lim_{W_+} \mathbb{T}$$

upon taking weighted limits defining a map that we denote by $u^t: \text{Alg}_{\mathbb{T}}(B) \twoheadrightarrow B$ and refer to as the **monadic forgetful functor**. This map is the leg of the W_- -shaped limit cone indexed by the unique object $+$ in $\mathcal{M}nd$.

By Corollary 7.3.3 and Lemma 9.2.4:

9.2.6. PROPOSITION. Any homotopy coherent monad in an ∞ -cosmos admits an ∞ -category of algebras. \square

We now introduce the generic bar resolution $\Delta_{\top} \rightarrow \text{Fun}(\text{Alg}_{\mathbb{T}}(B), B)$ associated to the ∞ -category of \mathbb{T} -algebras for a homotopy coherent monad acting on B .

9.2.7. DEFINITION (generic bar resolution). The limit cone $\beta: W_- \Rightarrow \text{Fun}(\text{Alg}_{\mathbb{T}}(B), \mathbb{T}(-))$ defines the **generic bar resolution** of a homotopy coherent monad \mathbb{T} acting on an ∞ -category B . By Lemma 9.2.2 and Example 9.2.3, a W_- -cone with summit $\text{Alg}_{\mathbb{T}}(B) := \lim_{W_-} \mathbb{T}$ over a homotopy coherent monad acting on \mathbb{T} is given by a simplicial map $\beta: \Delta_{\top} \rightarrow \text{Fun}(\text{Alg}_{\mathbb{T}}(B), B)$ so that the square

$$\begin{array}{ccc} \Delta_+ \times \Delta_{\top} & \xrightarrow{\mathbb{T} \times \beta} & \text{Fun}(B, B) \times \text{Fun}(\text{Alg}_{\mathbb{T}}(B), B) \\ \downarrow \circ & & \downarrow \circ \\ \Delta_{\top} & \xrightarrow{\beta} & \text{Fun}(\text{Alg}_{\mathbb{T}}(B), B) \end{array}$$

commutes. Under the identification $\Delta_{\mathbb{T}} \cong \mathcal{A}dj(-, +)$, we write u^t and $\beta^t: tu^t \rightarrow u^t$ for the 0- and 1-arrows of $\mathbf{Fun}(\mathbf{Alg}_{\mathbb{T}}(B), B)$ defined to be the images of \underline{u} and $\underline{u\epsilon}$ under $\beta: \Delta_{\mathbb{T}} \rightarrow \mathbf{Fun}(\mathbf{Alg}_{\mathbb{T}}(B), B)$ respectively. This 0-arrow u^t is the monadic forgetful functor of Definition 9.2.5. Then in the notation of (9.1.9), the generic bar resolution has the form of a homotopy coherent diagram

$$\begin{array}{ccccccc}
 u^t & \xrightleftharpoons[\beta^t]{\eta u^t} & tu^t & \xrightleftharpoons[t\beta^t]{\eta tu^t} & ttu^t & \xrightleftharpoons[t\eta u^t]{\mu u^t} & tttu^t & \cdots & \in \mathbf{Fun}(\mathbf{Alg}_{\mathbb{T}}(B), B)
 \end{array}
 \quad (9.2.8)$$

that restricts along the embedding $\Delta_+ \hookrightarrow \Delta_{\mathbb{T}}$ that freely adjoins the top element in each ordinal to the monad resolution (9.1.10) applied to u^t .

For any generalized element $X \rightarrow \mathbf{Alg}_{\mathbb{T}}(B)$ of the ∞ -category of \mathbb{T} -algebras associated to a homotopy coherent monad acting on B , an X -family of \mathbb{T} -algebras in B , the generic bar resolution (9.2.8) restricts to define a **bar resolution**

$$\begin{array}{ccccccc}
 b & \xrightleftharpoons[\beta]{\eta b} & tb & \xrightleftharpoons[t\beta]{\eta tb} & ttb & \xrightleftharpoons[t\eta b]{\mu b} & tttb & \cdots
 \end{array}
 \quad (9.2.9)$$

9.2.10. PROPOSITION. *The monadic forgetful functor $u^t: \mathbf{Alg}_{\mathbb{T}}(B) \rightarrow B$ is conservative: for any 2-cell γ with codomain $\mathbf{Alg}_{\mathbb{T}}(B)$ if $u^t\gamma$ is invertible, then so is γ .*

PROOF. Conservativity of the functor u^t asserts that for all X the isofibration of quasi-categories $u_*^t: \mathbf{Fun}(X, \mathbf{Alg}_{\mathbb{T}}(B)) \rightarrow \mathbf{Fun}(X, B)$ reflects invertible 1-cells. Working with marked simplicial sets, this is the case just when this map has the right lifting property with respect to the inclusion $\mathbb{2} \hookrightarrow \mathbb{2}^\#$ of the walking arrow into the walking marked arrow.

By Definition 9.2.5, the monadic forgetful functor is defined by applying $\lim_- \mathbb{T}$ to the projective cell complex $W_+ \hookrightarrow W_-$ of Lemma 9.2.4. By Proposition 7.3.1, the isofibration $u^t: \mathbf{Alg}_{\mathbb{T}}(B) \rightarrow B$ then factors as the inverse limit of a tower of isofibrations, each layer of which is constructed as the pullback of products of projective cells $B^{\Delta[n]} \rightarrow B^{\partial\Delta[n]}$ for $n \geq 1$. The cosmological functor $\mathbf{Fun}(X, -): \mathcal{K} \rightarrow \mathbf{QCat}$ preserves this limit, so $u_*^t: \mathbf{Fun}(X, \mathbf{Alg}_{\mathbb{T}}(B)) \rightarrow \mathbf{Fun}(X, B)$ is similarly the inverse limit of pullbacks of products of maps $\mathbf{Fun}(X, B)^{\Delta[n]} \rightarrow \mathbf{Fun}(X, B)^{\partial\Delta[n]}$ for $n \geq 1$. Since conservativity of a functor between quasi-categories may be captured by a lifting property, it suffices to show that the maps $\mathbf{Fun}(X, B)^{\Delta[n]} \rightarrow \mathbf{Fun}(X, B)^{\partial\Delta[n]}$ reflect invertibility of 1-simplices. Since for $n \geq 1$, the inclusion $\partial\Delta[n] \hookrightarrow \Delta[n]$ is bijective on vertices, this is immediate from Lemma ??, which says that invertibility in exponentiated quasi-categories is detected pointwise. \square

We now show that any homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ on an ∞ -category B in an ∞ -cosmos extends to a homotopy coherent adjunction $\mathbb{A}^{\mathbb{T}}: \mathcal{A}dj \rightarrow \mathcal{K}$ whose right adjoint is u^t .

9.2.11. PROPOSITION (the monadic adjunction). *For any homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ on B , the monadic forgetful functor $u^t: \mathbf{Alg}_{\mathbb{T}}(B) \rightarrow B$ is the right adjoint of a homotopy coherent adjunction*

$$\mathbb{A}^{\mathbb{T}}: \mathcal{A}dj \rightarrow \mathcal{K}$$

$$B \begin{array}{c} \xrightarrow{f^t} \\ \perp \\ \xleftarrow{u^t} \end{array} \text{Alg}_{\mathbb{T}}(B) \quad \eta^t: \text{id}_B \Rightarrow u^t f^t \quad \epsilon^t: f^t u^t \Rightarrow \text{id}_{\text{Alg}_{\mathbb{T}}(B)}.$$

whose underlying homotopy coherent monad is \mathbb{T} . This constructs the *monadic adjunction of the homotopy coherent monad*.

In particular, the triple $(u^t f^t, \eta^t, u^t \epsilon^t f^t)$ recovers the monad (t, η, μ) on B defined in 9.1.8.

PROOF. Recall the weights W_+ and W_- are defined in Example 9.2.3 to be restrictions of the representable functors on $\mathcal{A}dj$; in the case of W_+ this restriction defines the representable functor for $\mathcal{M}nd$ since the inclusion $\mathcal{M}nd \hookrightarrow \mathcal{A}dj$ is full on $+$. The weight for the monadic homotopy coherent adjunction is defined to be the composite of the Yoneda embedding with the restriction functor

$$\begin{array}{ccc} \mathcal{A}dj^{\text{op}} & \xrightarrow{\mathcal{Y}} & \mathcal{S}Set^{\mathcal{A}dj} \xrightarrow{\text{res}} \mathcal{S}Set^{\mathcal{M}nd} \\ + \vdash & \xrightarrow{\quad} & W_+ \\ \underline{f} \left(\begin{array}{c} \downarrow \\ \downarrow \\ \downarrow \end{array} \right) \underline{u} & \mapsto & - \circ \underline{f} \uparrow \vdash - \circ \underline{u} \\ - & \xrightarrow{\quad} & W_- \end{array}$$

which can be interpreted as defining an adjunction of weights whose left and right adjoints, in the encoding of Observation 9.2.1, are given by the maps

$$\Delta_+ \begin{array}{c} \xrightarrow{- \circ \underline{u}} \\ \perp \\ \xleftarrow{- \circ \underline{f}} \end{array} \Delta_+$$

that act on strictly undulating n -arrows by precomposing with $\underline{u} = (+, -)$ or $\underline{f} = (-, +)$ as appropriate; these maps commute with the left Δ_+ -actions by postcomposition with a strictly undulating squiggle from $+$ to $+$.

Composing with the weighted limit functor $\lim_- \mathbb{T}$ defines a simplicial functor

$$\mathbb{A}^{\mathbb{T}} := \lim_{\text{res}} \mathcal{Y}_{(-)} \mathbb{T}: \mathcal{A}dj \rightarrow \mathcal{K},$$

i.e., a homotopy coherent adjunction between $\lim_{W_+} \mathbb{T} \cong B$ and $\lim_{W_-} \mathbb{T} \cong \text{Alg}_{\mathbb{T}}(B)$ whose right adjoint is given by the action of the 0-arrow \underline{u} , which is the monadic forgetful functor $u^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow B$ is defined in 9.2.5.

Finally, the underlying homotopy coherent monad of the homotopy coherent adjunction just constructed is defined to be the limit of $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ weighted by

$$\mathcal{M}nd^{\text{op}} \hookrightarrow \mathcal{A}dj^{\text{op}} \xrightarrow{\mathcal{Y}} \mathcal{S}Set^{\mathcal{A}dj} \xrightarrow{\text{res}} \mathcal{S}Set^{\mathcal{M}nd}$$

which is just the Yoneda embedding for $\mathcal{M}nd$. By the first axiom of Definition 7.1.3, this functor is isomorphic to \mathbb{T} . \square

In §9.4, we give a characterization of the monadic adjunction of a homotopy coherent monad. To build towards this result, we spend the next section establishing important special properties of the

monadic forgetful functor $u^t: \text{Alg}_{\mathbb{T}}(B) \twoheadrightarrow B$ and its left adjoint $f^t: B \rightarrow \text{Alg}_{\mathbb{T}}(B)$, whose essential image identifies the free \mathbb{T} -algebras.

Exercises.

9.2.i. EXERCISE. Prove that the ∞ -category of algebras associated to the homotopy coherent monad $W_+: \mathcal{M}nd \rightarrow \mathcal{Q}Cat$ on Δ_+ is Δ_\perp . What is the monadic adjunction?

9.3. Limits and colimits in the ∞ -category of algebras

The key technical insight enabling Beck's proof of the monadicity theorem [1] is the observation that any algebra is canonically a colimit of a particular diagram of free algebras. In the case of a monad (t, η, μ) acting on a 1-category B , the data of a t -algebra in B is given by a u^t -split coequalizer diagram

$$\begin{array}{ccc} & \xleftarrow{\eta t b} & \\ & \xleftarrow{ub} & \\ t^2 b & \xleftarrow{t \eta b} & t b \xleftarrow{\eta b} b \\ & \xrightarrow{t \beta} & \end{array} \quad (9.3.1)$$

Here the solid arrows are maps which respect the t -algebra structure where the dotted splittings do not. Split coequalizers are examples of *absolute colimits*, which are preserved by any functor, and in particular by $t: B \rightarrow B$, a fact we may exploit to show that the underlying fork of (9.3.1) defines a reflexive coequalizer diagram in the category of t -algebras.

In the ∞ -categorical context, we require a higher-dimensional version of the diagram (9.3.1), namely the bar resolution constructed in (9.2.9) for any generalized element $X \rightarrow \text{Alg}_{\mathbb{T}}(B)$ of the ∞ -category of \mathbb{T} -algebras for a homotopy coherent monad acting on B . This replaces the u^t -split coequalizer by a canonically-defined u^t -split augmented simplicial object.

Before defining this special class of colimits, we establish a more general result:

9.3.2. PROPOSITION. *Let $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ be a homotopy coherent monad on an ∞ -category B with functor part $t: B \rightarrow B$. Then if B admits and t preserves colimits of shape J , then the monadic forgetful functor $u^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow B$ creates colimits of shape J .*

PROOF. The 0-arrows in the image of a homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ are given by the identity functor at B , the “functor part” $t: B \rightarrow B$ defined as the image of the unique atomic 0-arrow of $\mathcal{M}nd$, and finite composites $t^n: B \rightarrow B$ for each $n \geq 1$. If t preserves colimits of shape J in B , then so does t^n . Thus, in the case where B admits and t preserves J -shaped colimits, the homotopy coherent monad lifts to homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}_{\perp, J}$ in the ∞ -cosmos of Proposition 7.4.14. Since the inclusion $\mathcal{K}_{\perp, J} \hookrightarrow \mathcal{K}$ creates flexible weighted limits, such as those weighted by W_- , it follows that the limit cone $u^t: \text{Alg}_{\mathbb{T}}(B) \twoheadrightarrow B$ lifts to $\mathcal{K}_{\perp, J}$. This monadic forgetful functor is the unique 0-arrow component of the limit cone, so by Proposition 7.4.14 this tells us that $\text{Alg}_{\mathbb{T}}(B)$ admits and $u^t: \text{Alg}_{\mathbb{T}}(B) \twoheadrightarrow B$ creates J -shaped colimits. \square

A dual argument, employing the ∞ -cosmos $\mathcal{K}_{\top, J}$ of ∞ -categories that admit and functors that preserve J -indexed limits, proves that if B admits and t preserves limits of shape J , then the monadic forgetful functor $u^t: \text{Alg}_{\mathbb{T}}(B) \twoheadrightarrow B$ creates limits of shape J . We don't explicitly consider this dual version here, however, because we will prove a stronger result in Theorem 9.3.9 that drops the hypotheses on t .

9.3.3. DEFINITION (u -split simplicial objects). The image of the embedding

$$\begin{array}{ccc} \Delta_+^{\text{op}} & \xleftarrow{[0] \oplus -} & \Delta_{\top} \\ \Downarrow & & \Downarrow \\ \mathcal{A}dj(-, -) & \xleftarrow{u \circ -} & \mathcal{A}dj(-, +) \end{array}$$

is the subcategory of Δ_{\top} generated by all of its elementary operators except for the face operators $\delta^0: [n-1] \rightarrow [n]$ for each $n \geq 1$. We refer to these extra face maps as **splitting operators**. By Definition 2.3.9, a simplicial object $X \rightarrow B^{\Delta^{\text{op}}}$ in B **admits an augmentation** if it lifts along the restriction functor $B^{\Delta_+^{\text{op}}} \rightarrow B^{\Delta^{\text{op}}}$, and an augmented simplicial object $X \rightarrow B^{\Delta_+^{\text{op}}}$ in B **admits a splitting** if it lifts along the restriction functor $B^{\Delta_{\top}} \rightarrow B^{\Delta_+^{\text{op}}}$. Thus, given any functor $u: A \rightarrow B$ of ∞ -categories, the ∞ -categories $S^{\Delta^{\text{op}}}(u)$ and $S^{\Delta_+^{\text{op}}}(u)$ of u -split simplicial objects and u -split augmented simplicial objects in A are defined by the pullbacks

$$\begin{array}{ccc} S^{\Delta^{\text{op}}}(u) & \longrightarrow & B^{\Delta_{\top}} \\ \downarrow & \lrcorner & \downarrow \text{res} \\ A^{\Delta^{\text{op}}} & \xrightarrow{u^{\Delta^{\text{op}}}} & B^{\Delta^{\text{op}}} \end{array} \quad \begin{array}{ccc} S^{\Delta_+^{\text{op}}}(u) & \longrightarrow & B^{\Delta_{\top}} \\ \downarrow & \lrcorner & \downarrow \text{res} \\ A^{\Delta_+^{\text{op}}} & \xrightarrow{u^{\Delta_+^{\text{op}}}} & B^{\Delta_+^{\text{op}}} \end{array}$$

and there exists a forgetful functor

$$\begin{array}{ccc} A^{\Delta_+^{\text{op}}} & \longleftarrow & S^{\Delta_+^{\text{op}}}(u) \\ \text{res} \downarrow & & \downarrow \text{dashed} \\ A^{\Delta^{\text{op}}} & \longleftarrow & S^{\Delta^{\text{op}}}(u) \end{array} \quad \begin{array}{c} \nearrow \\ \searrow \end{array} \quad B^{\Delta_{\top}}$$

Our interest in these notions is explained by the following example: if $u: A \rightarrow B$ is a right adjoint functor between ∞ -categories, any homotopy coherent adjunction extending u defines a canonical u -split augmented simplicial object.

9.3.4. LEMMA. Let $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ be a homotopy coherent adjunction with right adjoint $u: A \rightarrow B$. Then the comonad resolution and bar resolution

$$\begin{array}{ccc} A & \xrightarrow{\text{bar}} & B^{\Delta_{\top}} \\ k_{\bullet} \downarrow & & \downarrow \text{res} \\ A^{\Delta_+^{\text{op}}} & \xrightarrow{u^{\Delta_+^{\text{op}}}} & B^{\Delta_+^{\text{op}}} \end{array}$$

jointly define a u -split augmented simplicial object $A \rightarrow S^{\Delta_+^{\text{op}}}(u)$.

PROOF. Functoriality of \mathbb{A} supplies a commutative diagram below-left

$$\begin{array}{ccc} \Delta_+^{\text{op}} \cong \mathcal{A}dj(-, -) & \xrightarrow{\mathbb{A}} & \text{Fun}(A, A) \\ \downarrow u \circ - & & \downarrow u \circ - \\ \Delta_{\top} \cong \mathcal{A}dj(-, +) & \xrightarrow{\mathbb{A}} & \text{Fun}(A, B) \end{array}$$

which internalizes to the commutative diagram of the statement. By the definition of the ∞ -category of u -split augmented simplicial objects in 9.3.3, this induces the claimed functor $A \rightarrow S^{\Delta^{\text{op}}}_+(u)$. Thus the comonad resolution $k_\bullet: A \rightarrow A^{\Delta^{\text{op}}}_+$ defines an augmented simplicial object in A that is u -split by the bar resolution for \mathbb{A} . \square

9.3.5. PROPOSITION. *The monadic forgetful functor $u^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow B$ creates colimits of u^t -split simplicial objects. Moreover, for any u^t -split augmented simplicial object, the augmentation defines the colimit cone for the underlying simplicial object in $\text{Alg}_{\mathbb{T}}(B)$.*

PROOF. The ∞ -category of u^t -split simplicial objects is defined by the pullback

$$\begin{array}{ccc} S^{\Delta^{\text{op}}}(u^t) & \longrightarrow & B^{\Delta_{\mathbb{T}}} \\ \downarrow & \lrcorner & \downarrow \text{res} \\ \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{(u^t)^{\Delta^{\text{op}}}} & B^{\Delta^{\text{op}}} \end{array}$$

By Proposition 2.3.11, the canonical 2-cell (2.3.10) defined by the initial object in Δ_+ defines an absolute left lifting diagram

$$\begin{array}{ccccc} & & & B & \\ & & & \uparrow \text{ev}_{-1} & \downarrow \Delta \\ S^{\Delta^{\text{op}}}(u^t) & \longrightarrow & B^{\Delta_{\mathbb{T}}} & \xrightarrow{\text{res}} & B^{\Delta^{\text{op}}} \\ & & & \uparrow B^{\nu^{\text{op}}} & \\ & & & B^{\Delta^{\text{op}}} & \end{array} \quad (9.3.6)$$

that is also an absolute colimit in B , preserved by all functors and in particular by $t: B \rightarrow B$.

Now Proposition 9.3.2 tells us that $u^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow B$ creates this colimit, which means that there exists an absolute left lifting diagram as below-left

$$\begin{array}{ccccc} & \text{Alg}_{\mathbb{T}}(B) & & \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{u^t} B \\ & \uparrow \text{colim} & & \uparrow \text{colim} & \downarrow \Delta \\ S^{\Delta^{\text{op}}}(u^t) & \twoheadrightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & S^{\Delta^{\text{op}}}(u^t) & \twoheadrightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{(u^t)^{\Delta^{\text{op}}}} B^{\Delta^{\text{op}}} \\ & & & & \uparrow B^{\nu^{\text{op}}} \\ & & & & B^{\Delta^{\text{op}}} \end{array} = \begin{array}{ccc} & B & \\ \uparrow \text{ev}_{-1} & & \downarrow \Delta \\ S^{\Delta^{\text{op}}}(u^t) & \twoheadrightarrow B^{\Delta^{\text{op}}} & \xrightarrow{\text{res}} B^{\Delta^{\text{op}}} \end{array}$$

that when postcomposed with $(u^t)^{\Delta^{\text{op}}}: \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \rightarrow B^{\Delta^{\text{op}}}$ recovers the absolute left lifting diagram (9.3.6), in the sense expressed by the pasting equality above-right. Thus, the monadic forgetful functor creates colimits of u^t -split simplicial objects in $\text{Alg}_{\mathbb{T}}(B)$.

Upon precomposing with the $S^{\Delta^{\text{op}}}_+(u^t) \rightarrow S^{\Delta^{\text{op}}}(u^t)$ the fact that Proposition 9.3.2 tells us that $u^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow B$ creates the colimit (9.3.6) also means that whenever there exists a pasting equality

$$\begin{array}{ccccc} & \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{u^t} & B & \\ & \uparrow \text{ev}_{-1} & & \downarrow \Delta & \\ S^{\Delta^{\text{op}}}_+(u^t) & \twoheadrightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{\text{res}} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{(u^t)^{\Delta^{\text{op}}}} B^{\Delta^{\text{op}}} \\ & & & \uparrow \text{Alg}_{\mathbb{T}}(B)^{\nu^{\text{op}}} & \\ & & & B^{\Delta^{\text{op}}} & \end{array} = \begin{array}{ccc} & B & \\ \uparrow \text{ev}_{-1} & & \downarrow \Delta \\ S^{\Delta^{\text{op}}}_+(u^t) & \twoheadrightarrow B^{\Delta_{\mathbb{T}}} & \xrightarrow{\text{res}} B^{\Delta^{\text{op}}} \end{array}$$

such as arises here by 2-functoriality of the simplicial cotensor construction, the 2-cell

$$S^{\Delta^{\text{op}}}_+(u^t) \longrightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+ \xrightarrow{\text{res}} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \xrightarrow{\text{ev}_{-1}} \text{Alg}_{\mathbb{T}}(B) \xrightarrow{\Delta} \text{Alg}_{\mathbb{T}}(B)^{\nu^{\text{op}}}$$

is an absolute left lifting diagram. This proves that $u^t: \text{Alg}_{\mathbb{T}}(B) \twoheadrightarrow B$ creates colimits of u^t -split simplicial objects. \square

Now, as displayed by the bar resolution (9.2.8), any \mathbb{T} -algebra in B canonically gives rise to a u^t -split simplicial object to which Proposition 9.3.5 applies; the bar resolution $\Delta_{\mathbb{T}} \rightarrow \text{Fun}(\text{Alg}_{\mathbb{T}}(B), B)$ internalizes to a diagram $\text{bar}: \text{Alg}_{\mathbb{T}}(B) \rightarrow B^{\Delta_{\mathbb{T}}}$. The colimit cone in $\text{Alg}_{\mathbb{T}}(B)$ is given by the Δ^{op}_+ -shaped subdiagram of the bar resolution that omits the dashed maps

$$\begin{array}{ccccc} u^t & \xleftarrow{\eta u^t} & tu^t & \xleftarrow{\mu u^t} & ttu^t & \xleftarrow{\quad} & tttu^t & \dots \\ & \searrow \beta^t & \swarrow t\eta u^t & \searrow t\mu u^t & \swarrow t\eta u^t & \searrow & \swarrow & \\ & & & & & & & \end{array}$$

This subdiagram admits a concise description: it is the comonad resolution for the comonad induced by the monadic adjunction $f^t \dashv u^t$ on $\text{Alg}_{\mathbb{T}}(B)$, this being a functor $\Delta^{\text{op}}_+ \rightarrow \text{Fun}(\text{Alg}_{\mathbb{T}}(B), \text{Alg}_{\mathbb{T}}(B))$ that internalizes to a functor $k^t_{\bullet}: \text{Alg}_{\mathbb{T}}(B) \rightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+$.

9.3.7. THEOREM (canonical colimit representation of algebras). *For any homotopy coherent monad \mathbb{T} on B , the induced comonad resolution $k^t_{\bullet}: \text{Alg}_{\mathbb{T}}(B) \rightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+$ on the ∞ -category of \mathbb{T} -algebras in B encodes an absolute left lifting diagram*

$$\begin{array}{ccc} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & \text{Alg}_{\mathbb{T}}(B) \\ \parallel & \uparrow \beta & \downarrow \Delta \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k^t_{\bullet}} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+ \end{array} \quad := \quad \begin{array}{ccc} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & \text{Alg}_{\mathbb{T}}(B) \\ \parallel & \uparrow \beta & \downarrow \Delta \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k^t_{\bullet}} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+ \xrightarrow{\text{res}} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \xrightarrow{\text{ev}_{-1}} \text{Alg}_{\mathbb{T}}(B) \end{array} \quad (9.3.8)$$

created from the u^t -split simplicial object in B .

$$\begin{array}{ccc} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & \text{Alg}_{\mathbb{T}}(B) \\ \parallel & \uparrow \beta & \downarrow \Delta \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k^t_{\bullet}} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+ \xrightarrow{\text{res}} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \xrightarrow{\text{ev}_{-1}} \text{Alg}_{\mathbb{T}}(B) \end{array} \quad = \quad \begin{array}{ccc} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & \text{Alg}_{\mathbb{T}}(B) \\ \parallel & \uparrow \beta & \downarrow \Delta \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\text{bar}} & B^{\Delta_{\mathbb{T}}} \xrightarrow{\text{res}} B^{\Delta^{\text{op}}}_+ \xrightarrow{\text{res}} B^{\Delta^{\text{op}}} \end{array}$$

Thus (9.3.8) exists the algebras for a homotopy coherent monad as colimits of canonical simplicial objects of free algebras.

PROOF. Applying Lemma 9.3.4 to the monadic adjunction of Proposition 9.2.11, we see that the comonad resolution $k^t_{\bullet}: \text{Alg}_{\mathbb{T}}(B) \rightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+$ on $\text{Alg}_{\mathbb{T}}(B)$ and the bar resolution $\text{bar}: \text{Alg}_{\mathbb{T}}(B) \rightarrow$

$B^{\Delta_{\top}}$ defined in (9.2.8) together define a canonical u^t -split augmented cosimplicial object:

$$\begin{array}{ccccc}
 \mathrm{Alg}_{\mathbb{T}}(B) & & \xrightarrow{\text{bar}} & & B^{\Delta_{\top}} \\
 & \searrow \text{dashed} & & \searrow & \downarrow \text{res} \\
 & & S^{\Delta_+^{\mathrm{op}}}(u^t) & \longrightarrow & B^{\Delta_{\top}} \\
 & & \downarrow \lrcorner & & \downarrow \text{res} \\
 & & \mathrm{Alg}_{\mathbb{T}}(B)^{\Delta_+^{\mathrm{op}}} & \xrightarrow[(u^t)^{\Delta_+^{\mathrm{op}}}]{} & B^{\Delta_+^{\mathrm{op}}} \\
 & \searrow k^t & & & \\
 & & & &
 \end{array}$$

Now the claimed result follows immediately from Proposition 9.3.5. \square

Our final task for this section is to generalize the dual of Proposition 9.3.2, proving that the monadic forgetful functor creates all limits that B admits, whether or not t preserves them.

9.3.9. THEOREM. *Let $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$ be a homotopy coherent monad on an ∞ -category B . Then the monadic forgetful functor $u^t: \mathrm{Alg}_{\mathbb{T}}(B) \rightarrow B$ creates all limits that B admits.*

PROOF. See [50, §5] for now. \square

Exercises.

9.4. The monadicity theorem

Consider an adjunction

$$A \begin{array}{c} \xleftarrow{f} \\ \perp \\ \xrightarrow{u} \end{array} B \quad \eta: \mathrm{id}_B \Rightarrow uf, \quad \epsilon: fu \Rightarrow \mathrm{id}_A$$

between ∞ -categories, that is in the homotopy 2-category of an ∞ -cosmos. Theorem 8.3.4 proves that this data lifts to a homotopy coherent adjunction $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$, which then restricts to define a homotopy coherent monad $\mathbb{T}: \mathcal{A}dj \rightarrow \mathcal{K}$ on B . Proposition 9.2.11 then constructs a new homotopy coherent adjunction with \mathbb{T} as its underlying homotopy coherent monad: namely the **monadic adjunction** $f^t \dashv u^t$ between B and the ∞ -category of \mathbb{T} -algebras $\mathrm{Alg}_{\mathbb{T}}(B)$. Immediately from its construction as a right Kan extension — there is a simplicial natural transformation from the first homotopy coherent adjunction to the second whose component at $+$ is the identity and whose component at $-$ defines a functor that we call $r: A \rightarrow \mathrm{Alg}_{\mathbb{T}}(B)$ commuting strictly with all of the data of each homotopy coherent adjunction

$$\begin{array}{ccc}
 & & r \\
 & \xrightarrow{\text{dashed}} & \mathrm{Alg}_{\mathbb{T}}(B) \\
 A & \begin{array}{c} \xleftarrow{f} \\ \lrcorner \\ \xrightarrow{u} \end{array} & B \\
 & \begin{array}{c} \xleftarrow{f^t} \\ \lrcorner \\ \xrightarrow{u^t} \end{array} &
 \end{array}$$

This **monadicity theorem**, originally proven for 1-categories by Beck [1] and first proven for quasi-categories by Lurie [37], supplies conditions under which this comparison functor r is an equivalence, so that the ∞ -category A can be identified with the ∞ -category of \mathbb{T} -algebras.

To construct this simplicial natural transformation, we re-express the ∞ -category of algebras as a weighted limit of the full homotopy coherent adjunction diagram, not merely as a weighted limit of its underlying homotopy coherent monad.

9.4.1. PROPOSITION. *The ∞ -category of algebras associated to the homotopy coherent monad underlying a homotopy coherent adjunction $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ is the limit weighted by the weight $\text{lan } W_-$ defined by the left Kan extension*

$$\begin{array}{ccc} & \mathcal{A}dj & \\ \nearrow & \uparrow \cong & \searrow \text{lan } W_- \\ \mathcal{M}nd & \xrightarrow{W_-} & \mathcal{S}Set \end{array}$$

Explicitly, $\text{lan } W_-: \mathcal{A}dj \rightarrow \mathcal{S}Set$ is the homotopy coherent adjunction displayed on the top below

$$\begin{array}{ccc} \begin{array}{ccc} & \xleftarrow{f \circ -} & \\ \Delta^{\text{op}} & \perp & \Delta_+ \\ & \xrightarrow{u \circ -} & \\ & \xleftarrow{f \circ -} & \\ \text{Adj}(-, -) & \perp & \text{Adj}(-, +) \\ & \xrightarrow{u \circ -} & \end{array} & \begin{array}{c} \rightsquigarrow \\ \rightsquigarrow \end{array} & \begin{array}{c} \text{Adj} \xrightarrow{\text{lan } W_-} \mathcal{S}Set \\ \\ \text{Adj} \xrightarrow{\text{Adj}_-} \mathcal{S}Set \end{array} \end{array}$$

defined by restricting the domain of the right adjoint and codomain of the left adjoint of the representable adjunction $\mathcal{A}dj_-$ along the canonical inclusion $\Delta^{\text{op}} \hookrightarrow \Delta_+^{\text{op}}$

PROOF. Recall Lemma 7.1.20, which says that the weighted limit of a restricted diagram can be computed as the limit of the original diagram weighted by the left Kan extension of the weight. Thus

$$\lim_{\text{lan } W_-}^{\mathcal{A}dj} \mathbb{A} \cong \lim_{W_-}^{\mathcal{M}nd} \text{res } \mathbb{A}$$

recovers the ∞ -category of algebras for the homotopy coherent monad underlying \mathbb{A} .

All that remains is to compute the functor $\text{lan } W_-: \mathcal{A}dj \rightarrow \mathcal{S}Set$ explicitly. Because the inclusion $\mathcal{M}nd \hookrightarrow \mathcal{A}dj$ is full on $+$, $\text{lan } W_-(+) \cong W_-(+) \cong \mathcal{A}dj(-, +)$, since W_- was defined as the restriction of the covariant representable functor $\mathcal{A}dj_-: \mathcal{A}dj \rightarrow \mathcal{S}Set$ along $\mathcal{M}nd \hookrightarrow \mathcal{A}dj$. By the standard formula for left Kan extensions reviewed in Example 7.1.19 presented in the form of (7.1.6), the value of $\text{lan } W_-$ at the object $-$ is computed by

$$\begin{aligned} \text{lan } W_-(-) &\cong \int^{\mathcal{M}nd} \mathcal{A}dj(+, -) \times \mathcal{A}dj(-, +) \\ &\cong \text{coeq} \left(\mathcal{A}dj(+, -) \times \mathcal{A}dj(+, +) \times \mathcal{A}dj(-, +) \xrightarrow[\text{id} \times \circ]{\circ \times \text{id}} \mathcal{A}dj(+, -) \times \mathcal{A}dj(-, +) \right). \end{aligned}$$

By associativity of composition in $\mathcal{A}dj$, the composition map

$$\mathcal{A}dj(+, -) \times \mathcal{A}dj(-, +) \xrightarrow{\circ} \mathcal{A}dj(-, -)$$

defines a cone under the coequalizer diagram. By the graphical calculus and Proposition 8.1.10, the image of this map in $\mathcal{A}dj(-, -) \cong \Delta_+^{\text{op}}$ is comprised of those strictly undulating squiggles from $-$ to $-$

that pass through $+$. This is the subcategory $\Delta^{\text{op}} \hookrightarrow \Delta_+^{\text{op}}$. In fact, we claim that

$$\mathcal{A}dj(+, -) \times \mathcal{A}dj(+, +) \times \mathcal{A}dj(-, +) \xrightarrow[\text{id} \times \circ]{\circ \times \text{id}} \mathcal{A}dj(+, -) \times \mathcal{A}dj(-, +) \xrightarrow{\circ} \Delta^{\text{op}} \quad (9.4.2)$$

is a coequalizer diagram. The map from the coequalizer to Δ^{op} is surjective for the reason just described: a strictly undulating squiggle from $-$ to $-$ that passes through $+$ can be decomposed as a horizontal composite of a squiggle in $\mathcal{A}dj(-, +)$ followed by a squiggle in $\mathcal{A}dj(+, -)$. To see that the map from the coequalizer to Δ^{op} is injective, consider two distinct subdivisions of a squiggle from $-$ to $-$ into a pair of squiggles from $-$ to $+$ and from $+$ to $-$. The subsquiggle between the two chosen $+$ symbols in this an element of $\mathcal{A}dj(+, +)$, and thus this pair of elements of $\mathcal{A}dj(+, -) \times \mathcal{A}dj(-, +)$ are identified in the coequalizer diagram. \square

9.4.3. LEMMA. For any homotopy coherent adjunction $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$, there exists a simplicial natural transformation from \mathbb{A} to the monadic adjunction $\lim_{\text{lan } W_-}^{\mathcal{A}dj} \mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ whose components at $+$ and $-$ defined on weights by the counit of the adjunction

$$\begin{array}{ccc} \mathcal{S}Set^{\mathcal{A}dj} & \xleftarrow{\text{lan}} & \mathcal{S}Set^{\text{Mnd}} \\ & \perp & \\ & \xrightarrow{\text{res}} & \end{array} \quad \begin{array}{l} \text{lan } W_- = \text{lan res } \mathcal{A}dj_- \xrightarrow{\epsilon_-} \mathcal{A}dj_- \\ \mathcal{A}dj_+ \cong \text{lan res } \mathcal{A}dj_+ \xrightarrow[\cong]{\epsilon_+} \mathcal{A}dj_+ \end{array}$$

PROOF. Consider the diagram of weights in $\mathcal{S}Set^{\mathcal{A}dj}$.

$$\begin{array}{ccc} & \xleftarrow{\epsilon} & \\ \mathcal{A}dj_- & \xleftarrow{-\circ f} & \text{lan res } \mathcal{A}dj_- \\ & \searrow \text{lan res } (-\circ u) & \nearrow \\ & \mathcal{A}dj_+ \cong \text{lan res } \mathcal{A}dj_+ & \\ & \swarrow \text{lan res } (-\circ f) & \nearrow \\ & \xleftarrow{-\circ u} & \end{array}$$

Applying these weights to a homotopy coherent adjunction $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ with underlying adjunction $f \dashv u: A \rightarrow B$ yields

$$\begin{array}{ccc} A & \xleftarrow{f} & \text{Alg}_{\mathbb{T}}(B) \\ & \searrow u & \nearrow f^t \\ & B & \end{array}$$

(with a dashed arrow $r: A \rightarrow \text{Alg}_{\mathbb{T}}(B)$ and a curved arrow $u^t: B \rightarrow A$)

with the component ϵ_- inducing the non-identity component of the canonical comparison functor with the monadic adjunction. \square

9.4.4. EXAMPLE. Returning to Example 9.1.11, there is a Kan-complex enriched category $\text{Mon}(\mathcal{M})$ of monoids in \mathcal{M} equipped with a simplicially enriched adjunction

$$\begin{array}{ccc} \text{Mon}(\mathcal{M}) & \xleftarrow{F} & \mathcal{M} \\ & \perp & \\ & \xrightarrow{U} & \end{array}$$

Applying the homotopy coherent nerve, this defines a homotopy coherent adjunction between the quasi-categories $\mathfrak{R}Mon(\mathcal{M})$ and $\mathfrak{R}\mathcal{M}$. By Lemma 9.4.3, there is a canonical comparison map to the monadic homotopy coherent adjunction

$$\begin{array}{ccc}
 & & r \\
 & \swarrow & \searrow \\
 \mathfrak{R}Mon(\mathcal{M}) & & \text{Alg}_{\mathbb{T}}(\mathfrak{R}\mathcal{M}) \\
 & \nwarrow f & \nearrow u^t \\
 & \mathfrak{R}\mathcal{M} & \\
 & \nwarrow u & \nearrow f^t
 \end{array}$$

that is not an equivalence. Elements of $\mathfrak{R}Mon(\mathcal{M})$ are strict monoids in \mathcal{M} , while elements of $\text{Alg}_{\mathbb{T}}(\mathfrak{R}\mathcal{M})$ are homotopy coherent monoids, objects $X \in \mathcal{M}$ equipped with n -ary multiplication maps $\mu_n: X^{\otimes n} \rightarrow X$ for all n that are coherently associative up to higher homotopy.

9.4.5. LEMMA. *Let $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ be a homotopy coherent adjunction with right adjoint $u: A \rightarrow B$ and let $\mathbb{A}^{\mathbb{T}}: \mathcal{A}dj \rightarrow \mathcal{K}$ be the associated monadic adjunction. Then there is a canonical functor $L: \text{Alg}_{\mathbb{T}}(B) \rightarrow A^{\Delta^{\text{op}}}$ that*

- (i) *is u -split by the bar resolution $\text{bar}: \text{Alg}_{\mathbb{T}}(B) \rightarrow B^{\Delta^{\text{op}}}$,*
- (ii) *is so that the composite $L \circ r: A \rightarrow A^{\Delta^{\text{op}}}$ is the simplicial object underlying the comonad resolution $k_{\bullet}: A \rightarrow A^{\Delta^{\text{op}}}_+$, and*
- (iii) *is so that the composite $r^{\Delta^{\text{op}}} \circ L: \text{Alg}_{\mathbb{T}}(B) \rightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}$ is the simplicial object underlying the comonad resolution $k^t_{\bullet}: \text{Alg}_{\mathbb{T}}(B) \rightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}_+$.*

PROOF. The first two statements ask for a functor L that fits into a commutative diagram below-left

$$\begin{array}{ccc}
 A & \xrightarrow{k_{\bullet}} & A^{\Delta^{\text{op}}}_+ \\
 \downarrow r & & \downarrow \text{res} \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{L} & A^{\Delta^{\text{op}}} \\
 \downarrow \text{bar} & & \downarrow u^{\Delta^{\text{op}}} \\
 B^{\Delta^{\text{op}}} & \xrightarrow{\text{res}} & B^{\Delta^{\text{op}}}
 \end{array}
 \quad \Leftrightarrow \quad
 \begin{array}{ccc}
 \mathcal{A}dj_- & \xleftarrow{\circ} & \mathcal{A}dj_- \times \Delta^{\text{op}}_+ \\
 \uparrow \epsilon & & \uparrow \\
 \text{lan res } \mathcal{A}dj_- & \xleftarrow{\circ} & \mathcal{A}dj_- \times \Delta^{\text{op}} \\
 \uparrow \circ & & \uparrow (-\circ u) \times \text{id} \\
 \mathcal{A}dj_+ \times \Delta_{\top} & \xleftarrow{\text{id} \times (u \circ -)} & \mathcal{A}dj_+ \times \Delta^{\text{op}}
 \end{array}$$

in which each of the objects and all but the map L have been described as maps induced by taking weighted limits of the homotopy coherent adjunction diagram, with the weights in $\mathcal{S}Set^{\mathcal{A}dj}$ displayed above-right. By the Yoneda lemma, each of the three maps of weights labeled “ \circ ” are defined by a single map of simplicial sets. In the case of $\circ: \mathcal{A}dj_- \times \Delta^{\text{op}}_+ \rightarrow \mathcal{A}dj_-$ the Yoneda lemma says it suffices to define a map $\Delta^{\text{op}}_+ \rightarrow \mathcal{A}dj_-(-) = \Delta^{\text{op}}_+$; we take this map to be the identity, which implies that $\circ: \mathcal{A}dj_- \times \Delta^{\text{op}}_+ \rightarrow \mathcal{A}dj_-$ acts in both components by composing over $-$ in $\mathcal{A}dj$. In light of the explicit description of the adjunction $\text{lan res } \mathcal{A}dj_-$ given in Proposition 9.4.1 the other two maps labelled “ \circ ” may be defined similarly by identity maps. Since the dashed map makes the right-hand diagram of weights commute, the induced functor on weighted limits has the desired properties (i) and (ii).

The final statements demands commutativity of the diagram below left, which again follows from the commutativity of the corresponding diagram of weights below-right

$$\begin{array}{ccc}
 \text{Alg}_{\mathbb{T}}(B) & & \text{lan res } \mathcal{A}dj_{-} \\
 \downarrow L & \searrow k_{\bullet}^t & \uparrow \circ \\
 A^{\Delta^{\text{op}}} & \xrightarrow{r^{\Delta^{\text{op}}}} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \mathcal{A}dj_{-} \times \Delta^{\text{op}} \xleftarrow{\epsilon \times \text{id}} \text{lan res } \mathcal{A}dj_{-} \times \Delta^{\text{op}}
 \end{array} \quad \rightsquigarrow$$

this just amounting to the simple observation that the counit component $\epsilon: \text{lan res } \mathcal{A}dj_{-} \hookrightarrow \mathcal{A}dj_{-}$ is just given by the natural inclusion $\Delta^{\text{op}} \hookrightarrow \Delta_{+}^{\text{op}}$. \square

9.4.6. LEMMA. *Given any homotopy coherent adjunction with left adjoint $f: B \rightarrow A$, the diagram defined by restricting the canonical cone (2.3.10) built from the internalized comonad resolution $k_{\bullet}: A \rightarrow A^{\Delta_{+}^{\text{op}}}$ along $f: B \rightarrow A$*

$$\begin{array}{ccc}
 & A & \\
 f \nearrow & \downarrow \Delta & \\
 B \xrightarrow{k_{\bullet} f} A^{\Delta^{\text{op}}} & \uparrow \zeta & \\
 & & \\
 B \xrightarrow{f} A \xrightarrow{k_{\bullet}} A^{\Delta_{+}^{\text{op}}} & \xrightarrow{\text{res}} & A^{\Delta^{\text{op}}} \\
 & \uparrow A^{\nu^{\text{op}}} & \uparrow \text{ev}_{-1} \\
 & & A \downarrow \Delta
 \end{array}$$

displays f as an absolute colimit of the family of diagrams $k_{\bullet} f: B \rightarrow A^{\Delta^{\text{op}}}$.

PROOF. The homotopy coherent adjunction provides a commutative diagram below-left

$$\begin{array}{ccc}
 \Delta_{+}^{\text{op}} & \xrightarrow{\mathbb{A}} & \text{Fun}(A, A) \\
 f \circ - \downarrow & & \downarrow f \circ - \\
 \Delta_{\perp} & \xrightarrow{\mathbb{A}} & \text{Fun}(B, A)
 \end{array}
 \quad
 \begin{array}{ccc}
 B & \xrightarrow{f} & A \\
 \text{cobar} \downarrow & & \downarrow k_{\bullet} \\
 A^{\Delta_{\top}} & \xrightarrow{\text{res}} & A^{\Delta_{+}^{\text{op}}}
 \end{array}$$

which transposes to the commutative diagram above-right, which tells us that when the internalized comonad resolution $k_{\bullet}: A \rightarrow A^{\Delta_{+}^{\text{op}}}$ is restricted along f , it extends to a split augmented simplicial object, with the splittings on the opposite side as usual; this is no matter since Δ_{+}^{op} , considered as a full sub 2-category of $\mathcal{S}Set$ spanned by finite ordinals, is isomorphic to its co-dual via an isomorphism that commutes with $\Delta_{\top}^{\text{co}} \cong \Delta_{\perp}$. This tells us that the colimit cone of the statement is the one of Proposition 2.3.11. \square

There are many versions of the monadicity theorem. For expediency's sake, we prove just one for now. We break its statement into two parts, first constructing a left adjoint to the canonical comparison functor, which under additional hypotheses we prove defines an adjoint equivalence.

9.4.7. THEOREM. *Let $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ be a homotopy coherent adjunction with right adjoint $u: A \rightarrow B$ with underlying homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$. If A admits colimits of u -split simplicial objects then the canonical comparison functor admits a left adjoint:*

$$\begin{array}{ccc}
 & \ell & \\
 A & \xleftarrow{\quad} & \text{Alg}_{\mathbb{T}}(B) \\
 & \perp & \\
 & r &
 \end{array}$$

PROOF. If A admits colimits of u -split simplicial objects, then there exists an absolute left lifting of the u -split simplicial object $L: \text{Alg}_{\mathbb{T}}(B) \rightarrow A^{\Delta^{\text{op}}}$ defined in Lemma 9.4.5

$$\begin{array}{ccc} & & A \\ & \nearrow \ell & \downarrow \Delta \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow[L]{} & A^{\Delta^{\text{op}}} \end{array} \quad (9.4.8)$$

whose functor part we take to be the definition of the left adjoint $\ell: \text{Alg}_{\mathbb{T}}(B) \rightarrow A$. By Lemma 9.4.5(ii), the diagram defined by restricting along r agrees with the cosimplicial object underlying the comonad resolution, which has a canonical cone (2.3.10) as displayed below-left:

$$\begin{array}{ccc} & & A \\ & \nearrow \text{cv}_{-1} & \downarrow \Delta \\ A & \xrightarrow[k_{\bullet}]{} A^{\Delta^{\text{op}}} & \xrightarrow[\text{res}]{} A^{\Delta^{\text{op}}} \end{array} \quad = \quad \begin{array}{ccc} & & A \\ & \nearrow \exists! \uparrow \epsilon & \downarrow \Delta \\ A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow[L]{} A^{\Delta^{\text{op}}} \end{array} \quad (9.4.9)$$

By the universal property of the absolute left lifting diagram $(\ell r, \lambda r)$, this induces a unique 2-cell $\epsilon: \ell r \Rightarrow \text{id}_A$.

The unit is induced from the absolute left lifting diagram (9.3.8). By Lemma 9.4.5(iii), the comonad resolution $k_{\bullet}^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}}$ factors as $r^{\Delta^{\text{op}}} \cdot L$, so the pasted composite below left factors through the absolute left lifting diagram as below right.

$$\begin{array}{ccc} & A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) \\ & \nearrow \ell & \downarrow \Delta \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow[L]{} A^{\Delta^{\text{op}}} & \xrightarrow[r^{\Delta^{\text{op}}}]{} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array} \quad = \quad \begin{array}{ccc} & A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) \\ & \nearrow \exists! \uparrow \eta & \downarrow \Delta \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow[k_{\bullet}^t]{} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \end{array} \quad (9.4.10)$$

To verify the triangle equalities, note that by construction

$$\begin{array}{ccc} & A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) \\ & \nearrow \ell & \downarrow \Delta \\ A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow[k_{\bullet}^t]{} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array} \quad = \quad \begin{array}{ccc} & A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) \\ & \nearrow \exists! \uparrow \epsilon & \downarrow \Delta \\ A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow[L]{} A^{\Delta^{\text{op}}} & \xrightarrow[r^{\Delta^{\text{op}}}]{} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array}$$

$$= \begin{array}{ccc} & A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) \\ & \nearrow \uparrow A^{\nu^{\text{op}}} & \downarrow \Delta \\ A & \xrightarrow[k_{\bullet}]{} A^{\Delta^{\text{op}}} & \xrightarrow[r^{\Delta^{\text{op}}}]{} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array} \quad = \quad \begin{array}{ccc} & \text{Alg}_{\mathbb{T}}(B) & \\ & \nearrow \uparrow \beta & \downarrow \Delta \\ A & \xrightarrow[r]{} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow[k_{\bullet}^t]{} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array}$$

the last equality following from simplicial naturality of r and the definition of β as $\text{Alg}_{\mathbb{T}}(B)^{\nu^{\text{op}}}$ in Theorem 9.3.7. Thus the triangle equality composite $r\epsilon \cdot \eta r = \text{id}_r$.

It follows that the other triangle equality composite $\phi := \epsilon \ell \cdot \ell \eta$ is an idempotent:

$$\phi \cdot \phi := (\epsilon \ell \cdot \ell \eta) \cdot (\epsilon \ell \cdot \ell \eta) = \epsilon \ell \cdot \epsilon \ell r \ell \cdot \ell r \ell \eta \cdot \ell \eta = \epsilon \ell \cdot \ell r \epsilon \ell \cdot \ell \eta r \ell \cdot \ell \eta = \epsilon \ell \cdot \ell \eta =: \phi,$$

so to prove that $\epsilon\ell \cdot \ell\eta = \text{id}_\ell$ it suffices to show that ϕ is an isomorphism. To demonstrate this, we will show:

- (i) that ϕf^t is invertible, i.e., that ϕ is an isomorphism when restricted to free \mathbb{T} -algebras
- (ii) and that the putative left adjoint ℓ preserves the canonical colimit (9.3.8) that expresses every \mathbb{T} -algebra as a colimit of free \mathbb{T} -algebras.

We then combine (i) and (ii) to argue that ϕ is invertible.

To this end, we first observe by Lemma 9.4.6 and the definition of ℓ above that we have a pair of absolute left lifting diagrams:

$$\begin{array}{ccc} & A & \\ f \nearrow & \downarrow \Delta & \\ B & \xrightarrow{k_\bullet f} & A^{\Delta^{\text{op}}} \end{array} \cong \begin{array}{ccccc} & & A & & \\ & & \downarrow \Delta & & \\ B & \xrightarrow{f^t} & \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{L} & A^{\Delta^{\text{op}}} \\ & & \uparrow \lambda & & \end{array}$$

By simplicial naturality of the canonical comparison map $rf = f^t$, and by Lemma 9.4.5(ii) $Lf^t = Lrf = k_\bullet f$. Thus the absolute left lifting problems coincide and we obtain a canonical natural isomorphism $\gamma: \ell f^t \cong f$.

Now to prove the claim of (i) that ϕf^t is an isomorphism it suffices to prove that ηf^t is an isomorphism and that $\epsilon \ell f^t$ is an isomorphism — and by naturality of whiskering and the isomorphism $\gamma: \ell f^t \cong f$ just constructed, $\epsilon \ell f^t$ is an isomorphism if and only if ϵf is an isomorphism.

By (9.4.10), the construction of γ , and simplicial naturality of r , which implies that $r^{\Delta^{\text{op}}} k_\bullet = k_\bullet^t r$:

$$\begin{array}{ccc} \begin{array}{ccc} & A & \xrightarrow{r} \text{Alg}_{\mathbb{T}}(B) \\ f \nearrow & \uparrow \ell & \uparrow \eta \\ B & \xrightarrow{f^t} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_\bullet} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array} & = & \begin{array}{ccccc} & & A & \xrightarrow{r} & \text{Alg}_{\mathbb{T}}(B) \\ & & \downarrow \Delta & & \downarrow \Delta \\ B & \xrightarrow{f^t} & \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{L} & A^{\Delta^{\text{op}}} \xrightarrow{r^{\Delta^{\text{op}}}} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \\ & & \uparrow \lambda & & \end{array} \\ & & & & \cong \gamma \\ & & & & \uparrow \beta \\ & & & & \downarrow \Delta \\ & & & & \text{Alg}_{\mathbb{T}}(B) \\ & & & & \uparrow \beta \\ & & & & \downarrow \Delta \\ & & & & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array} \\ & = & & & = \\ & \begin{array}{ccc} & A & \xrightarrow{r} \text{Alg}_{\mathbb{T}}(B) \\ f \nearrow & \uparrow & \downarrow \Delta \\ B & \xrightarrow{k_\bullet f} A^{\Delta^{\text{op}}} & \xrightarrow{r^{\Delta^{\text{op}}}} \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \end{array} & & \begin{array}{ccc} & A & \xrightarrow{r} \text{Alg}_{\mathbb{T}}(B) \\ f \nearrow & \uparrow \zeta & \downarrow \Delta \\ B & \xrightarrow{k_\bullet f} A^{\Delta^{\text{op}}} & \end{array} \end{array}$$

So ηf^t is the inverse of the isomorphism $r\gamma$, and is consequently invertible.

Similarly, by (9.4.9),

$$\begin{array}{ccc} \begin{array}{ccccc} & & A & & \\ & & \downarrow \Delta & & \\ B & \xrightarrow{f} A & \xrightarrow{r} \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{L} & A^{\Delta^{\text{op}}} \\ & & \uparrow \epsilon & & \uparrow \lambda \end{array} & = & \begin{array}{ccc} & A & \\ f \nearrow & \downarrow \Delta & \\ B & \xrightarrow{k_\bullet f} & A^{\Delta^{\text{op}}} \end{array} \\ & & \cong \gamma \\ & & \uparrow \lambda \\ & & \downarrow \Delta \\ & & \text{Alg}_{\mathbb{T}}(B) \end{array}$$

so $\epsilon f = \gamma$ is also an isomorphism. Thus, we conclude that ϕf^t is invertible as claimed in (i).

To prove (ii), we must show that

$$\begin{array}{ccccc}
 & & \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\ell} & A \\
 & \nearrow \beta & \downarrow \Delta & & \downarrow \Delta \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_{\bullet}^t} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{\ell^{\Delta^{\text{op}}}} & A^{\Delta^{\text{op}}}
 \end{array} \tag{9.4.11}$$

is an absolute left lifting diagram. Of course, we expect this to be true because left adjoints preserve colimits by Theorem ??, but as we have not yet shown that ℓ is a left adjoint, this requires a direct argument.

By the equational characterization of Theorem ??, the cosmological functor $(-)^{\Delta^{\text{op}}}: \mathcal{K} \rightarrow \mathcal{K}$ preserves the absolute left lifting diagram (9.4.8); thus

$$\begin{array}{ccc}
 & & A^{\Delta^{\text{op}}} \\
 & \nearrow \ell^{\Delta^{\text{op}}} & \downarrow \Delta^{\Delta^{\text{op}}} \\
 \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{L^{\Delta^{\text{op}}}} & (A^{\Delta^{\text{op}}})^{\Delta^{\text{op}}}
 \end{array}$$

is absolute left lifting. Since $\lambda^{\Delta^{\text{op}}} \cdot \Delta = \Delta^{\Delta^{\text{op}}} \cdot \lambda$, there are two equivalent ways to compute the horizontal composite of this 2-cell with β , displayed below-left and below-right

$$\begin{array}{ccc}
 \begin{array}{ccccc}
 & & A & & \\
 & \nearrow \ell & \downarrow \Delta & & \\
 & \text{Alg}_{\mathbb{T}}(B) & & A^{\Delta^{\text{op}}} & \\
 & \downarrow \Delta & \nearrow \ell^{\Delta^{\text{op}}} & \downarrow \Delta^{\Delta^{\text{op}}} & \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_{\bullet}^t} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{L^{\Delta^{\text{op}}}} & (A^{\Delta^{\text{op}}})^{\Delta^{\text{op}}}
 \end{array} & = & \begin{array}{ccccc}
 & & A & & \\
 & \nearrow \ell & \downarrow \Delta & & \\
 & \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{L} & A^{\Delta^{\text{op}}} & \\
 & \downarrow \Delta & \nearrow \lambda & \downarrow \Delta^{\Delta^{\text{op}}} & \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_{\bullet}^t} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{L^{\Delta^{\text{op}}}} & (A^{\Delta^{\text{op}}})^{\Delta^{\text{op}}}
 \end{array}
 \end{array}$$

By Lemma 2.4.1, to show that (9.4.11) is absolute left lifting, i.e., that ℓ preserves the absolute left lifting diagram β , it suffices to prove that L preserves the absolute left lifting diagram β . By Proposition 4.3.15, to show that this diagram is absolute left lifting it suffices to show that for each $[n] \in \Delta$, that the diagram

$$\begin{array}{ccccc}
 & & \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{L} & A^{\Delta^{\text{op}}} & \xrightarrow{\text{ev}_n} & A \\
 & \nearrow \beta & \downarrow \Delta & & \downarrow \Delta^{\Delta^{\text{op}}} & & \downarrow \Delta \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_{\bullet}^t} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \xrightarrow{L^{\Delta^{\text{op}}}} & (A^{\Delta^{\text{op}}})^{\Delta^{\text{op}}} & \xrightarrow{\text{ev}_n} & A^{\Delta^{\text{op}}}
 \end{array}$$

is absolute left lifting.

By the construction of L in Lemma 9.4.5, $\text{ev}_n L: \text{Alg}_{\mathbb{T}}(B) \rightarrow A$ is the map induced by taking the weighted limits of the homotopy coherent adjunction $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ by the map of weights $- \circ (\underline{fu})^{n+1}: \mathcal{A}dj_- \rightarrow \text{lan res } \mathcal{A}dj_-$. Thus we see that $\text{ev}_n L$ is the map $ft^n u^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow A$, and in particular factors through $u^t: \text{Alg}_{\mathbb{T}}(B) \rightarrow B$. Since the canonical colimit of Theorem 9.3.7 is u^t -split, $(u^t, u^t \beta)$ is an absolute left lifting diagram preserved under postcomposition by all functors, and in

particular by $f(uf)^n$. Thus, the above diagram is absolute left lifting as claimed, which tells us that L and thus ℓ preserves the colimit (9.3.8).

It remains only to combine (i) and (ii) to argue that ϕ is invertible. For this, we consider the pasting equality

$$\begin{array}{ccc}
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\ell} & A \\
 \parallel \nearrow \uparrow \beta & \downarrow \Delta & \downarrow \Delta \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_{\bullet}^t} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \xrightarrow{\ell^{\Delta^{\text{op}}}} A^{\Delta^{\text{op}}} \\
 & \searrow \uparrow \phi^{\Delta^{\text{op}}} & \uparrow \ell^{\Delta^{\text{op}}}
 \end{array}
 =
 \begin{array}{ccc}
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\ell} & A \\
 \parallel \nearrow \uparrow \beta & \downarrow \Delta & \uparrow \phi \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_{\bullet}^t} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \xrightarrow{\ell^{\Delta^{\text{op}}}} A^{\Delta^{\text{op}}} \\
 & \searrow \uparrow \phi^{\Delta^{\text{op}}} & \uparrow \ell
 \end{array}$$

By the definition of k_{\bullet}^t , the components of the whiskered natural transformation $\phi^{\Delta^{\text{op}}} \cdot k_{\bullet}^t$ at $[n] \in \Delta^{\text{op}}$ is $\phi(f^t u^t)^{n+1}$, which is an isomorphism by (i). By Lemma ??, this proves that $\phi^{\Delta^{\text{op}}} \cdot k_{\bullet}^t$ is invertible. Thus, by (ii) the left hand diagram is isomorphic to an absolute left lifting diagram and thus is absolute left lifting. The pasting equality describes a factorization of the left hand absolute left lifting diagram through the absolute left lifting diagram of (ii) via ϕ , so by the uniqueness in the universal property of absolute left lifting diagrams we conclude that ϕ is invertible as desired. This proves that $(\ell \dashv r, \eta, \epsilon)$ defines an adjunction as claimed. \square

We now describe conditions under which the adjunction just constructed defines an adjoint equivalence. As the proof will reveal, condition (ii) implies that the unit is an isomorphism, while conditions (ii) and (iii) together imply that the counit is an isomorphism.

9.4.12. THEOREM (monadicity). *Let $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ be a homotopy coherent adjunction with right adjoint $u: A \rightarrow B$ with underlying homotopy coherent monad $\mathbb{T}: \mathcal{M}nd \rightarrow \mathcal{K}$. If*

- (i) *A admits colimits of u -split simplicial objects,*
- (ii) *$u: A \rightarrow B$ preserves them, and*
- (iii) *$u: A \rightarrow B$ is conservative*

then the canonical comparison functor $r: A \rightarrow \text{Alg}_{\mathbb{T}}(B)$ admits a left adjoint $\ell: \text{Alg}_{\mathbb{T}}(B) \rightarrow A$ defining an adjoint equivalence.

Note that Theorem 9.3.7 and Proposition 9.2.10 establish these properties for the monadic adjunction.

PROOF. Theorem 9.4.7 constructs an adjunction $(\ell \dashv r, \eta, \epsilon)$ under the hypothesis (i), with the left adjoint $\ell: \text{Alg}_{\mathbb{T}}(B) \rightarrow A$ defined as the colimit of the u -split family of diagrams $L: \text{Alg}_{\mathbb{T}}(B) \rightarrow A^{\Delta^{\text{op}}}$ with colimit cone $\lambda: \Delta \ell \Rightarrow L$. It remains to show that this defines an adjoint equivalence.

By hypothesis (ii), u preserves the u -split colimit diagram that defines ℓ . By Lemma 9.4.5(i), $u^{\Delta^{\text{op}}} L: \text{Alg}_{\mathbb{T}}(B) \rightarrow B^{\Delta^{\text{op}}}$ is the monadic bar resolution, so the absolute left lifting diagrams below-left and below-center are isomorphic:

$$\begin{array}{ccc}
 \begin{array}{ccc}
 A & \xrightarrow{u} & B \\
 \ell \nearrow & \downarrow \Delta & \downarrow \Delta \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{L} & A^{\Delta^{\text{op}}} \xrightarrow{u^{\Delta^{\text{op}}}} B^{\Delta^{\text{op}}}
 \end{array}
 & \cong &
 \begin{array}{ccc}
 & \xrightarrow{u^t} & B \\
 & \nearrow \text{ev}_0 & \downarrow \Delta \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\text{bar}} & B^{\Delta_{\mathbb{T}}} \xrightarrow{\text{res}} B^{\Delta^{\text{op}}}
 \end{array}
 \\
 & & = &
 \begin{array}{ccc}
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{u^t} & B \\
 \parallel \nearrow \uparrow \beta & \downarrow \Delta & \downarrow \Delta \\
 \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{k_{\bullet}^t} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \xrightarrow{(u^t)^{\Delta^{\text{op}}}} B^{\Delta^{\text{op}}}
 \end{array}
 \end{array}$$

By the construction of the bar resolution in Lemma 9.3.4, the absolute left lifting diagram above-left coincides with the one above-right. Now consulting (9.4.10), we see that the left-hand diagram above factors through the right-hand diagram above via $u^t\eta$. Thus $u^t\eta$ is invertible, and by Proposition 9.2.10, $\eta: \text{id}_{\text{Alg}_{\mathbb{T}}(B)} \cong r\ell$ is also an isomorphism.

By the same line of reasoning, the diagrams $Lr: A \rightarrow A^{\Delta^{\text{op}}}$ and $k_{\bullet}: A \rightarrow A^{\Delta^{\text{op}}}$ are both u -split by the bar resolution by Lemmas 9.4.5 and 9.3.4 respectively. Again by the hypothesis that $u: A \rightarrow B$ preserves u -split colimits, the absolute left lifting diagram below-left must be isomorphic to the one below-center, which equals the absolute left lifting diagram below-right:

$$\begin{array}{c}
 \begin{array}{ccccc}
 & A & \xrightarrow{u} & B & \\
 \nearrow \ell r & \downarrow \Delta & & \downarrow \Delta & \\
 A & \xrightarrow{Lr} A^{\Delta^{\text{op}}} & \xrightarrow{u^{\Delta^{\text{op}}}} & B^{\Delta^{\text{op}}} & \\
 \uparrow \lambda r & & & &
 \end{array} \cong \begin{array}{ccccc}
 & A & \xrightarrow{u} & B & \\
 & \searrow \text{bar} & \nearrow \text{cv}_0 & \downarrow \Delta & \\
 A & \xrightarrow{\text{bar}} B^{\Delta_{\top}} & \xrightarrow{\text{res}} B^{\Delta^{\text{op}}} & & \\
 & \uparrow B^{\nu^{\text{op}}} & & &
 \end{array} = \begin{array}{ccccc}
 & A & \xrightarrow{u} & B & \\
 \nearrow \text{double} & \downarrow \Delta & & \downarrow \Delta & \\
 A & \xrightarrow{k_{\bullet}} A^{\Delta^{\text{op}}} & \xrightarrow{u^{\Delta^{\text{op}}}} & B^{\Delta^{\text{op}}} & \\
 \uparrow A^{\nu^{\text{op}}} & & & &
 \end{array}
 \end{array}$$

By the uniqueness of factorization through absolute lifting diagrams it follows that $u\epsilon$ must be an isomorphism, and since u is conservative, this means that $\epsilon: \ell r \cong \text{id}_A$ is also invertible.

This completes the proof, but in fact we can sidestep the most difficult part of the proof of Theorem 9.4.7 — the proof of the triangle equality $\epsilon\ell \cdot \ell\eta = \text{id}_{\ell}$ — under the additional hypotheses (ii) and (iii) that imply invertibility of the unit and counit constructed there. Since η and ϵ are both invertible, the triangle equality composite $\epsilon\ell \cdot \ell\eta$ is an isomorphism. Since the other triangle equality composite is an identity, as in the proof of Proposition 2.1.11 this composite is also an idempotent and hence, by cancelation, this idempotent isomorphism is also an identity. \square

Exercises.

9.4.i. EXERCISE. Dualize the work of this section to define and characterize the *comonadic* adjunction between A and the ∞ -category of coalgebras for the homotopy coherent comonad acting on A .

9.5. Monadic descent

Consider once more the canonical comparison functor

$$\begin{array}{ccc}
 A & & \text{Alg}_{\mathbb{T}}(B) \\
 \swarrow f & \xleftarrow{u^t} & \searrow f^t \\
 B & &
 \end{array}
 \quad
 \begin{array}{c}
 \xrightarrow{r} \\
 \nwarrow u \\
 \nearrow f
 \end{array}$$

defining the component at $- \in \mathcal{A}dj$ of a simplicial natural transformation $\mathbb{A} \rightarrow \mathbb{A}^{\mathbb{T}}$ from a homotopy coherent adjunction to the monadic homotopy coherent adjunction built from its underlying homotopy coherent monad. The monadicity theorem of the previous section characterizes when the comparison functor $r: A \rightarrow \text{Alg}_{\mathbb{T}}(B)$ is an equivalence. Our aim in this section is to present a theorem proven by Sulyma [60], which characterizes when the functor $r: A \rightarrow \text{Alg}_{\mathbb{T}}(B)$ is fully faithful, which is the case just when the canonical map

$$\ulcorner \text{id}_r \urcorner: A^2 \rightarrow \text{Hom}_{\text{Alg}_{\mathbb{T}}(B)}(r, r)$$

is an equivalence over $A \times A$.

To analyze this situation, we consider the homotopy coherent comonad $\mathbb{K}: \mathcal{C}md \rightarrow \mathcal{K}$ underlying the homotopy coherent adjunction $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$. We write $k := fu$ for the functor part of the homotopy coherent comonad, an endomorphism $k: A \rightarrow A$ defined as the image of the unique atomic 0-arrow in $\mathcal{C}md$. Our first partial result, true for formal reasons under no additional hypotheses, observes that the canonical comparison functor r is always fully faithful on maps out of the comonad $k := fu: A \rightarrow A$ of the homotopy coherent adjunction.

9.5.1. LEMMA ([60, 3.5]). *The canonical comparison map pulls back along the substitution of the comonad $k: A \rightarrow A$ into its domain variable to define a fibered equivalence:*

$$\begin{array}{ccccc}
 \mathrm{Hom}_A(k, A) & \xrightarrow{\quad} & A^2 & \xrightarrow{\quad \lceil \mathrm{id}_r \rceil \quad} & \mathrm{Hom}_{\mathrm{Alg}_{\mathbb{T}}(B)}(r, r) \\
 \downarrow & \dashrightarrow \sim & \downarrow & & \downarrow \\
 & & \mathrm{Hom}_{\mathrm{Alg}_{\mathbb{T}}(B)}(rk, r) & \xrightarrow{\quad} & \\
 & & \downarrow & & \downarrow \\
 A \times A & \xrightarrow{\quad \mathrm{id} \times k \quad} & A \times A & &
 \end{array}$$

PROOF. By Proposition 4.1.1 applied to the adjunctions $f \dashv u$ and $f^t \dashv u^t$ and the relations $k = fu$, $u = u^t r$, and $rf = f^t$:

$$\begin{aligned}
 \mathrm{Hom}_A(k, A) &:= \mathrm{Hom}_A(fu, A) \simeq_{A \times A} \mathrm{Hom}_A(u, u) = \mathrm{Hom}_A(u^t r, u^t r) \simeq_{A \times A} \mathrm{Hom}_A(f^t u^t r, r) \\
 &= \mathrm{Hom}_A(rfu, r) =: \mathrm{Hom}_A(rk, r),
 \end{aligned}$$

and this equivalence is the one induced by id_r : the first equivalence is induced by pasting with $\eta = \eta^t$, while the second equivalence is induced by pasting with $\epsilon^t r = r\epsilon$. By the triangle equality $\epsilon f \cdot f \epsilon = \mathrm{id}_f$, the composite map is the one induced by pasting with id_r . \square

The statement of the main theorem requires the following definition, recall that the homotopy coherent comonad \mathbb{K} internalizes to define a functor $k_\bullet: A \rightarrow A^{\Delta_+^{\mathrm{op}}}$ that we call the **comonad resolution**, which restricts to a canonical cosimplicial object together with a cone under it.

9.5.2. DEFINITION. A generalized element $a: X \rightarrow A$ is **\mathbb{K} -cocomplete** if the restriction of the canonical diagram

$$\begin{array}{ccccc}
 X & \xrightarrow{a} & A & \xrightarrow{k_\bullet} & A^{\Delta_+^{\mathrm{op}}} \\
 & & \nearrow \mathrm{ev}_{-1} & \nearrow \uparrow A^{\nu^{\mathrm{op}}} & \downarrow \Delta \\
 & & & & A^{\Delta^{\mathrm{op}}}
 \end{array}$$

is an absolute left lifting diagram.

The terminology is adapted from Hess [22], who refers to such elements as “strongly \mathbb{K} -cocomplete.”

9.5.3. EXAMPLE (algebras are cocomplete). Theorem 9.3.7 proves that in a monadic homotopy coherent adjunction, the identity functor at the ∞ -category of algebras is $\mathbb{K}^{\mathbb{T}}$ -cocomplete. By restricting the absolute left lifting diagram, all generalized elements in the ∞ -category of \mathbb{T} -algebras are $\mathbb{K}^{\mathbb{T}}$ -cocomplete.

We now argue that the canonical comparison functor associated to a homotopy coherent adjunction is full and faithful if and only if all generalized elements of A are \mathbb{K} -cocomplete.

9.5.4. THEOREM ([60, 3.14]). *The canonical comparison functor $r: A \rightarrow \text{Alg}_{\mathbb{T}}(B)$ for a homotopy coherent adjunction \mathbb{A} with underlying homotopy coherent comonad \mathbb{K} is full and faithful if and only if the identity $\text{id}_A: A \rightarrow A$ is \mathbb{K} -cocomplete, i.e.,*

$$\begin{array}{ccc} & A & \\ \nearrow & \downarrow \Delta & \\ A & \xrightarrow{k_\bullet} & A^{\Delta^{\text{op}}} \end{array} \quad \uparrow \alpha \quad := \quad \begin{array}{ccccc} & & & A & \\ & & & \downarrow \Delta & \\ & & & A^{\Delta^{\text{op}}} & \\ \nearrow & \xrightarrow{k_\bullet} & A^{\Delta^{\text{op}}_+} & \xrightarrow{\text{res}} & A^{\Delta^{\text{op}}} \\ & & \uparrow A^{\Delta^{\text{op}}} & \nearrow \text{ev}_{-1} & \end{array} \quad (9.5.5)$$

is an absolute left lifting diagram.

In the special case where A admits colimits of u -split simplicial objects, the diagram (9.4.9) in the proof of Theorem 9.4.12 establishes the result: the composite $\ell r: A \rightarrow A$ defines the colimit of the comonad resolution $k_\bullet: A \rightarrow A^{\Delta^{\text{op}}}$, and this functor is related to the identity via the counit $\epsilon: \ell r \Rightarrow \text{id}_A$. To say that id_A is \mathbb{K} -cocomplete, is to say that $\text{id}_A: A \rightarrow A$ is the colimit of this diagram, which is the case if and only if ϵ is fully faithful. Since a right adjoint r is fully faithful just when the counit is an isomorphism (see Proposition 12.3.5 or Exercise 9.5.i), the result follows.

In the absence of this hypothesis, we cannot construct the left adjoint $\ell: \text{Alg}_{\mathbb{T}}(B) \rightarrow A$. In its place, we make use of the functor $L: \text{Alg}_{\mathbb{T}}(B) \rightarrow A^{\Delta^{\text{op}}}$ of Lemma 9.4.5. In the terminology of §3.4, the following lemma proves that the ∞ -category of cones under this diagram is right-represented by the canonical comparison functor $r: A \rightarrow \text{Alg}_{\mathbb{T}}(B)$.

9.5.6. LEMMA. *There is a fibered equivalence $\text{Hom}_{A^{\Delta^{\text{op}}}}(L, \Delta) \simeq \text{Hom}_{\text{Alg}_{\mathbb{T}}(B)}(\text{Alg}_{\mathbb{T}}(B), r)$ over $A \times \text{Alg}_{\mathbb{T}}(B)$.*

PROOF. The inverse equivalences are defined by 1-cell induction:

$$\begin{array}{ccc} & \text{Hom}_{A^{\Delta^{\text{op}}}}(L, \Delta) & \\ p_1 \swarrow & & \searrow p_0 \\ A & & \text{Alg}_{\mathbb{T}}(B) \\ \downarrow r & \Delta & \downarrow L \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & A^{\Delta^{\text{op}}} \\ & \Delta & \downarrow r^{\Delta^{\text{op}}} \\ & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \end{array} \quad \begin{array}{c} \phi \\ \Leftarrow \\ \end{array} \quad \begin{array}{c} k_\bullet \\ \curvearrowright \\ \end{array} \quad = \quad \begin{array}{ccc} & \text{Hom}_{A^{\Delta^{\text{op}}}}(L, \Delta) & \\ p_1 \swarrow & & \searrow p_0 \\ A & & \text{Alg}_{\mathbb{T}}(B) \\ \downarrow r & & \downarrow \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \\ & \Delta & \downarrow \\ & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \end{array} \quad \begin{array}{c} \exists! \zeta \\ \Leftarrow \\ \beta \\ \Leftarrow \\ \end{array} \quad \begin{array}{c} k_\bullet \\ \curvearrowright \\ \end{array}$$

and then

$$\begin{array}{ccc} & \text{Hom}_{A^{\Delta^{\text{op}}}}(L, \Delta) & \\ p_1 \swarrow & & \searrow p_0 \\ A & & \text{Alg}_{\mathbb{T}}(B) \\ \downarrow r & & \downarrow \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \\ & \Delta & \downarrow \\ & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \end{array} \quad \begin{array}{c} \zeta \\ \Leftarrow \\ \end{array} \quad = \quad \begin{array}{ccc} & \text{Hom}_{A^{\Delta^{\text{op}}}}(L, \Delta) & \\ p_1 \swarrow & & \searrow p_0 \\ A & & \text{Alg}_{\mathbb{T}}(B) \\ \downarrow r & & \downarrow \\ \text{Alg}_{\mathbb{T}}(B) & \xrightarrow{\Delta} & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} \\ & \Delta & \downarrow \\ & \text{Alg}_{\mathbb{T}}(B)^{\Delta^{\text{op}}} & \end{array} \quad \begin{array}{c} \downarrow \zeta \\ \text{Hom}_{\text{Alg}_{\mathbb{T}}(B)}(\text{Alg}_{\mathbb{T}}(B), r) \\ \phi \\ \Leftarrow \end{array}$$

And conversely,

$$\begin{array}{ccc}
 & \text{Hom}_{\text{Alg}_{\mathbb{T}}(B)}(\text{Alg}_{\mathbb{T}}(B), r) & \\
 p_1 \swarrow & \Downarrow \phi & \searrow p_0 \\
 A & \xrightarrow{r} & \text{Alg}_{\mathbb{T}}(B) \\
 \Delta \searrow \alpha & \Downarrow k_{\bullet} & \swarrow L \\
 & A^{\Delta^{\text{op}}} &
 \end{array}
 =
 \begin{array}{ccc}
 & \text{Hom}_{\text{Alg}_{\mathbb{T}}(B)}(\text{Alg}_{\mathbb{T}}(B), r) & \\
 p_1 \swarrow & \Downarrow \phi & \searrow p_0 \\
 A & \xrightarrow{r} & \text{Alg}_{\mathbb{T}}(B) \\
 \Delta \searrow & \Downarrow \phi & \swarrow L \\
 & A^{\Delta^{\text{op}}} &
 \end{array}$$

We leave the verification that these maps define inverse images to the reader. \square

PROOF OF THEOREM 9.5.4. By Lemma 9.4.5(ii), the fibered equivalence of Lemma 9.5.6 pulls back along $A \times r: A \times A \rightarrow A \times \text{Alg}_{\mathbb{T}}(B)$ to a fibered equivalence

$$\text{Hom}_{A^{\Delta^{\text{op}}}}(k_{\bullet}, \Delta) \simeq \text{Hom}_{\text{Alg}_{\mathbb{T}}(B)}(r, r)$$

over $A \times A$. Moreover this equivalence commutes with the canonical functors up to natural isomorphism

$$\begin{array}{ccc}
 & A^2 & \\
 \lceil \alpha \rceil \swarrow & \cong & \searrow \lceil \text{id}_r \rceil \\
 \text{Hom}_{A^{\Delta^{\text{op}}}}(k_{\bullet}, \Delta) & \simeq & \text{Hom}_{\text{Alg}_{\mathbb{T}}(B)}(r, r)
 \end{array}$$

Under the universal property of Proposition 3.3.7, the functor $\lceil \text{id}_r \rceil$ is classified by the 2-cell

$$\begin{array}{ccc}
 A^2 & \xrightarrow{p_1} & A \\
 \lceil \kappa \rceil \nearrow & & \searrow p_0 \\
 & A & \xrightarrow{r} \text{Alg}_{\mathbb{T}}(B)
 \end{array}$$

defined as the whiskered composite of the generic arrow over A . The equivalence converts this into a 2-cell under A^2 and over the cospan $A \xrightarrow{\Delta} A^{\Delta^{\text{op}}} \xleftarrow{k_{\bullet}} A$ by forming the horizontal composite of κ with α :

$$\begin{array}{ccccc}
 & & & & A \\
 & & & & \downarrow \Delta \\
 A^2 & \xrightarrow{p_1} & A & \xrightarrow{r} & \text{Alg}_{\mathbb{T}}(B) \xrightarrow{L} A^{\Delta^{\text{op}}} \\
 \lceil \kappa \rceil \nearrow & & \searrow p_0 & & \uparrow \alpha \\
 & & & & k_{\bullet}
 \end{array}$$

and this is the 2-cell that classifies the map labelled $\lceil \alpha \rceil$.

By Theorem 3.4.3, the left-diagonal map is an equivalence if and only if (9.5.5) is an absolute left lifting diagram. By Corollary 3.4.6, the right-diagonal map is an equivalence if and only if r is fully faithful. By the 2-of-3 property, either map is an equivalence if and only if both are, which is what we wished to show. \square

9.5.7. REMARK. Sulyma observes that the same argument shows that the canonical comparison functor $r: A \rightarrow \text{Alg}_{\mathbb{T}}(B)$ is fully faithful on maps out of $a: X \rightarrow A$ if and only if $a: X \rightarrow A$ is \mathbb{K} -cocomplete [60, 3.14].

The motivation for the result of Theorem 9.5.4 arises from the theory of monadic descent. To explain, we first require some definitions.

9.5.8. DEFINITION. The ∞ -category of descent data $\text{Dsc}_{\mathbb{T}}(B)$ of a homotopy coherent monad \mathbb{T} acting on an ∞ -category B is the ∞ -category of $\mathbb{K}^{\mathbb{T}}$ -coalgebras in the ∞ -category of \mathbb{T} -algebras:

$$\text{Dsc}_{\mathbb{T}}(B) := \text{Coalg}_{\mathbb{K}^{\mathbb{T}}}(\text{Alg}_{\mathbb{T}}(B)).$$

Elements are called **descent data**.

Unpacking Definition 9.5.8, we can clarify the meaning of “descent data.”

9.5.9. PROPOSITION. Let \mathbb{T} be a homotopy coherent monad acting on an ∞ -category $B \in \mathcal{K}$. The ∞ -category of descent data is the limit of $\mathbb{T}: \mathcal{Mnd} \rightarrow \mathcal{K}$ weighted by the weight $W_{\text{dsc}}: \mathcal{Mnd} \rightarrow \mathcal{SSet}$ given by the category Δ with the left Δ_+ -action by ordinal sum.

PROOF. Recall from Proposition 9.2.11 that the monadic adjunction associated to a homotopy coherent monad is defined as the limit of the homotopy coherent monad diagram \mathbb{T} weighted by the restriction of the Yoneda embedding $\mathcal{Y} \in \mathcal{SSet}^{\mathcal{Adj}^{\text{op}} \times \mathcal{Adj}}$ along the inclusion $\mathcal{Mnd} \hookrightarrow \mathcal{Adj}$ in the codomain variable, a weight we denote by $\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}} \mathcal{Y}$. From the monadic homotopy coherent adjunction

$$\mathbb{A}^{\mathbb{T}} := \lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}}} \mathcal{Y} \mathbb{T}: \mathcal{Adj} \rightarrow \mathcal{K},$$

the induced homotopy coherent comonad on $\text{Alg}_{\mathbb{T}}(B)$ is defined by restricting along the inclusion $\mathcal{Cmd} \hookrightarrow \mathcal{Adj}$, producing a diagram

$$\mathbb{T}^{\mathbb{K}} := \text{res}_{\mathcal{Adj}}^{\mathcal{Cmd}} (\lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}}} \mathcal{Y} \mathbb{T}): \mathcal{Cmd} \rightarrow \mathcal{K}.$$

Now dualizing Definition 9.2.5, the descent object is defined to be the ∞ -category of coalgebras for this homotopy coherent comonad, which is define to be the lifted weighted by the restriction of the representable functor $\mathcal{Adj}_+: \mathcal{Adj} \rightarrow \mathcal{SSet}$ along the inclusion $\mathcal{Cmd} \hookrightarrow \mathcal{Adj}$ in its codomain variable:

$$\text{Dsc}_{\mathbb{T}}(B) := \lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Cmd}} \mathcal{Adj}_+} \text{res}_{\mathcal{Adj}}^{\mathcal{Cmd}} (\lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}}} \mathcal{Y} \mathbb{T}).$$

Our aim is now to express this iterated weighted limit as a single weighted limit of the diagram \mathbb{T} . By Lemma 7.1.20, the weighted limit of the restricted diagram $\text{res}_{\mathcal{Adj}}^{\mathcal{Cmd}} (\lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}}} \mathcal{Y} \mathbb{T}): \mathcal{Cmd} \rightarrow \mathcal{K}$ is isomorphic to the limit of the diagram $\lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}}} \mathcal{Y} \mathbb{T}: \mathcal{Adj} \rightarrow \mathcal{K}$ weighted by the left Kan extension of the weight along $\mathcal{Cmd} \hookrightarrow \mathcal{Adj}$. Thus:

$$\begin{aligned} \text{Dsc}_{\mathbb{T}}(B) &:= \lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Cmd}} \mathcal{Adj}_+} \text{res}_{\mathcal{Adj}}^{\mathcal{Cmd}} (\lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}}} \mathcal{Y} \mathbb{T}) \\ &\cong \lim_{\text{lan}_{\mathcal{Cmd}}^{\mathcal{Adj}} \text{res}_{\mathcal{Adj}}^{\mathcal{Cmd}} \mathcal{Adj}_+} (\lim_{\text{res}_{\mathcal{Adj}}^{\mathcal{Mnd}}} \mathcal{Y} \mathbb{T}). \end{aligned}$$

By Definition 7.1.3(ii), the weighted limit of a weighted limit of a diagram is the limit of that diagram weighted by the weighted colimit of the weights:

$$\cong \lim_{\text{colim}_{\text{lan}_{\text{Cmd}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+}^{\text{Mnd}} \text{Adj}}^{\text{Mnd}} \text{res}_{\text{Adj}}^{\text{Mnd}} \mathcal{Y} \mathbb{T}.$$

By the symmetry of Definition 7.1.4, this weighted colimit of the weights is isomorphic to the weighted colimit of weights with the weight and diagram swapped, yielding the first isomorphism below. Now by Definition 7.1.3(i), this reduces to the restricting of the diagram along $\text{Mnd} \hookrightarrow \text{Adj}$, yielding the second isomorphism below:

$$\text{colim}_{\text{lan}_{\text{Cmd}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+}^{\text{Adj}} \text{res}_{\text{Adj}}^{\text{Mnd}} \mathcal{Y} \cong \text{colim}_{\text{res}_{\text{Adj}}^{\text{Mnd}} \mathcal{Y}}^{\text{Adj}} \text{lan}_{\text{Cmd}}^{\text{Adj}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+ \cong \text{res}_{\text{Adj}}^{\text{Mnd}} \text{lan}_{\text{Cmd}}^{\text{Adj}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+.$$

Upon substituting into our formula for $\text{Dsc}_{\mathbb{T}}(B)$ we conclude that

$$\cong \lim_{\text{res}_{\text{Adj}}^{\text{Mnd}} \text{lan}_{\text{Cmd}}^{\text{Adj}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+}^{\text{Mnd}} \mathbb{T}$$

as desired.

It remains only to simplify the description of the weight

$$W_{\text{dsc}} := \text{res}_{\text{Adj}}^{\text{Mnd}} \text{lan}_{\text{Cmd}}^{\text{Adj}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+ \in \mathcal{SSet}^{\text{Mnd}}.$$

By Observation 9.2.1, this diagram defines a category $W_{\text{dsc}}(+)$ — which we will shortly identify, defined by evaluating at $+\in \text{Mnd}$ — and a homotopy coherent monad on it. This is the dual of the calculation of Proposition 9.4.1. By the formula for pointwise left Kan extensions, the value of $\text{lan}_{\text{Cmd}}^{\text{Adj}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+$ at the object $+$ is computed by

$$\begin{aligned} W_{\text{dsc}}(+) &:= (\text{lan}_{\text{Cmd}}^{\text{Adj}} \text{res}_{\text{Adj}}^{\text{Cmd}} \text{Adj}_+)(+) \\ &\cong \int^{\text{Cmd}} \text{Adj}(-, +) \times \text{Adj}(+, -) \\ &\cong \text{coeq} \left(\text{Adj}(-, +) \times \text{Adj}(-, -) \times \text{Adj}(+, -) \xrightarrow[\text{id} \times \circ]{\circ \times \text{id}} \text{Adj}(-, +) \times \text{Adj}(+, -) \right) \\ &\cong \text{coeq} \left(\Delta_{\top} \times \Delta_+^{\text{op}} \times \Delta_{\perp} \xrightarrow[\text{id} \times \circ]{\circ \times \text{id}} \Delta_{\top} \times \Delta_{\perp} \right) \\ &\cong \Delta. \end{aligned}$$

The monad structure is given by a “left action of Δ_+ ,” in this case by the functor

$$\oplus: \Delta_+ \times \Delta \rightarrow \Delta$$

obtained by restricting the ordinal sum composition in Adj . □

9.5.10. REMARK. The W_{dsc} -weighted limit cone on $\text{Dsc}_{\mathbb{T}}(B)$ takes the form of a Δ_+ -invariant diagram $\Delta \rightarrow \text{Fun}(\text{Dsc}_{\mathbb{T}}(B), B)$ that we refer to as the **generic descent datum**. Writing $b: \text{Dsc}_{\mathbb{T}}(B) \rightarrow B$ for

the 0-arrow in the image of the terminal element of Δ , this diagram has the form

$$\begin{array}{ccccc} & & -\eta \rightarrow & & \\ & -\eta \rightarrow & \leftarrow \mu - & & \\ b \leftarrow \beta - & tb & -t\eta \rightarrow & t^2b & \cdots \\ & -\theta \rightarrow & \leftarrow t\beta - & & \\ & & -t\theta \rightarrow & & \end{array}$$

The generic descent datum, internalizes to a functor $\mathrm{Dsc}_{\mathbb{T}}(B) \rightarrow B^{\Delta}$.

9.5.11. OBSERVATION. The weights $W_-, W_{\mathrm{dsc}}, W_+ \in \mathcal{SSet}^{Mnd}$ are given by the categories Δ, Δ_{\top} , and Δ_+ , respectively, with the left Δ_+ -action in each case given by ordinal sum. Thus the inclusions

$$\Delta \hookrightarrow \Delta_{\top} \hookrightarrow \Delta_+ \quad \Leftrightarrow \quad W_- \rightarrow W_{\mathrm{dsc}} \rightarrow W_+ \in \mathcal{SSet}^{Mnd}$$

are Δ_+ -equivariant, defining maps of weights. On weighted limits, we thus get canonical maps that fit into a commutative diagram

$$\begin{array}{ccccc} \lim_{W_+} \mathbb{T} & \longrightarrow & \lim_{W_{\mathrm{dsc}}} \mathbb{T} & \longrightarrow & \lim_{W_-} \mathbb{T} \\ \wr & & \wr & & \wr \\ B & \xrightarrow{c} & \mathrm{Dsc}_{\mathbb{T}}(B) & \longrightarrow & \mathrm{Alg}_{\mathbb{T}}(B) \\ & \searrow f^t & & \nearrow & \end{array}$$

The canonical functor $c: B \rightarrow \mathrm{Dsc}_{\mathbb{T}}(B)$ can also be described as the non-identity component of the simplicial natural transformation from the monadic homotopy coherent adjunction $\mathbb{A}^{\mathbb{T}}$ to the comonadic homotopy coherent adjunction associated to its homotopy coherent comonad $\mathbb{K}^{\mathbb{T}}$.

$$\begin{array}{ccc} & \xrightarrow{c} & \\ B & \xleftarrow{u^t} & \mathrm{Dsc}_{\mathbb{T}}(B) \\ & \searrow f^t & \nearrow c^{kt} \\ & \mathrm{Alg}_{\mathbb{T}}(B) & \end{array}$$

(Note: The diagram shows curved arrows u^t and u^{kt} from $\mathrm{Dsc}_{\mathbb{T}}(B)$ to B and $\mathrm{Alg}_{\mathbb{T}}(B)$ respectively, and curved arrows f^t and c^{kt} from B and $\mathrm{Dsc}_{\mathbb{T}}(B)$ to $\mathrm{Alg}_{\mathbb{T}}(B)$ respectively. There are also small triangles indicating naturality or coherence.)

9.5.12. DEFINITION. The homotopy coherent monad \mathbb{T} satisfies **descent** if $c: B \rightarrow \mathrm{Dsc}_{\mathbb{T}}(B)$ is fully faithful and satisfies **effective descent** if $c: B \rightarrow \mathrm{Dsc}_{\mathbb{T}}(B)$ is an equivalence. The homotopy coherent monad \mathbb{T} satisfies effective descent just when the monadic homotopy coherent adjunction is also *comonadic*.

Specializing the dual of Theorem 9.5.4, we have:

9.5.13. COROLLARY. A homotopy coherent monad \mathbb{T} acting on B satisfies descent if and only if $\mathrm{id}_B: B \rightarrow B$ is \mathbb{T} -complete. *finish*

Dually, for a homotopy coherent comonad \mathbb{K} acting on an ∞ -category A , the ∞ -category of **codescent data** is

$$\mathrm{Codesc}_{\mathbb{K}}(A) := \mathrm{Alg}_{\mathbb{T}\mathbb{K}}(\mathrm{Coalg}_{\mathbb{K}}(A)).$$

The homotopy coherent comonad \mathbb{K} satisfies **codescent** if the canonical comparison map $c: A \rightarrow \mathrm{Codesc}_{\mathbb{K}}(A)$ is fully faithful and satisfies **effective codescent** if $c: A \rightarrow \mathrm{Codesc}_{\mathbb{K}}(A)$ is an equivalence, which is the case just when the comonadic homotopy coherent adjunction is also *monadic*. The former holds just when $\mathrm{id}_A: A \rightarrow A$ is \mathbb{K} -cocomplete.

Exercises.

9.5.i. EXERCISE. Use Corollary 3.4.10 and Proposition 4.1.1 to anticipate the proof of Proposition 12.3.5: show that a right adjoint is fully faithful if and only if the counit of the adjunction is an isomorphism.

9.5.ii. EXERCISE. Prove the claim made in Remark 9.5.7.

9.6. Homotopy coherent monad maps

Two adjunctions are *equivalent* just when there exists a pair of equivalences as displayed horizontally below that commute up to isomorphism with the right adjoints

$$\begin{array}{ccc} A & \xrightarrow{\sim a} & A' \\ f \left(\begin{array}{c} \lrcorner \downarrow u \\ \lrcorner \downarrow \lrcorner \end{array} \right) & \cong & u' \left(\begin{array}{c} \lrcorner \downarrow \lrcorner \\ \lrcorner \downarrow \lrcorner \end{array} \right) f' \\ B & \xrightarrow{\sim b} & B' \end{array}$$

and so that the mate of the isomorphism $bu \cong u'a$ defines an isomorphism $f'b \cong af$ in the square formed with the left adjoints. The pair $f \dashv u$ extends to a homotopy coherent adjunction, which defines a homotopy coherent monad on B , and similarly $f' \dashv u'$ defines a homotopy coherent monad on B' . But are the monadic adjunctions induced by these homotopy coherent monads similarly equivalent?

A simpler question also requires some argument. Consider just a single adjunction $f \dashv u$ in the homotopy 2-category $\mathbf{h}\mathcal{K}$ of an ∞ -cosmos and two extensions to homotopy coherent adjunctions $\mathbb{A}, \mathbb{A}': \mathcal{A}dj \rightarrow \mathcal{K}$. By Proposition 8.4.8, \mathbb{A} and \mathbb{A}' are isomorphic as vertices of the Kan complex $\mathbf{cohadj}(\mathcal{K})$. But what does this actually mean?

Unpacking Definition 8.4.1, we are given a homotopy coherent adjunction $\hat{\mathbb{A}}: \mathcal{A}dj \rightarrow \mathcal{K}^{\mathbb{I}}$ whose target is the quasi-categorically enriched category whose objects are the same as in \mathcal{K} and whose functor-spaces are defined as the cotensor of the functor spaces of \mathcal{K} with \mathbb{I} so that when $\hat{\mathbb{A}}$ is evaluated at the endpoints of \mathbb{I} , this returns the homotopy coherent adjunctions \mathbb{A} and \mathbb{A}' . Note this data does *not* define a simplicial natural transformation $\mathbb{A} \rightarrow \mathbb{A}'$, in particular, there would be no obvious choices for its components other than the identity functors at A and B , so we cannot directly apply Proposition 7.3.1 to construct an equivalence between the ∞ -categories of algebras. The following result explains how to construct an equivalence between two homotopy coherent adjunctions that are isomorphic as vertices of $\mathbf{cohadj}(\mathcal{K})$ in slightly greater generality than described here.

9.6.1. PROPOSITION. *Suppose $u, u': A \rightarrow B$ are naturally isomorphic right adjoints in the homotopy 2-category $\mathbf{h}\mathcal{K}$ of an ∞ -cosmos \mathcal{K} . Then any homotopy coherent adjunctions $\mathbb{A}: \mathcal{A}dj \rightarrow \mathcal{K}$ and $\mathbb{A}': \mathcal{A}dj \rightarrow \mathcal{K}$ extending u and u' are connected by a zig zag of simplicial natural equivalences, and hence the monadic homotopy coherent adjunctions for \mathbb{A} and \mathbb{A}' are naturally equivalent.*

PROOF. By Theorem 8.4.14, the forgetful functor $p_R: \mathbf{cohadj}(\mathcal{K}) \rightrightarrows \mathbf{rightadj}(\mathcal{K})$ defines a trivial fibration of Kan complexes, where $\mathbf{rightadj}(\mathcal{K})$ is defined as a sub-quasi-category of $\coprod_{A, B \in \mathcal{K}} \mathbf{Fun}(A, B)$

containing the right adjoint functors and isomorphisms between them. The postulated natural isomorphism $\alpha: u \cong u'$ defines a lifting problem

$$\begin{array}{ccc} \partial \mathbb{I} & \xrightarrow{A+A'} & \text{cohadj}(\mathcal{K}) \\ \downarrow & \nearrow \hat{A} & \downarrow p_R \\ \mathbb{I} & \xrightarrow{\alpha} & \text{rightadj}(\mathcal{K}) \end{array}$$

whose solution defines a simplicial functor $\hat{A}: \mathcal{A}dj \rightarrow \mathcal{K}^{\mathbb{I}}$.

Consulting the definition of the cotensor of a quasi-categorically enriched category with a simplicial set U in Definition 8.4.1, we see that when \mathcal{K} is an ∞ -cosmos (and in particular admits simplicial cotensors of objects inside \mathcal{K}), \mathcal{K}^U is concisely defined as the Kleisli category for the monad $(-)^U: \mathcal{K} \rightarrow \mathcal{K}$, with the unit defined by the constant map $\Delta: A \rightarrow A^U$ and the multiplication defined by the fold map $\nabla: (A^U)^U \cong A^{U \times U} \rightarrow A^U$, both arising from the comonoid $(U, !: U \rightarrow \mathbb{1}, \Delta: U \rightarrow U \times U)$ in $\mathcal{S}Set$. As such, the quasi-categorically enriched categories \mathcal{K} and \mathcal{K}^U are connected by the Kleisli adjunction

$$\begin{array}{ccc} & \Delta & \\ \mathcal{K} & \xrightarrow{\quad} & \mathcal{K}^U \\ & \perp & \\ & K & \end{array}$$

whose left adjoint is identity on objects and acts on homs by post-composing with the constant map

$$\text{Fun}(X, A) \xrightarrow{\Delta_*} \text{Fun}(X, A^U) \cong \text{Fun}(X, A)^U,$$

while the right adjoint sends A to A^U and acts on homs by

$$\text{Fun}(X, A)^U \cong \text{Fun}(X, A^U) \xrightarrow{(-)^U} \text{Fun}(X^U, (A^U)^U) \xrightarrow{\nabla_*} \text{Fun}(X^U, A^U).$$

Now for each vertex $u: \mathbb{1} \rightarrow U$, there is a simplicial natural transformation $K \Rightarrow \text{ev}_u$ whose components are given by $\text{ev}_u: A^U \twoheadrightarrow A$.

Specializing to $U = \mathbb{I}$, we obtain a zig-zag of simplicial natural transformations

$$\begin{array}{ccc} & \text{ev}_0 & \\ \mathcal{K}^{\mathbb{I}} & \xrightarrow{\hat{A}'} & \mathcal{K} \\ & \downarrow K & \\ & \text{ev}_1 & \end{array}$$

whose components are the trivial fibrations $\text{ev}_0, \text{ev}_1: A^{\mathbb{I}} \twoheadrightarrow A$, and in particular, define equivalences. Precomposing with \hat{A}' , this defines a zig-zag of simplicial natural equivalences between the homotopy coherent adjunction \hat{A} and the homotopy coherent adjunction \hat{A}' . The homotopy coherent monadic adjunction is computed as a flexible weighted limit of these diagrams, so Proposition 7.3.1 implies that the homotopy coherent monadic adjunctions are equivalent, as claimed. \square

Proposition 9.6.1 can be understood as presenting an affirmative answer to the question posed at the start of this section. The equivalence a and b can be promoted to adjoint equivalences by Proposition 2.1.11, then composed with the adjunctions $f \dashv u$ and $f' \dashv u'$ to produce a pair of naturally isomorphic adjunctions between the same ∞ -categories, to which Proposition 9.6.1 applies. The details are left as Exercise 9.6.i. But even with this question resolved, such considerations inspire

a more general avenue of inquiry that is worth pursuing, which we do following Zaganidis work in his PhD thesis [65].

To state the question, we first review a bit of classical 2-category theory.

9.6.2. DEFINITION (monad morphism in a 2-category). Let (t, η, μ) be a monad on B and let (s, ι, ν) be a monad on A in a 2-category. A **(lax) monad morphism** $(f, \chi): (t, \eta, \mu) \rightarrow (s, \iota, \nu)$ is given by:

- a functor $f: B \rightarrow A$
- a 2-cell $\chi: sf \Rightarrow ft$

so that the following pasting equalities hold

$$\begin{array}{c}
 \begin{array}{ccc}
 & A & \\
 s \nearrow & & \searrow s \\
 A & \xrightarrow{s} & A \\
 f \uparrow & \Downarrow \chi & \uparrow f \\
 B & \xrightarrow{t} & B
 \end{array}
 =
 \begin{array}{ccc}
 & A & \\
 s \nearrow & & \searrow s \\
 A & \xrightarrow{f} & B \\
 f \uparrow & \Downarrow \chi & \uparrow f \\
 B & \xrightarrow{t} & B
 \end{array}
 \end{array}
 \quad
 \begin{array}{ccc}
 & A & \\
 \Downarrow \iota & & \\
 A & \xrightarrow{s} & A \\
 f \uparrow & \Downarrow \chi & \uparrow f \\
 B & \xrightarrow{t} & B
 \end{array}
 =
 \begin{array}{ccc}
 & A & \\
 & \xrightarrow{\quad} & A \\
 f \uparrow & & \uparrow f \\
 B & \xrightarrow{t} & B
 \end{array}
 \begin{array}{ccc}
 & A & \\
 & \xrightarrow{\quad} & A \\
 & \Downarrow \eta & \\
 & B & \\
 & \xrightarrow{t} &
 \end{array}$$

If $(g, \psi): (t, \eta, \mu) \rightarrow (s, \iota, \nu)$ is a second monad morphism, a **monad transformation** $\alpha: (f, \chi) \Rightarrow (g, \psi)$ is given by a 2-cell $\alpha: f \Rightarrow g$ so that

$$\begin{array}{ccc}
 B & \xrightarrow{f} & A \\
 t \downarrow & \Downarrow \chi & \downarrow s \\
 B & \xrightarrow{f} & A \\
 & \Downarrow \alpha & \\
 B & \xrightarrow{g} & A
 \end{array}
 =
 \begin{array}{ccc}
 B & \xrightarrow{f} & A \\
 & \Downarrow \alpha & \\
 B & \xrightarrow{g} & A \\
 & \Downarrow \psi & \\
 B & \xrightarrow{g} & A
 \end{array}$$

This defines the 2-category of monads and monad morphisms in a fixed 2-category \mathcal{C} [56]. If \mathcal{C} admits *Eilenberg-Moore objects*, which are to represent the “category of algebras functor,”³ then this 2-category defines a reflective subcategory of a particular 2-category of adjunctions that we now introduce.

9.6.3. DEFINITION. A **right adjunction morphism** is a commutative square between the right adjoints

$$\begin{array}{ccc}
 A & \xrightarrow{a} & A' \\
 f \downarrow \dashv u & & u' \downarrow \dashv f' \\
 B & \xrightarrow{b} & B'
 \end{array}$$

and a **right adjunction transformation** is a pair of natural transformations

$$\begin{array}{ccc}
 A & \xrightarrow{a} & A' \\
 \Downarrow \alpha & & \\
 A & \xrightarrow{a'} & A' \\
 f \downarrow \dashv u & & u' \downarrow \dashv f' \\
 B & \xrightarrow{b} & B' \\
 \Downarrow \beta & & \\
 B & \xrightarrow{b'} & B'
 \end{array}$$

³A 2-category \mathcal{C} admits Eilenberg-Moore objects whenever it admits the PIE limits alluded to in Digression 7.2.6 [30].

so that $u'\alpha = \beta u$.

9.6.4. PROPOSITION. *If \mathcal{C} is a 2-category admitting the construction of Eilenberg-Moore objects, the forgetful 2-functor from the 2-category of adjunctions, right adjunction morphisms, and right adjunction transformations to the 2-category of monads admits a fully faithful right 2-adjoint.*

PROOF. Exercise 9.6.ii or see [12]. □

9.6.5. REMARK. A lax morphism of monads $(f: B \rightarrow A, \chi: sf \Rightarrow ft)$ as in Definition 9.6.2 corresponds to a lift of f along the right adjoints of the monadic adjunctions for t and s , but this lifted functor does not commute with the left adjoints. In general, the mate of the identity functor is non-invertible.

The question is what is a homotopy coherent monad morphism?

9.6.6. DIGRESSION. Consider homotopy coherent monads $\mathbb{T}: \mathcal{Mnd} \rightarrow \mathcal{K}$ and $\mathbb{S}: \mathcal{Mnd} \rightarrow \mathcal{K}$ on B and A . A simplicial natural transformation $f: \mathbb{T} \Rightarrow \mathbb{S}$ is given by its unique component $f: B \rightarrow A$ satisfying a strict naturality condition relative to the bar resolutions

$$\begin{array}{ccc} \Delta_+ & \xrightarrow{\mathbb{T}} & \text{Fun}(B, B) \\ s \downarrow & & \downarrow f_* \\ \text{Fun}(A, A) & \xrightarrow{f^*} & \text{Fun}(B, A) \end{array}$$

Such data defines a monad morphism in the homotopy 2-category whose component $\chi: sf \Rightarrow ft$ is the identity 2-cell. So in general, this definition is too strict.

By Remark 8.4.2, if the vertices \mathbb{T} and \mathbb{S} are in the same connected component of $\text{Icon}(\mathcal{Mnd}, \mathcal{K})$, then necessarily $B = A$, which is also too rigid a notion of monad morphism to consider in general.

We present the data of a homotopy coherent monad morphism by means of a simplicial computad \mathcal{Mnd}_2 introduced by Zaganidis. Generalizing the relationship between the simplicial computad \mathcal{Mnd} and the simplicial computad \mathcal{Adj} , \mathcal{Mnd}_2 defines a simplicial subcategory of a simplicial category \mathcal{Adj}_2 that we introduce first via a graphical calculus developed in Zaganidis [65, ?]. This graphical calculus extends to a sequence of composable adjunction morphisms so we might as well introduce \mathcal{Adj}_n in its full generality.

The simplicial category \mathcal{Adj}_n is a 2-category whose hom-wise nerve can be presented via a graphical calculus, exactly as was the case for \mathcal{Adj} . A 2-categorical description of \mathcal{Adj}_n is given in [65, §3.1.1]. The graphical calculus that presents \mathcal{Adj}_n as a simplicial category is described in more detail in [65, §3.1.2].

9.6.7. DEFINITION. The objects of \mathcal{Adj}_n are pairs whose first component is either $+$ or $-$ and whose second component $i \in \{0, 1, \dots, n-1\}$ is best thought of as a *color* drawn from a linearly ordered set where the color 0 is the “lightest” and the color $n-1$ is the “darkest.” Note the objects of \mathcal{Adj}_n are the objects of the product simplicial category $\mathcal{Adj} \times \mathbb{n}$; we write $+_i$ or $-_i$ for the two objects with color i or either \pm_i or \mp_i to denote a generic object of $\mathcal{Adj} \times \mathbb{n}$.

The n -arrows in \mathcal{Adj}_n are **strictly undulating colored squiggles on n -lines**. In more detail, an n -arrow $\pm_k \rightarrow \mp_j$ is permitted only if $k \geq j$; that is the color of the domain, appearing on the right, must be “darker” than the color of the codomain, appearing on the left. The data of a morphism

$\pm_k \rightarrow \mp_j$ is given by a strictly undulating squiggle of $\mathcal{A}dj$ from \pm to \mp as appropriate, with all four choices of $+$ or $-$ possible, together with a **coloring**, with colors drawn from the interval $[j, k]$, of the connected components of each of the strips between the lines i and $i-1$ for some $i \in [n]$ of the shaded region under the squiggle diagram. This coloring must satisfy the axioms:

- In the strip between the i th and $i-1$ th lines for $i \in [n]$, the coloring function is monotone, becoming darker as you move from left to right.
- If a connected component of a strip above the line i shares a boundary with a connected component of a strip below the line i , then color of the top strip is lighter than the color of the bottom strip, i.e., the coloring function is monotone, becoming darker as you move from top to bottom in a single vertical section of the squiggle diagram.
- Finally, in the case of a morphism $\neg_k \rightarrow \pm_j$, each of the strips that touches the right-hand boundary must be colored the maximal color k .

For a fully formal definition together with a description of the composition, face, and degeneracy actions are described in [65, §3.1.2].

The monochromatic strictly undulating squiggles in $\mathcal{A}dj_{\mathfrak{n}}$ define the data found in just one of its n homotopy coherent adjunctions.

9.6.8. EXAMPLE. The atomic 0-arrows of $\mathcal{A}dj_{\mathfrak{n}}$ define n adjunctions that we denote by $\underline{f}_{-i} \dashv \underline{u}_i$ and $n-1$ adjunction morphisms as depicted below:

$$\begin{array}{ccccccc}
 -0 & \xleftarrow{\underline{a}_1} & -1 & \xleftarrow{\quad} & \cdots & \xleftarrow{\quad} & -n-2 & \xleftarrow{\underline{a}_{n-1}} & -n-1 \\
 \uparrow \underline{f}_{-0} \left(\begin{array}{c} \dashv \\ \downarrow \end{array} \right) \underline{u}_0 & & \uparrow \underline{f}_{-1} \left(\begin{array}{c} \dashv \\ \downarrow \end{array} \right) \underline{u}_1 & & & & \uparrow \underline{f}_{-n-2} \left(\begin{array}{c} \dashv \\ \downarrow \end{array} \right) \underline{u}_{n-2} & & \uparrow \underline{f}_{-n-1} \left(\begin{array}{c} \dashv \\ \downarrow \end{array} \right) \underline{u}_{n-1} \\
 +0 & \xleftarrow{\underline{b}_1} & +1 & \xleftarrow{\quad} & \cdots & \xleftarrow{\quad} & +n-2 & \xleftarrow{\underline{b}_{n-1}} & +n-1
 \end{array}$$

We now state a few of the key results from Zaganidis' thesis whose proofs are too long to reproduce here. Note that $\mathcal{A}dj_{\mathfrak{n}}$ is *not* a simplicial computad, since the diagram of right adjoints and adjunction morphisms in Example 9.6.8 commutes strictly at the level of 0-arrows. However, this is the only obstruction, in a sense made precise by the following result

9.6.9. PROPOSITION ([65, 3.2.5]). Consider the inclusion $\mathbb{2} \times \mathfrak{n} \hookrightarrow \mathcal{A}dj_{\mathfrak{n}}$ whose image is the subcategory comprised of the right adjoints \underline{u}_i and the 0-arrow components \underline{a}_i and \underline{b}_i of the adjunction morphisms. Then $\mathbb{2} \times \mathfrak{n} \hookrightarrow \mathcal{A}dj_{\mathfrak{n}}$ is a relative simplicial computad.

9.6.10. REMARK. Diagrams of morphisms between adjunctions of more general 2-categorical pasting diagram shapes are also of interest. Zaganidis constructs a generalization $\mathcal{A}dj_{\mathfrak{n}}^S$ of $\mathcal{A}dj_{\mathfrak{n}}$ for any “shape” $S \subset \mathfrak{C}\Delta[n-1]$ with the universal property that for a 2-category \mathcal{C} , 2-functors $\mathcal{A}dj_{\mathfrak{n}}^S \rightarrow \mathcal{C}$ correspond to 2-functors from S into the 2-category of adjunctions, right adjunction morphisms, and right adjunction transformations of Definition 9.6.3. Zaganidis' construction requires S to be a simplicial computad, although $S \hookrightarrow \mathfrak{C}\Delta[n-1]$ need not be a simplicial subcomputad inclusion. Instead, any factorization in $\mathfrak{C}\Delta[n-1]$ of an atomic arrow of S must be through an object that is not contained in the subcategory S .

An argument along the lines of that given in §8.2 and §8.3 proves that homotopy coherent adjunction morphisms are generated by what we term a **diagram of n -right adjoints**: this being given by a commutative diagram in \mathcal{K}

$$\begin{array}{ccccccc}
 A_0 & \xleftarrow{a_1} & A_1 & \xleftarrow{\quad} & \cdots & \xleftarrow{\quad} & A_{n-2} \xleftarrow{a_{n-1}} A_{n-1} \\
 \downarrow u_0 & & \downarrow u_1 & & & & \downarrow u_{n-2} \quad \downarrow u_{n-1} \\
 B_0 & \xleftarrow{b_1} & B_1 & \xleftarrow{\quad} & \cdots & \xleftarrow{\quad} & B_{n-2} \xleftarrow{b_{n-1}} B_{n-1}
 \end{array}$$

together with a choice of left adjoint and unit for each u_i . We state just one of the many extension theorems proven as Theorems A and 5.12-13 in [65]:

9.6.11. THEOREM. *Any diagram of n -right adjoints in a quasi-categorically enriched category extends to a simplicial functor $\mathcal{A}dj_{\mathfrak{n}} \rightarrow \mathcal{K}$. And, moreover the space of extensions over a given diagram of right adjoints is a trivial Kan complex.*

9.6.12. DEFINITION. Let $\mathcal{M}nd_{\mathfrak{n}}$ be the full subcategory of $\mathcal{A}dj_{\mathfrak{n}}$ on the objects $+_0, \dots, +_{n-1}$. By [65, 5.19] it is a simplicial computad.

9.6.13. THEOREM ([65, 5.20, 5.24-5]). *For any homotopy coherent diagram of monads $\mathbb{T}: \mathcal{M}nd_{\mathfrak{n}} \rightarrow \mathcal{K}$, the simplicially enriched right Kan extension $\mathbb{A}^{\mathbb{T}}: \mathcal{A}dj_{\mathfrak{n}} \rightarrow \mathcal{K}$ exists. For each $i \in \{0, \dots, n-1\}$, the object $\mathbb{A}^{\mathbb{T}}(-_i)$ is equivalent to the ∞ -category of algebras for the i th underlying homotopy coherent monad.*

Note that its not the case that the value of the right Kan extension along $\mathcal{M}nd_{\mathfrak{n}} \hookrightarrow \mathcal{A}dj_{\mathfrak{n}}$ at $-_i$ recovers the ∞ -category of algebras for the i th homotopy coherent monad on the nose. However, by applying Theorem 9.4.12 this ∞ -category can be shown to be equivalent to the ∞ -category of algebras. See §5.3 of [65] for more details.

Exercises.

9.6.i. EXERCISE. Use Proposition 9.6.1 to prove that the ∞ -categories of algebras associated to any homotopy coherent adjunctions extending equivalent adjunctions, in the sense described at the start of this section, are equivalent.

9.6.ii. EXERCISE. Prove Proposition 9.6.4, perhaps just in the 2-category of categories.

Part III

The calculus of modules

Two-sided fibrations

Recall from Proposition 7.4.15 that for any ∞ -category B in an ∞ -cosmos \mathcal{K} , the quasi-categorically enriched categories $coCart(\mathcal{K})_B$ and $Cart(\mathcal{K})_B$ define sub ∞ -cosmoi of \mathcal{K}_B . In this section, we introduce another sub ∞ -cosmos ${}_A\mathcal{Fib}(\mathcal{K})_B \subset \mathcal{K}_{A \times B}$ whose objects are *two-sided fibrations* from A to B . Several equivalent definitions of this notion are given in §10.1. Iterating Proposition 7.4.15 reveals that ${}_A\mathcal{Fib}(\mathcal{K})_B$ is again an ∞ -cosmos, which we study in §10.2. Importantly, two-sided fibration from B to 1 is simply a cocartesian fibration over B , while a two-sided fibration from 1 to B is a cartesian fibration over B , so results about two-sided fibrations simultaneously generalize these one-sided notions. For instance, in §10.3, we introduce two-sided representables and prove the Yoneda lemma, generalizing Theorem 5.5.3 for representable (co)cartesian fibrations.

Another reason for our interest in two-sided fibrations is the fact that the discrete objects in ${}_A\mathcal{Fib}_B$ are precisely the *modules* from A to B , which we define and study in §10.4. The calculus of modules, developed in Chapter 11, is the main site of the formal category theory of ∞ -categories, which is the subject of Chapter 12.

10.1. Four equivalent definitions of two-sided fibrations

By factoring, any span in \mathcal{K} from A to B may be replaced up to equivalence by a **two-sided isofibration**, a span $A \xleftarrow{q} E \xrightarrow{p} B$ for which the functor $(q, p): E \rightarrow A \times B$ is an isofibration. Two-sided isofibrations from A to B are the objects of the ∞ -cosmos $\mathcal{K}_{A \times B}$. In this section, we describe what it means for a two-sided isofibration to be *cocartesian on the left* or *cartesian on the right*, and then introduce *two-sided fibrations*, which integrate these notions.

10.1.1. LEMMA (cocartesian on the left). *For a two-sided isofibration $A \xleftarrow{q} E \xrightarrow{p} B$ in an ∞ -cosmos \mathcal{K} , the following are equivalent:*

(i) *The functor*

$$\begin{array}{ccc} E & \xrightarrow{(q,p)} & A \times B \\ p \searrow & & \swarrow \pi \\ & B & \end{array}$$

is a cocartesian fibration in the slice ∞ -cosmos \mathcal{K}_B .

(ii) *The functor*

$$\begin{array}{ccc} E & \xrightarrow{(q,p)} & A \times B \\ q \searrow & & \swarrow \pi \\ & A & \end{array}$$

in \mathcal{K}_A lies in the sub ∞ -cosmos $coCart(\mathcal{K})_A$.

(iii) The functor induced by id_q

$$\begin{array}{ccc}
 E & \xleftarrow[\perp]{\ell} & \text{Hom}_A(q, A) \\
 & \xrightarrow[i]{} & \\
 (q,p) \searrow & & \swarrow (p_1, pp_0) \\
 & A \times B &
 \end{array}$$

admits a left adjoint in $\mathcal{K}_{/A \times B}$.

(iv) The isofibration $q: E \twoheadrightarrow A$ is a cocartesian fibration in \mathcal{K} and for every q -cocartesian transformation

$$X \begin{array}{c} \xrightarrow{e} \\ \Downarrow \chi \\ \xrightarrow{e'} \end{array} E, \text{ the composite } X \begin{array}{c} \xrightarrow{e} \\ \Downarrow \chi \\ \xrightarrow{e'} \end{array} E \xrightarrow{p} B \text{ is an isomorphism.}$$

If any of these equivalent conditions are satisfied, we say that $A \xleftarrow{q} E \xrightarrow{p} B$ is **cocartesian on the left**.

PROOF. We first prove that the equivalence (i) \Leftrightarrow (iii) is exactly the interpretation of the equivalence Theorem 5.1.11(i) \Leftrightarrow (ii) applied to the isofibration $(q, p): E \twoheadrightarrow A \times B$ in the ∞ -cosmos \mathcal{K}_B . This latter result asserts that the isofibration $(q, p): E \twoheadrightarrow A \times B$ is a cocartesian fibration in \mathcal{K}_B if and only if a certain canonical functor from E to the left representation of the functor $(q, p): E \twoheadrightarrow A \times B$ admits a left adjoint over the codomain $\pi: A \times B \twoheadrightarrow B$; since $(\mathcal{K}_B)_{/\pi: A \times B \twoheadrightarrow B} \cong \mathcal{K}_{/A \times B}$ this is the same as asserting this adjunction over $A \times B$.

The only subtlety in interpreting Theorem 5.1.11 in \mathcal{K}_B has to do with the correct interpretation of the left representable comma ∞ -category in \mathcal{K}_B for the functor $(q, p): E \twoheadrightarrow A \times B$. This comma ∞ -category is constructed as a subobject of the 2-cotensor of the object $\pi: A \times B \twoheadrightarrow B$ in \mathcal{K}_B , which Proposition 1.2.17 tells us is formed as the left-hand vertical of the pullback diagram

$$\begin{array}{ccc}
 A^2 \times B & \longrightarrow & (A \times B)^2 \\
 \pi \downarrow & \lrcorner & \downarrow \pi^2 \\
 B & \xrightarrow{\Delta} & B^2
 \end{array}$$

By (3.3.2) the comma ∞ -category is constructed by the pullback in \mathcal{K}_B

$$\begin{array}{ccccc}
 \text{Hom}_A(q, A) & \xrightarrow{\quad} & A^2 \times B & \xrightarrow{p_1 \times \text{id}} & A \times B \\
 p_0 \downarrow & \swarrow pp_0 \lrcorner & \pi \downarrow & \downarrow p_0 \times \text{id} & \downarrow \pi \\
 E & \xrightarrow{(q,p)} & A \times B & & \\
 & \searrow p & \swarrow \pi & \searrow \pi & \\
 & B & & &
 \end{array} \tag{10.1.2}$$

which is created by the forgetful functor $\mathcal{K}_B \rightarrow \mathcal{K}$, and its codomain-projection functor is the top composite $(p_1, pp_0): \text{Hom}_A(q, A) \twoheadrightarrow A \times B$. Now we see that the interpretation of Theorem 5.1.11(i) \Leftrightarrow (ii) is exactly the equivalence (i) \Leftrightarrow (iii).

It remains to demonstrate the equivalence with (ii) and 10.4. Assuming (iii) and composing with $\pi: A \times B \twoheadrightarrow A$, we are left with a fibered adjunction that demonstrates that q is a cocartesian fibration.

The unit of both fibered adjunctions is the same, and by Theorem 5.1.11(v) the composite

$$\begin{array}{ccc} \mathrm{Hom}_A(q, A) & \xRightarrow{\quad \Downarrow \eta \quad} & \mathrm{Hom}_A(q, A) - p_0 \Rightarrow E \\ & \searrow \ell \quad \nearrow i & \\ & E & \end{array}$$

is the generic q -cocartesian cell. Since η is fibered over $A \times B$, when we postcompose with p we get an identity, which tells us that $p: E \rightarrow B$ carries q -cocartesian cells to isomorphisms. This proves 10.4.

In fact, 10.4 can easily be seen to be equivalent to (ii). By Example 5.2.5, the cocartesian cells for the cocartesian fibration $\pi: A \times B \rightarrow A$ are precisely those 2-cells whose component with codomain B is an isomorphism, so 10.4 says exactly that $(q, p): E \rightarrow A \times B$ defines a cartesian functor from q to π . Thus 10.4 implies (ii).

For the converse, assume (ii) and consider a 2-cell in \mathcal{K}_B

$$\begin{array}{ccc} X & \xrightarrow{e} & E \\ & \searrow \Downarrow (\alpha, \mathrm{id}) & \downarrow (q, p) \\ & (a, b) & A \times B \end{array}$$

Because q is a cocartesian fibration, $\alpha: qe \Rightarrow a$ has a q -cocartesian lift $\chi: e \Rightarrow e': X \rightarrow E$, and since (q, p) is a cartesian functor, the whiskered 2-cell $p\chi: b \Rightarrow pe'$ is an isomorphism. Because $(q, p): E \rightarrow A \times B$ is an isofibration, we may lift the 2-cell $(\mathrm{id}, p\chi^{-1}): e' \Rightarrow (a, b)$ to an invertible 2-cell $\gamma: e' \Rightarrow e''$ with $q\gamma = \mathrm{id}_a$. The composite $\gamma \cdot \chi: e \Rightarrow e''$ is a lift of (α, id) along (q, p) over B , which is easily verified to define a (q, p) -cocartesian lift of (α, id) in \mathcal{K}_B . \square

If $(q, p): E \rightarrow A \times B$ is a *discrete* cocartesian fibration in \mathcal{K}_B then the converse to the last statement of 10.4 holds: any 2-cell χ for which $p\chi$ is an isomorphism is q -cocartesian. See Exercise 10.1.i.

By Lemma 10.1.1 and its dual:

10.1.3. COROLLARY. A two-sided isofibration $A \xleftarrow{q} E \xrightarrow{p} B$ is cocartesian on the left and cartesian on the right if the following equivalent conditions are satisfied:

(i) The functor

$$\begin{array}{ccc} E & \xrightarrow{(q, p)} & A \times B \\ & \searrow q \quad \swarrow \pi & \\ & A & \end{array}$$

lies in $\mathrm{coCart}(\mathcal{K})_A$ and defines a cartesian fibration in \mathcal{K}_A .

(ii) The functor

$$\begin{array}{ccc} E & \xrightarrow{(q, p)} & A \times B \\ & \searrow p \quad \swarrow \pi & \\ & B & \end{array}$$

lies in $\mathrm{Cart}(\mathcal{K})_B$ and defines a cocartesian fibration in \mathcal{K}_B . \square

A two-sided fibration is a span that is cocartesian on the left, cartesian on the right, and satisfies a further compatibility condition that can be stated in a number of equivalent ways, which boil down to the assertion that the processes of taking q -cocartesian and p -cartesian lifts commute:

10.1.4. THEOREM. For a two-sided isofibration $A \xleftarrow{q} E \xrightarrow{p} B$ in \mathcal{K} , the following are equivalent:

(i) The functor

$$\begin{array}{ccc} E & \xrightarrow{(q,p)} & A \times B \\ q \searrow & & \swarrow \pi \\ & A & \end{array}$$

defines a cartesian fibration in $\text{coCart}(\mathcal{K})_{/A}$.

(ii) The functor

$$\begin{array}{ccc} E & \xrightarrow{(q,p)} & A \times B \\ p \searrow & & \swarrow \pi \\ & B & \end{array}$$

defines a cocartesian fibration in $\text{Cart}(\mathcal{K})_{/B}$.

(iii) The canonical functors admit the displayed adjoints in $\mathcal{K}_{/A \times B}$

$$\begin{array}{ccc} E & \xleftarrow[\tau]{r} & \text{Hom}_B(B, p) \\ \ell \uparrow \downarrow i & & (ip_1, \text{id}) \downarrow \uparrow \ell \\ \text{Hom}_A(q, A) & \xrightarrow[\perp]{(\text{id}, ip_0)} & \text{Hom}_A(q, A) \times_E \text{Hom}_B(B, p) \end{array}$$

(dashed arrows: r from E to $\text{Hom}_A(q, A)$ and r from $\text{Hom}_A(q, A) \times_E \text{Hom}_B(B, p)$ to E)

and the mate of the identity 2-cell in this displayed commutative square defines an isomorphism $\ell r \cong r \ell$.

(iv) $A \xleftarrow{q} E \xrightarrow{p} B$ is cocartesian on the left, cartesian on the right, and for any $a: X \rightarrow A$, $b: X \rightarrow B$, and $e: X \rightarrow E$ and pair of 2-cells $\alpha: qe \Rightarrow a$ and $\beta: b \Rightarrow pe$, the map $\beta^* \alpha_*(e): X \rightarrow E$, obtained as the domain of a p -cartesian lift of the composite of β with a q -cocartesian lift $\chi_\alpha: e \Rightarrow \alpha_*(e)$ of α over B , is isomorphic over $A \times B$ to the map $\alpha_* \beta^*(e): X \rightarrow E$ obtained as the codomain of a q -cocartesian lift of the composite of α with a p -cartesian lift $\chi_\beta: \beta^*(e) \Rightarrow e$ of β over A .

A span $A \xleftarrow{q} E \xrightarrow{p} B$ defines a **two-sided fibration** from A to B if any of these equivalent conditions are satisfied:

PROOF. Our strategy will be to show that condition (i) is equivalent to (iii), an equationally witnessed condition in the slice ∞ -cosmos $\mathcal{K}_{/A \times B}$. A dual argument will show that condition (ii) is equivalent to (iii). We then unpack this condition to prove its equivalence with (iv).

We use Theorem 5.1.11(ii), which provides a condition that characterizes the cartesian fibrations in any ∞ -cosmos via the presence of a fibered adjunction, to re-express (i) in $\mathcal{K}_{/A \times B}$. To apply this characterization to the map displayed in (i), we must first compute the right representable comma object in $\text{coCart}(\mathcal{K})_{/A} \subset \mathcal{K}_{/A}$ associated to the functor $(q, p): E \rightarrow A \times B$ over A . By Proposition 7.4.15, it suffices to compute this comma object in $\mathcal{K}_{/A}$. By the dual of the calculation (10.1.2) we gave in the proof of Lemma 10.1.1, the comma object covariantly representing the functor $(q, p): E \rightarrow A \times B$ in $\text{coCart}(\mathcal{K})_{/A} \subset \mathcal{K}_{/A}$ is the cocartesian fibration $qp_1: \text{Hom}_B(B, p) \twoheadrightarrow A$.

$$\begin{array}{ccc}
 E & \xrightarrow[\perp]{i} & \text{Hom}_B(B, p) \\
 \swarrow (q, p) & \text{---} r \text{---} & \nwarrow (qp_1, p_0) \\
 & A \times B &
 \end{array} \tag{10.1.5}$$

By Lemma 10.1.1, to say that (q, p) defines a cartesian functor between cocartesian fibrations is to say that the span $A \xleftarrow{q} E \xrightarrow{p} B$ is cocartesian on the left, which is the case if and only if the canonical functor i admits a left adjoint

in $\mathcal{K}_{/A \times B}$. Similarly, to say that (qp_1, p_0) defines a cartesian functor between cocartesian fibrations is to say that the span $A \xleftarrow{qp_1} \mathbf{Hom}_B(B, p) \xrightarrow{p_0} B$ is cocartesian on the left. By Lemma 10.1.1 again, this is equivalent to the hypothesis that the canonical functor from $\mathbf{Hom}_B(B, p)$ to the comma object contravariantly representing qp_1 admits a left adjoint

Finally, by Theorem 5.1.19, to say that the functor i of (10.1.5) is cartesian is to say that in the commutative solid-arrow diagram in $\mathcal{K}_{/A \times B}$,

the mate of this identity 2-cell involving the left adjoints ℓ is an isomorphism. This “Beck-Chevalley” condition is equivalent to saying that the other mate, displayed above right, associated to the functor r of (10.1.5) is an isomorphism. Finally, to say that r is also a cartesian functor between cocartesian

fibrations is to say that the further mate

$$\begin{array}{ccc}
 E & \xleftarrow{\quad r \quad} & \mathrm{Hom}_B(B, p) \\
 \uparrow \ell & \Uparrow \cong & \uparrow \ell \\
 \mathrm{Hom}_A(q, A) & \xleftarrow{\quad r \quad} & \mathrm{Hom}_A(q, A) \times_E \mathrm{Hom}_B(B, p)
 \end{array} \tag{10.1.7}$$

is an isomorphism.

Thus, we have shown that condition (i) is equivalent to (iii) positing the existence of adjunctions (10.1.6) in $\mathcal{K}_{A \times B}$ so that all of the mates of the solid-arrow diagram are isomorphisms. Dualizing and reversing this argument, we see that this is equivalent to condition (ii).

Finally, (iii) and (iv) are equivalent since the existence of the left adjoints in (10.1.6) is equivalent to the span being cocartesian on the left, the existence of the right adjoints is equivalent to being cartesian on the right, and the compatibility condition for the cartesian and cocartesian lifts is the meaning of the isomorphism (10.1.7). \square

10.1.8. COROLLARY. *Any two-sided isofibration $(a, b): X \twoheadrightarrow A \times B$ that is equivalent over $A \times B$ to a two-sided fibration $(q, p): E \twoheadrightarrow A \times B$ is a two-sided fibration.*

PROOF. The assertion of Theorem 10.1.4(iii) is invariant under fibered equivalence. \square

Theorem 10.1.4 will help us establish an important family of examples.

10.1.9. PROPOSITION. *For any ∞ -category A and any $n \geq 2$, the two-sided isofibration $A \xleftarrow{p_{n-1}} A^n \xrightarrow{p_0} A$ defines a two-sided fibration.*

This result is a generalization of Proposition 5.1.23 and its dual and the proof uses similar ideas.

PROOF. We use Theorem 10.1.4(iii). The right representable comma ∞ -category associated to $p_0: A^n \twoheadrightarrow A$ is constructed by the pullback

$$\begin{array}{ccc}
 A^{2 \vee n} & \twoheadrightarrow & A^2 \\
 \downarrow & \lrcorner & \downarrow p_1 \\
 A^n & \twoheadrightarrow & A \\
 & p_0 &
 \end{array}$$

which is equivalent to $(p_n, p_0): A^{n+1} \twoheadrightarrow A \times A$ over the endpoint evaluation maps. The canonical map

$$\begin{array}{ccc}
 A^n & \xleftarrow{\quad A^{\delta^1} \quad} & A^{n+1} \\
 \xrightarrow{\quad A^{\sigma^0} \quad} & & \searrow (p_n, p_0) \\
 & A \times A & \\
 \swarrow (p_{n-1}, p_0) & &
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathfrak{n} & \xleftarrow{\quad \delta^1 \quad} & \mathfrak{n} + \mathbb{1} \\
 \xrightarrow{\quad \sigma_0 \quad} & & \searrow (n, 0) \\
 & \mathbb{1} + \mathbb{1} & \\
 \swarrow (n-1, 0) & &
 \end{array}$$

that tests whether $(p_{n-1}, p_0): A^n \twoheadrightarrow A \times A$ is cartesian on the right is given by restriction along the epimorphism $\sigma^0: \mathfrak{n} + \mathbb{1} \rightarrow \mathfrak{n}$ that sends the objects $0, 1 \in \mathfrak{n} + \mathbb{1}$ to $0 \in \mathfrak{n}$. This functor admits a left adjoint under the endpoint inclusions displayed above-right, which provides the desired fibered right adjoint displayed above left.

A dual argument shows that $(p_{n-1}, p_0): A^n \rightarrow A \times A$ is cocartesian on the left. The final condition asks that the mate of the commutative square defined by the degeneracy maps

$$\begin{array}{ccc}
 & \xleftarrow[\sigma^0]{\delta^1} & \\
 \delta^n \uparrow \dashv \sigma^n & & \sigma^{n+1} \uparrow \dashv \delta^{n+1} \\
 \mathfrak{n} & \xleftarrow[\sigma^0]{\perp} & \mathfrak{n} + \mathbb{1} \\
 \downarrow \sigma^n & & \downarrow \sigma^{n+1} \\
 \mathfrak{n} + \mathbb{1} & \xleftarrow[\sigma^0]{\perp} & \mathfrak{n} + 2 \\
 & \xleftarrow[\delta^1]{\sigma^0} &
 \end{array}$$

is an isomorphism, as is easily verified. The square in Theorem 10.1.4(iii) is obtained by applying $A^{(-)}$. \square

Theorem 10.1.4 has a relative analogue, whose proof is left to the reader, which characterizes what we call a **cartesian functor** between two-sided fibrations from A to B .

10.1.10. LEMMA. *A map of spans between a pair of two-sided fibrations from A to B*

$$\begin{array}{ccccc}
 & & E & & \\
 & \swarrow q & & \searrow p & \\
 A & & & & B \\
 & \swarrow s & & \searrow r & \\
 & & F & &
 \end{array} \tag{10.1.11}$$

defines a cartesian functor between the cartesian fibrations in $\text{coCart}(\mathcal{K})_A$ if and only if it defines a cartesian functor between the cocartesian fibrations in $\text{Cart}(\mathcal{K})_B$.

PROOF. A similar argument to that given in Theorem 10.1.4 shows that the map $g: E \rightarrow F$ of (10.1.11) is a cartesian functor between cartesian fibrations in $\text{coCart}(\mathcal{K})_A$ if and only if in two commutative diagrams over $A \times B$, the mates are isomorphisms. This condition also characterizes cartesian functors between cocartesian fibrations in $\text{Cart}(\mathcal{K})_B$. The details are left as Exercise 10.1.ii. \square

A cartesian functor is just a map of spans (10.1.11) that defines a cartesian functor between the cocartesian fibrations q and s and also a cartesian functor between the cartesian fibrations p and r . It follows from the internal characterization (iii) of Theorem 10.1.4 and a similar internal characterization of cartesian functors derived from Theorem 5.1.19 that:

10.1.12. COROLLARY. *Any cosmological functor preserves two-sided fibrations and cartesian functors between them.* \square

Exercises.

10.1.i. EXERCISE. Suppose $(q, p): E \rightarrow A \times B$ is a *discrete* cocartesian fibration in \mathcal{K}_B . Prove, for any 2-cell χ with codomain E , that if $p\chi$ is an isomorphism, then χ is q -cocartesian.

10.1.ii. EXERCISE. Prove Lemma 10.1.10.

10.1.iii. EXERCISE. Prove that

- (i) A two-sided isofibration $1 \xleftarrow{!} E \xrightarrow{p} B$ defines a two-sided fibration from 1 to B if and only if $p: E \rightarrow B$ is a cartesian fibration.

(ii) A map of spans

$$\begin{array}{ccccc}
 & & E & & \\
 & \swarrow ! & \downarrow g & \searrow p & \\
 1 & & F & & B \\
 & \swarrow ! & \downarrow q & \searrow & \\
 & & & &
 \end{array}$$

defines a cartesian functor of two-sided fibrations if and only if $g: E \rightarrow F$ defines a cartesian functor from p to q .

10.2. The ∞ -cosmos of two-sided fibrations

The equivalent conditions (i) and (ii) of Theorem 10.1.4 provide two equivalent ways to define the ∞ -cosmos of two-sided fibrations.

10.2.1. DEFINITION (the ∞ -cosmos of two-sided fibrations). By Theorem 10.1.4 and Lemma 10.1.10, the pair of quasi-categorically enriched subcategories

$$\text{Cart}(\text{coCart}(\mathcal{K})_{/A})_{/\pi: A \times B \rightarrow A} \quad \text{and} \quad \text{coCart}(\text{Cart}(\mathcal{K})_{/B})_{/\pi: A \times B \rightarrow B}$$

of $\mathcal{K}_{/A \times B}$ coincide. By Proposition 7.4.15, applied twice, this subcategory is an ∞ -cosmos, which we call the ∞ -cosmos of two-sided fibrations from A to B and denote by

$${}_A \backslash \text{Fib}(\mathcal{K})_{/B} \subset \mathcal{K}_{/A \times B}.$$

By definition

$$\text{Fun}_{{}_A \backslash \text{Fib}(\mathcal{K})_{/B}}(E, F) := \text{Fun}_{A \times B}^c(E, F) \subset \text{Fun}_{A \times B}(E, F)$$

is the quasi-category of maps of spans that define cartesian functors from E to F in the sense of Lemma 10.1.10.

10.2.2. PROPOSITION. The simplicial subcategory ${}_A \backslash \text{Fib}(\mathcal{K})_{/B} \hookrightarrow \mathcal{K}_{/A \times B}$ creates an ∞ -cosmos structure on the ∞ -cosmos of two-sided fibrations from the ∞ -cosmos of two-sided isofibrations.

PROOF. This inclusion factors as

$${}_A \backslash \text{Fib}(\mathcal{K})_{/B} \cong \text{coCart}(\text{Cart}(\mathcal{K})_{/B})_{/A \times B \rightarrow B} \hookrightarrow (\text{Cart}(\mathcal{K})_{/B})_{/A \times B \rightarrow B} \hookrightarrow (\mathcal{K}_{/B})_{/A \times B \rightarrow B} \cong \mathcal{K}_{/A \times B}$$

Applying Proposition 7.4.15, we see that both inclusions create ∞ -cosmos structures. \square

10.2.3. OBSERVATION (two-sided fibrations generalize (co)cartesian fibrations). By Exercise 10.1.iii, a two-sided fibration from B to 1 is a cocartesian fibration over B , while a two-sided fibration from 1 to B is a cartesian fibration over B . Indeed,

$$\text{coCart}(\mathcal{K})_{/B} \cong {}_B \backslash \text{Fib}(\mathcal{K})_{/1} \quad \text{and} \quad \text{Cart}(\mathcal{K})_{/B} \cong {}_1 \backslash \text{Fib}(\mathcal{K})_{/B}.$$

In this sense, statements about two-sided fibrations simultaneously generalize statements about cartesian and cocartesian fibrations.

10.2.4. PROPOSITION. For any pair of functors $a: A' \rightarrow A$ and $b: B' \rightarrow B$, the cosmological pullback functor

$$(a, b)^*: \mathcal{K}_{/A \times B} \longrightarrow \mathcal{K}_{/A' \times B'}$$

restricts to define a cosmological functor

$$(a, b)^*: {}_A \backslash \text{Fib}(\mathcal{K})_{/B} \longrightarrow {}_{A'} \backslash \text{Fib}(\mathcal{K})_{/B'}.$$

In particular, the pullback of a two-sided fibration is again a two-sided fibration.

PROOF. By factoring (a, b) as $A' \times B' \xrightarrow{\text{id} \times b} A' \times B \xrightarrow{a \times \text{id}} A \times B$ we see that it suffices to consider pullback along one side at a time. Proposition 5.1.20 proves that pullback along $b: B' \rightarrow B$ preserves cartesian fibrations and cartesian functors, defining a restricted functor

$$\begin{array}{ccc} \text{Cart}(\mathcal{K})_{/B} & \hookrightarrow & \mathcal{K}_{/B} \\ b^* \downarrow & & \downarrow b^* \\ \text{Cart}(\mathcal{K})_{/B'} & \hookrightarrow & \mathcal{K}_{/B'} \end{array}$$

Since limits and isofibrations in $\text{Cart}(\mathcal{K})_{/B}$ are created in $\mathcal{K}_{/B}$, this restricted functor is a cosmological functor. Applying this result to the map

$$\begin{array}{ccc} A \times B' & \xrightarrow{\text{id} \times b} & A \times B \\ \pi \searrow & & \swarrow \pi \\ & A & \end{array}$$

in the ∞ -cosmos $\text{coCart}(\mathcal{K})_{/A}$, we conclude that pullback restricts to define a cosmological functor

$$\begin{array}{ccccc} {}_{A\backslash} \text{Fib}(\mathcal{K})_{/B} \cong \text{Cart}(\text{coCart}(\mathcal{K})_{/A})_{/\pi: A \times B \twoheadrightarrow A} & \hookrightarrow & (\text{coCart}(\mathcal{K})_{/A})_{/\pi: A \times B \twoheadrightarrow A} & \hookrightarrow & \mathcal{K}_{/A \times B} \\ (\text{id} \times b)^* \downarrow & & \downarrow (\text{id} \times b)^* & & \downarrow (\text{id} \times b)^* \\ {}_{A\backslash} \text{Fib}(\mathcal{K})_{/B'} \cong \text{Cart}(\text{coCart}(\mathcal{K})_{/A})_{/\pi: A \times B' \twoheadrightarrow A} & \hookrightarrow & (\text{coCart}(\mathcal{K})_{/A})_{/\pi: A \times B' \twoheadrightarrow A} & \hookrightarrow & \mathcal{K}_{/A \times B'} \end{array}$$

□

10.2.5. LEMMA. If $A \xleftarrow{q} E \xrightarrow{p} B$ is a two-sided fibration from A to B , $v: A \twoheadrightarrow C$ is a cocartesian fibration and $u: B \twoheadrightarrow D$ is a cartesian fibration, then the composite span

$$C \xleftarrow{v} A \xleftarrow{q} E \xrightarrow{p} B \xrightarrow{u} D$$

defines a two-sided fibration from C to D . Moreover, a cartesian functor between two-sided fibrations from A to B induces a cartesian functor

$$\begin{array}{ccccc} & & E & & \\ & q \swarrow & \downarrow g & \searrow p & \\ C \xleftarrow{v} A & & & & B \xrightarrow{u} D \\ & s \swarrow & \downarrow r & \searrow & \\ & & F & & \end{array}$$

between two-sided fibrations from C to D .

Note composition in the sense being described here does not define a cosmological functor from ${}_{A\backslash} \text{Fib}(\mathcal{K})_{/B}$ to ${}_{C\backslash} \text{Fib}(\mathcal{K})_{/D}$ because it does not preserve flexible limits.

PROOF. By Theorem 10.1.4, it suffices to consider composition on one side at a time, say with a cocartesian fibration $v: A \twoheadrightarrow C$. Working in the ∞ -cosmos $\text{Cart}(\mathcal{K})_{/B}$, we are given cocartesian fibrations

$$\begin{array}{ccc} E \xrightarrow{(q,p)} A \times B & & A \times B \xrightarrow{v \times \text{id}} C \times B \\ p \searrow & \swarrow \pi & \pi \searrow & \swarrow \pi \\ & B & & B \end{array}$$

These compose vertically to define a cocartesian fibration

$$\begin{array}{ccc} E & \xrightarrow{(vq,p)} & C \times B \\ & \searrow p & \swarrow \pi \\ & B & \end{array}$$

and hence a two-sided fibration from C to B , as desired.

Now the vq -cocartesian cells are the q -cocartesian lifts of the v -cocartesian cells. If g is a cartesian functor from q to s , then these are clearly preserved, proving that g also defines a cartesian functor from vq to vs . \square

Proposition 10.2.4 and Lemma 10.2.5 combine to prove that two-sided fibrations can be composed “horizontally.”

10.2.6. PROPOSITION. *The pullback of a two-sided fibration from A to B along a two-sided fibration from B to C*

$$\begin{array}{ccccc} & & E \times_B F & & \\ & \swarrow \pi_1 & \downarrow \smile & \searrow \pi_0 & \\ & E & & F & \\ q \swarrow & & p \searrow & s \swarrow & r \searrow \\ A & & B & & C \end{array}$$

defines a two-sided fibration from A to C as displayed.

PROOF. The composite two-sided fibration is constructed in two stages, first by pulling back

$$\begin{array}{ccc} E \times_B F & \longrightarrow & F \\ \downarrow (\pi_1, r\pi_0) & \lrcorner & \downarrow (s, r) \\ E \times_B C & \xrightarrow{p \times C} & B \times C \end{array}$$

and then by composing the left leg with the cocartesian fibration $q: E \twoheadrightarrow A$. By Proposition 10.2.4 and Lemma 10.2.5, this results in a two-sided fibration from A to C . Alternatively, the composite can be constructed by pulling back along $A \times s$ and composing with the cartesian fibration $r: F \twoheadrightarrow C$, resulting in another two-sided fibration from A to C that is canonically isomorphic to the first. \square

10.2.7. EXAMPLE. If $p: E \twoheadrightarrow B$ is a cartesian fibration and $q: F \twoheadrightarrow A$ is a cocartesian fibration, then the span

$$A \xleftarrow{q} F \xleftarrow{\pi} F \times E \xrightarrow{\pi} E \xrightarrow{p} B$$

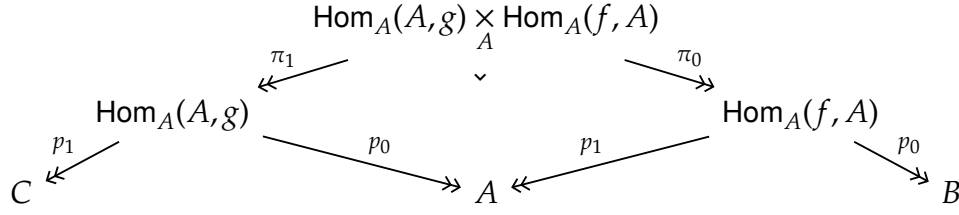
defines a two-sided fibration from A to B .

10.2.8. EXAMPLE. By Proposition 10.1.9 and Proposition 10.2.4, a general comma span

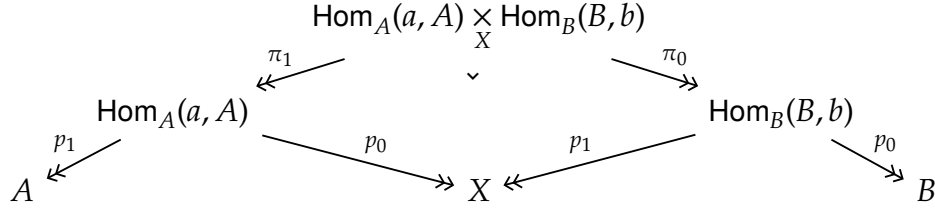
$$C \xleftarrow{p_1} \mathrm{Hom}_A(f, g) \xrightarrow{p_0} B$$

is a two-sided fibration, as a pullback of $A \xleftarrow{p_1} A^2 \xrightarrow{p_0} A$. By Proposition 10.2.6, “horizontal composites” of comma spans are also two-sided fibrations. In certain cases, a horizontal composite again

defines a span that is equivalent to a comma span, as is the case for:

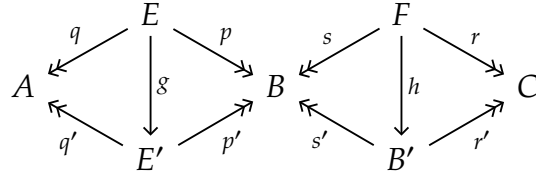


which is equivalent to $(p_1, p_0): \text{Hom}_A(f, g) \rightarrow C \times B$ over $C \times B$. Certain other horizontal composites are not equivalent to comma spans but nonetheless define two-sided fibrations, as is the case for:



Exercises.

10.2.i. EXERCISE. Consider a diagram



in which g and h define cartesian functors between two-sided fibrations, from A to B and from B to C , respectively. Prove that g and h pullback to define a cartesian functor $(g, h): E \times_B F \rightarrow E' \times_B B'$ between two-sided fibrations from A to C .

10.2.ii. EXERCISE. Prove the assertion made in Example 10.2.7.

10.3. Representable two-sided fibrations and the Yoneda lemma

We now introduce representable two-sided fibrations and prove a two-sided version of the external Yoneda lemma.

10.3.1. DEFINITION. Specializing Example 10.2.7, for any pair of elements $a: 1 \rightarrow A$ and $b: 1 \rightarrow B$, the span

$$A \xleftarrow{p_1\pi} \text{Hom}_A(a, A) \times \text{Hom}_B(B, b) \xrightarrow{p_0\pi} B$$

defines a two-sided fibration from A to B that we refer to as the **two-sided fibration represented by a and b** . Note there is a canonical element $(\text{id}_a, \text{id}_b): 1 \rightarrow \text{Hom}_A(a, A) \times \text{Hom}_B(B, b)$ in the fiber over $(a, b): 1 \rightarrow A \times B$.

The terminology of Definition 10.3.1 is justified by the Yoneda lemma for two-sided fibrations.

10.3.2. THEOREM (Yoneda lemma). For any elements $a: 1 \rightarrow A$ and $b: 1 \rightarrow B$ and any two-sided fibration $A \xleftarrow{q} E \xrightarrow{p} B$, restriction along $(\ulcorner \text{id}_a \urcorner, \ulcorner \text{id}_b \urcorner): 1 \rightarrow \text{Hom}_A(a, A) \times \text{Hom}_B(B, b)$ defines an equivalence of quasi-categories

$$\text{Fun}_{A \times B}^c \left(\begin{array}{ccc} \text{Hom}_A(a, A) \times \text{Hom}_B(B, b) & & E \\ \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right) \simeq \text{Fun}_{A \times B} \left(\begin{array}{ccc} 1 & & E \\ (a,b) \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right).$$

Interpreting this result in a slice ∞ -cosmos will enable us to replace the elements a and b with a pair of generalized elements $a: X \rightarrow A$ and $b: X \rightarrow B$; see Corollary 10.3.5.

PROOF. The two-sided fibration represented by a and b is defined by a pullback

$$\begin{array}{ccc} \text{Hom}_A(a, A) \times \text{Hom}_B(B, b) & \xrightarrow{\text{id} \times p_0} & \text{Hom}_A(a, A) \times B \\ p_1 \times \text{id} \downarrow & \lrcorner & \downarrow p_1 \times \text{id} \\ A \times \text{Hom}_B(B, b) & \xrightarrow{\text{id} \times p_0} & A \times B \end{array}$$

We will argue by applying the Yoneda lemma of Theorem 5.5.3 twice: first for cocartesian fibrations over the object $\pi: A \times \text{Hom}_B(B, b) \twoheadrightarrow \text{Hom}_B(B, b)$ the ∞ -cosmos $\text{Cart}(\mathcal{K})_{/\text{Hom}_B(B, b)}$, and then for cartesian fibrations over the object B in the \mathcal{K} .

To set up the first use of the Yoneda lemma, we begin by pulling back the two-sided fibration $A \xleftarrow{q} E \xrightarrow{p} B$ along $p_0: \text{Hom}_B(B, b) \rightarrow B$ to obtain a two-sided fibration

$$\begin{array}{ccccc} & & \text{Hom}_B(p, b) & & \\ & \swarrow p_0 & \downarrow \smile & \searrow p' & \\ & E & & & \text{Hom}_B(B, b) \\ & \swarrow q & \searrow p & \swarrow p_0 & \\ A & & B & & \end{array}$$

from A to $\text{Hom}_B(B, b)$. By the adjoint correspondence between cartesian functors established by Lemma 10.3.3(iii) below, there is an isomorphism

$$\begin{aligned} \text{Fun}_{A \times B}^c \left(\begin{array}{ccc} \text{Hom}_A(a, A) \times \text{Hom}_B(B, b) & & E \\ p_1 \times p_0 \downarrow & & \downarrow (q, p) \\ A \times B & & A \times B \end{array} \right) \\ \cong \text{Fun}_{A \times \text{Hom}_B(B, b)}^c \left(\begin{array}{ccc} \text{Hom}_A(a, A) \times \text{Hom}_B(B, b) & & \text{Hom}_B(p, b) \\ p_1 \times \text{id} \downarrow & & \downarrow (qp_0, p') \\ A \times \text{Hom}_B(B, b) & & A \times \text{Hom}_B(B, b) \end{array} \right). \end{aligned}$$

Consider the object $\pi: A \times \text{Hom}_B(B, b) \twoheadrightarrow \text{Hom}_B(B, b)$ in the ∞ -cosmos $\text{Cart}(\mathcal{K})_{/\text{Hom}_B(B, b)}$. The element

$$\begin{array}{ccc} \text{Hom}_B(B, b) & \xrightarrow{(a!, \text{id})} & A \times \text{Hom}_B(B, b) \\ & \swarrow \text{=} & \nwarrow \pi \\ & \text{Hom}_B(B, b) & \end{array}$$

has $p_1 \times \text{id}: \text{Hom}_A(a, A) \times \text{Hom}_B(B, b) \rightarrow A \times \text{Hom}_B(B, b)$ as its representing cocartesian fibration in $\text{Cart}(\mathcal{K})_{/\text{Hom}_B(B, b)}$. Applying the Yoneda lemma to this representable cocartesian fibration in $\text{Cart}(\mathcal{K})_{/\text{Hom}_B(B, b)}$, we see that restricting along this map defines an equivalence whose codomain

$$\text{Fun}_{A \times \text{Hom}_B(B, b)}^c(\text{Hom}_B(B, b) \rightarrow A \times \text{Hom}_B(B, b), \text{Hom}_B(p, b) \twoheadrightarrow A \times \text{Hom}_B(B, b))$$

is the mapping quasi-category defined by the pullback

$$\begin{array}{ccc} \bullet & \xrightarrow{\quad} & \text{Fun}_{\text{Hom}_B(B, b)}^c(\text{id}_{\text{Hom}_B(B, b)}, \text{Hom}_B(p, b) \twoheadrightarrow \text{Hom}_B(B, b)) \\ \downarrow & \lrcorner & \downarrow (qp_0 p')^{\circ-} \\ 1 & \xrightarrow{(a!, \text{id})} & \text{Fun}_{\text{Hom}_B(B, b)}^c(\text{id}_{\text{Hom}_B(B, b)}, A \times \text{Hom}_B(B, b) \xrightarrow{\pi} \text{Hom}_B(B, b)) \end{array}$$

By Lemma 10.3.3(iii) applied to the adjunction $(p_0 \circ -) \dashv p_0^*$ the right-hand vertical map is isomorphic to the left-hand vertical map displayed below

$$\begin{array}{ccc} \text{Fun}_B^c(\text{Hom}_B(B, b) \xrightarrow{p_0} B, E \xrightarrow{p} B) & \xrightarrow{\sim} & \text{Fun}_B(1 \xrightarrow{b} B, E \xrightarrow{p} B) \\ (q, p)^{\circ-} \downarrow & & \downarrow (q, p)^{\circ-} \\ \text{Fun}_B^c(\text{Hom}_B(B, b) \xrightarrow{p_0} \text{Hom}_B(B, b), A \times B \xrightarrow{\pi} B) & \xrightarrow{\sim} & \text{Fun}_B(1 \xrightarrow{b} B, A \times B \xrightarrow{\pi} B) \end{array}$$

which is equivalent to the vertical map on the right by the Yoneda lemma applied to the cartesian fibration $p_0: \text{Hom}_B(B, b) \twoheadrightarrow B$ corresponding to the element $b: 1 \rightarrow B$. Combining these observations, we obtain an equivalence to the pullback

$$\begin{array}{ccc} \text{Fun}_{A \times B}(1 \xrightarrow{(a, b)} A \times B, E \xrightarrow{(q, p)} A \times B) & \xrightarrow{\quad} & \text{Fun}_B(1 \xrightarrow{b} B, E \xrightarrow{p} B) \\ \downarrow & \lrcorner & \downarrow (q, p)^{\circ-} \\ 1 & \xrightarrow{(a, b)} & \text{Fun}_B(1 \xrightarrow{b} B, A \times B \xrightarrow{\pi} B) \end{array}$$

This composite equivalence is the map defined by precomposition with the canonical element

$$(\ulcorner \text{id}_a \urcorner, \ulcorner \text{id}_b \urcorner): 1 \rightarrow \text{Hom}_A(a, A) \times \text{Hom}_B(B, b),$$

completing the proof. □

10.3.3. LEMMA.

- (i) Suppose $s: B \rightarrow A$ is a discrete cartesian fibration and $p: E \rightarrow B$ is an isofibration. Then $p: E \rightarrow B$ is a cocartesian fibration if and only if $sp: E \twoheadrightarrow A$ is a cocartesian fibration.

(ii) Suppose that s is a discrete cocartesian fibration and p and q are cocartesian fibrations. Then (g, s) defines a cartesian functor from p to q if and only if g defines a cartesian functor from sp to r .

$$\begin{array}{ccc} E & \xrightarrow{g} & F \\ p \downarrow & & \downarrow q \\ B & \xrightarrow{s} & A \end{array} \qquad \begin{array}{ccc} E & \xrightarrow{g} & F \\ & \searrow sp & \swarrow q \\ & A & \end{array} \quad (10.3.4)$$

(iii) If $s: B \twoheadrightarrow A$ is a discrete cocartesian fibration, then the adjunction $s \circ - \dashv s^*$

$$\mathrm{Fun}_A(E \xrightarrow{p} B \xrightarrow{s} A, F \xrightarrow{q} A) \cong \mathrm{Fun}_B(E \xrightarrow{p} B, s^*F \xrightarrow{s^*q} B)$$

between composition with and pullback along s restricts to cartesian functors:

$$\mathrm{Fun}_A^c(E \xrightarrow{p} B \xrightarrow{s} A, F \xrightarrow{q} A) \cong \mathrm{Fun}_B^c(E \xrightarrow{p} B, s^*F \xrightarrow{s^*q} B).$$

PROOF. For (i) recall that Lemma 5.1.7 proves that cocartesian fibrations compose, with sp -cocartesian cells being the p -cocartesian lifts of s -cocartesian cells. This proves that sp is cocartesian if p is, and the converse follows as well by the proof of that result: if s is a discrete cocartesian fibration, then any 2-cell with codomain B is s -cocartesian, so we may take the p -cocartesian cells to be precisely the sp -cocartesian cells.

For (ii), note that in proving (i), we have just argued that sp -cocartesian cells are precisely the same as p -cocartesian cells when p is a cocartesian fibration and s is a discrete cocartesian fibration. This proves that the two notions of cartesian functor coincide.¹

Finally (iii) follows immediately from (ii) and Proposition 5.1.20, which tells us that a map to the pullback of a cocartesian fibration along $s: B \rightarrow A$ defines a cartesian functor over B if and only if the square as displayed on the left of (10.3.4) defines a cartesian functor. \square

10.3.5. COROLLARY. The inclusion

$$A \backslash \mathrm{Fib}_B \hookrightarrow \mathcal{K}_{A \times B}$$

admits a left biadjoint defined by sending a two-sided isofibration $A \xleftarrow{a} X \xrightarrow{b} B$ to the composite two-sided fibration

$$\begin{array}{ccccc} & & \mathrm{Hom}_A(a, A) \times_{\mathrm{Hom}_B(B, b)} & & \\ & \swarrow & \downarrow \vee & \searrow & \\ \mathrm{Hom}_A(a, A) & & & & \mathrm{Hom}_B(B, b) \\ p_1 \swarrow & & p_0 \searrow & & p_1 \swarrow \\ A & & X & & B \\ & \nwarrow p_0 & \nwarrow p_1 & & \end{array}$$

and equipped with a natural equivalence

$$\mathrm{Fun}_{A \times B}^c \left(\begin{array}{c} \mathrm{Hom}_A(a, A) \times_{\mathrm{Hom}_B(B, b)} \\ \downarrow \\ A \times B \end{array} , \begin{array}{c} E \\ \downarrow \\ A \times B \end{array} \right) \simeq \mathrm{Fun}_{A \times B} \left(\begin{array}{c} X \\ (a, b) \downarrow \\ A \times B \end{array} , \begin{array}{c} E \\ \downarrow \\ A \times B \end{array} \right).$$

¹If s is cocartesian but not discrete, then if the left-hand diagram defines a cartesian functor, then so does the right one, but the converse no longer holds.

of functor spaces.

PROOF. Let $(q, p): E \rightrightarrows A \times B$ be a two-sided fibration in \mathcal{K} . Then since $- \times X: \mathcal{K} \rightarrow \mathcal{K}_{/X}$ is a cosmological functor, the span

$$A \times X \xleftarrow{q \times \text{id}} E \times X \xrightarrow{p \times \text{id}} B \times X$$

is a two-sided fibration in $\mathcal{K}_{/X}$. The maps $a: X \rightarrow A$ and $b: X \rightarrow B$ induce a pair of elements $(a, \text{id}): X \rightarrow A \times X$ and $(b, \text{id}): X \rightarrow B \times X$ in $\mathcal{K}_{/X}$ which are respectively covariantly and contravariantly represented by

$$(p_1, p_0): \text{Hom}_A(a, A) \rightrightarrows A \times X \quad \text{and} \quad (p_1, p_0): \text{Hom}_B(B, b) \rightrightarrows B \times X.$$

Applying Theorem 10.3.2 in $\mathcal{K}_{/X}$ to this two-sided isofibration and pair of elements, we find that restriction along the canonical map

$$i: X \rightarrow \text{Hom}_A(a, A) \times_X \text{Hom}_B(B, b)$$

defines an equivalence of quasi-categories

$$\text{Fun}_{A \times B \times X}^c \left(\begin{array}{c} \text{Hom}_A(a, A) \times_X \text{Hom}_B(B, b) \\ \downarrow \\ A \times B \times X \end{array}, \begin{array}{c} E \times X \\ \downarrow \\ A \times B \times X \end{array} \right) \simeq \text{Fun}_{A \times B \times X} \left(\begin{array}{c} X \\ (a, b, \text{id}) \downarrow \\ A \times B \times X \end{array}, \begin{array}{c} E \times X \\ \downarrow \\ A \times B \times X \end{array} \right).$$

Transposing the domain and codomain across the adjunction

$$\begin{array}{ccc} & \Sigma_X & \\ \mathcal{K} & \xleftarrow{\quad} & \mathcal{K}_{/X} \\ & \xrightarrow{- \times X} & \\ & \perp & \end{array}$$

yields the equivalence of functor spaces

$$\text{Fun}_{A \times B}^c \left(\begin{array}{c} \text{Hom}_A(a, A) \times_X \text{Hom}_B(B, b) \\ \downarrow \\ A \times B \end{array}, \begin{array}{c} E \\ \downarrow \\ A \times B \end{array} \right) \simeq \text{Fun}_{A \times B} \left(\begin{array}{c} X \\ (a, b) \downarrow \\ A \times B \end{array}, \begin{array}{c} E \\ \downarrow \\ A \times B \end{array} \right)$$

of the statement. □

The argument used to establish the equivalence of functor spaces in Corollary 10.3.5 works for any pair of generalized elements $a: X \rightarrow A$ and $b: X \rightarrow B$, whether or not this span defines a two-sided isofibration. In the case of spans represented by a single non-identity functor a “one-sided” version of Corollary 10.3.5, which is much more simply established, may be preferred:

10.3.6. PROPOSITION (one-sided Yoneda for two-sided fibrations). For any two-sided isofibration $A \xleftarrow{q} E \xrightarrow{p} B$ and functor $f: A \rightarrow B$, restriction along the canonical functor

$$\begin{array}{ccc} & A & \\ \swarrow & \downarrow \text{``id}_f\text{''} & \searrow f \\ A & \text{Hom}_B(B, f) & B \\ \nwarrow p_1 & & \nearrow p_0 \end{array}$$

induce equivalences of functor spaces

$$\text{Fun}_{A \times B}^c \left(\begin{array}{c} \text{Hom}_B(B, f) \\ (p_1, p_0) \downarrow \\ A \times B \end{array}, \begin{array}{c} E \\ \downarrow (q, p) \\ A \times B \end{array} \right) \simeq \text{Fun}_{A \times B} \left(\begin{array}{c} A \\ (\text{id}_A, f) \downarrow \\ A \times B \end{array}, \begin{array}{c} E \\ \downarrow (q, p) \\ A \times B \end{array} \right).$$

PROOF. This follows immediately from the external Yoneda lemma of Theorem 5.5.3 applied to the element $(\text{id}_A, f): A \rightarrow A \times B$ and the cartesian fibration $(q, p): E \rightarrow A \times B$ in the ∞ -cosmos $\text{coCart}(\mathcal{K})/A$. \square

Exercises.

10.3.i. EXERCISE. State and prove the other one-sided Yoneda lemma for two-sided fibrations, establishing an equivalence of functor spaces below-left induced by restricting along the functor below-right

$$\text{Fun}_{A \times B}^c \left(\begin{array}{c} \text{Hom}_A(f, A) \\ (p_1, p_0) \downarrow \\ A \times B \end{array}, \begin{array}{c} E \\ \downarrow (q, p) \\ A \times B \end{array} \right) \simeq \text{Fun}_{A \times B} \left(\begin{array}{c} B \\ (f, \text{id}_B) \downarrow \\ A \times B \end{array}, \begin{array}{c} E \\ \downarrow (q, p) \\ A \times B \end{array} \right)$$

$$\begin{array}{ccc} & B & \\ \swarrow f & \downarrow i & \searrow \\ A & \text{Hom}_A(f, A) & B \\ \nwarrow p_1 & & \nearrow p_0 \end{array}$$

10.4. Modules as discrete two-sided fibrations

We are not so much interested in two-sided fibrations but the special case of those two-sided fibrations that are discrete as objects in $\mathcal{K}_{A \times B}$.

10.4.1. DEFINITION. A **module from A to B** is a two-sided fibration $A \xleftarrow{q} E \xrightarrow{p} B$ that is a discrete object in ${}_A \backslash \text{Fib}(\mathcal{K})/B$.

Note that an object in the replete subcosmos ${}_A \backslash \text{Fib}(\mathcal{K})/B \hookrightarrow \mathcal{K}_{A \times B}$ is discrete in there if and only if it is discrete as an object of $\mathcal{K}_{A \times B}$; see Exercise 7.4.v. Our work in this chapter enables us to give a direct characterization of modules:

10.4.2. LEMMA. A two-sided isofibration $A \xleftarrow{q} E \xrightarrow{p} B$ defines a module from A to B if and only if it is

- (i) cocartesian on the left,
- (ii) cartesian on the right,
- (iii) and discrete as an object of $\mathcal{K}_{A \times B}$.

PROOF. This follows immediately from the characterization of two-sided fibrations given as Theorem 10.1.4(iv). \square

Unpacking the definition, we easily establish the following properties of modules.

10.4.3. LEMMA. If $A \xleftarrow{q} E \xrightarrow{p} B$ defines a module from A to B , then

(i) The functors

$$\begin{array}{ccc} E & \xrightarrow{(q,p)} & A \times B \\ p \searrow & & \swarrow \pi \\ & B & \end{array} \qquad \begin{array}{ccc} E & \xrightarrow{(q,p)} & A \times B \\ q \searrow & & \swarrow \pi \\ & A & \end{array}$$

define a discrete cocartesian fibration and a discrete cartesian fibration, respectively, in the slice ∞ -cosmoi $\mathcal{K}_{/B}$ and $\mathcal{K}_{/A}$.

- (ii) The functors $q: E \rightarrow A$ and $p: E \rightarrow B$ respectively define a cocartesian fibration and a cartesian fibration in \mathcal{K} .
- (iii) For any 2-cell χ with codomain E , χ is p -cartesian if and only if $q\chi$ is invertible, and χ is q -cocartesian if and only if $p\chi$ is invertible.
- (iv) In particular, any 2-cell that is fibered over $A \times B$ is both p - and q -cocartesian and any map of spans from a two-sided fibration

$$\begin{array}{ccccc} & & F & & \\ & s \swarrow & & \searrow r & \\ A & & & & B \\ & q \swarrow & g \downarrow & \searrow p & \\ & & F & & \end{array}$$

to a module defines a cartesian functor of two-sided fibrations in the sense of Lemma 10.1.10, and also a cartesian functor from s to q and from r to p .

PROOF. By Lemma 10.1.1, conditions (i) and (iii) together assert exactly that $(q, p): E \rightarrow A \times B$ defines a discrete cocartesian fibration in $\mathcal{K}_{/B}$, proving (i). Statement (ii) holds for any two-sided fibration; the point of reasserting it here is that it is not necessarily the case that the legs of a module are themselves discrete fibrations (see Exercise 10.4.i).

One direction of statement (iii) is proven as Lemma 10.1.1 while the converse is proven in Exercise 10.1.i. Statement (iv) follows. \square

An important property of modules is that they are stable under pullback:

10.4.4. PROPOSITION. If $A \leftarrow E \rightarrow B$ is a module from A to B and $a: A' \rightarrow A$ and $b: B' \rightarrow B$ are any pair of functors, then the pullback defines a module $A' \leftarrow E(b, a) \rightarrow B'$ from A' to B' .

PROOF. The cosmological functor

$$(a, b)^*: {}_{A'}\mathcal{Fib}(\mathcal{K})_{/B} \longrightarrow {}_{A'}\mathcal{Fib}(\mathcal{K})_{/B'}$$

of Proposition 10.2.4 preserves discrete objects in these ∞ -cosmoi. \square

Applying Proposition 10.4.4 to a pair of elements $a: 1 \rightarrow A$ and $b: 1 \rightarrow B$, we see that a module from A to B is a two-sided fibration whose fibers $E(b, a)$ are discrete objects. The converse does not generally hold: being discrete as an object of the sliced ∞ -cosmos $\mathcal{K}_{/A \times B}$ is a stronger condition than merely having discrete fibers. However, in the ∞ -cosmos \mathbf{QCat} the point 1 is a generator in a suitable sense and we have:

10.4.5. LEMMA. If $E \rightrightarrows A \times B$ is a two-sided fibration of quasi-categories whose fibers are Kan complexes, then E is a module.

PROOF. By definition, $E \rightrightarrows A \times B$ defines a discrete object in $\mathbf{QCat}_{/A \times B}$ if any 1-simplex in E^X that lies over a degenerate 1-simplex in $(A \times B)^X$ is an isomorphism. As isomorphisms in functor quasi-categories are determined pointwise (see Lemma ??), it suffices to consider the case $X = 1$ and now this reduces to the hypothesis that the fibers $E(b, a)$ over any pair of points $(a, b) \in A \times B$ are Kan complexes. \square

The prototypical example of a module is given by the arrow ∞ -category construction.

10.4.6. PROPOSITION. For any ∞ -category A , the arrow ∞ -category A^2 defines a module from A to A .

The fact that $A^2 \rightrightarrows A \times A$ is discrete is related to but stronger than the fact that each fiber over a pair of elements in A , the **internal hom-space** between those elements of A , is a discrete ∞ -category, proven in Proposition 3.3.10.

PROOF. Proposition 10.1.9 proves that $(p_1, p_0): A^2 \rightrightarrows A \times A$ is a two-sided fibration, so it remains only to verify the discreteness condition, which we can do in $\mathcal{K}_{/A \times A}$. Discreteness of $A^2 \rightrightarrows A \times A$ as an object of $\mathcal{K}_{/A \times A}$ is an immediate consequence of 2-cell conservativity of Proposition 3.2.5: if γ is any 2-cell with codomain A^2 so that $p_0\gamma$ and $p_1\gamma$ are invertible, then γ is itself invertible. \square

By the construction of (3.3.2) and Proposition 10.4.4:

10.4.7. COROLLARY. The comma ∞ -category $\mathbf{Hom}_A(f, g) \rightrightarrows C \times B$ associated to a pair of functors $f: B \rightarrow A$ and $g: C \rightarrow A$ defines a module from C to B . \square

Two special cases of these comma modules, those studied in §3.4, deserve a special name:

10.4.8. DEFINITION. To any functor $f: A \rightarrow B$ between ∞ -categories

- (i) the module $\mathbf{Hom}_B(B, f)$ from A to B is **right** or **covariantly represented** by f , while
- (ii) the module $\mathbf{Hom}_B(f, B)$ from B to A is **left** or **contravariantly represented** by f .

As we saw in §5.5, the Yoneda lemma for two-sided fibrations simplifies when mapping into a module on account of the observation in Lemma 10.4.3(iv) that any map of spans from a two-sided fibration to a module defines a cartesian functor.

10.4.9. THEOREM (Yoneda lemma for modules). For any elements $a: X \rightarrow A$ and $b: X \rightarrow B$ and any module $A \xleftarrow{q} E \xrightarrow{p} B$, restriction along $(\ulcorner \mathrm{id}_a \urcorner, \ulcorner \mathrm{id}_b \urcorner): X \rightarrow \mathbf{Hom}_A(a, A) \times_X \mathbf{Hom}_B(B, b)$ defines an equivalence of Kan complexes

$$\mathrm{Fun}_{A \times B} \left(\begin{array}{ccc} \mathbf{Hom}_A(a, A) \times_X \mathbf{Hom}_B(B, b) & & E \\ \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right) \cong \mathrm{Fun}_{A \times B} \left(\begin{array}{ccc} X & & E \\ (a,b) \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right).$$

Similarly for any functors $f: A \rightarrow B$ or $g: B \rightarrow A$, restriction along $\ulcorner \text{id}_f \urcorner: A \rightarrow \text{Hom}_B(B, f)$ or $\ulcorner \text{id}_g \urcorner: B \rightarrow \text{Hom}_A(g, A)$ define equivalences of Kan complexes

$$\begin{aligned} \text{Fun}_{A \times B} \left(\begin{array}{ccc} \text{Hom}_B(B, f) & & E \\ \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right) &\simeq \text{Fun}_{A \times B} \left(\begin{array}{ccc} A & & E \\ (\text{id}, f) \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right) \\ \text{Fun}_{A \times B} \left(\begin{array}{ccc} \text{Hom}_A(g, A) & & E \\ \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right) &\simeq \text{Fun}_{A \times B} \left(\begin{array}{ccc} B & & E \\ (g, \text{id}) \downarrow & & \downarrow \\ A \times B & & A \times B \end{array} \right). \quad \square \end{aligned}$$

Exercises.

10.4.i. EXERCISE. Demonstrate by means of an example that if $A \xleftarrow{q} E \xrightarrow{p} B$ defines a module from A to B then it is not necessarily the case that $p: E \rightarrow B$ is a discrete cartesian fibration or $q: E \rightarrow A$ is a discrete cocartesian fibration.

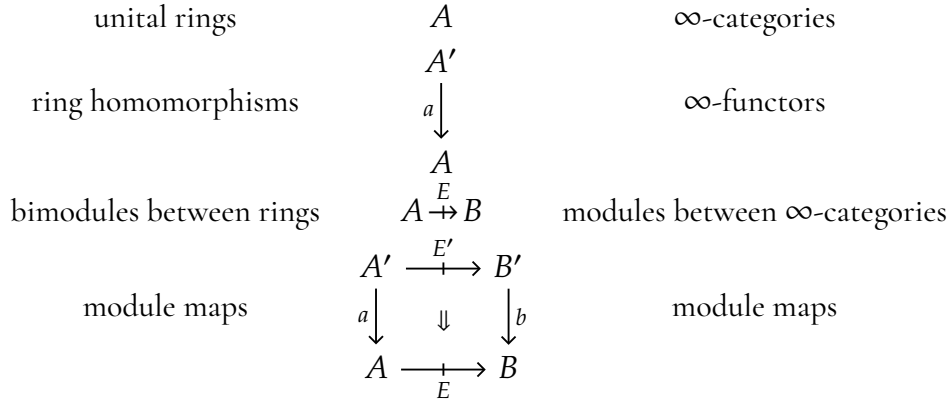
10.4.ii. EXERCISE.

- (i) Explain why the two-sided fibration $(p_{n-1}, p_n): A^n \rightarrow A \times A$ of Proposition 10.1.9 does not define a module for $n > 2$.
- (ii) Conclude that the horizontal composite of modules, as defined in Proposition 10.2.6, is not necessarily a module.

CHAPTER 11

The calculus of modules

The calculus of modules between ∞ -categories bears a strong resemblance to the calculus of (bi)modules between unital rings. Here ∞ -categories take the place of rings, with functors between ∞ -categories playing the role of ring homomorphisms, which we display vertically on the table below. A module E from A to B , like the two-sided fibrations considered in Chapter 10, is an ∞ -category on which A “acts on the left” and B “acts on the right” and these actions commute; this is analogous to the situation for bimodules in ring theory and explains our choice of terminology.¹ Modules will now be depicted as $A \xrightarrow{E} B$ whenever explicit names for the legs of the constituent span are not needed.



Finally, there is a notion of module map, that we shall introduce below, whose boundary in the most general case is a square comprised of two modules and two functors as above. In ring theory, a module map with this boundary is given by an $A'-B'$ module homomorphism $E' \rightarrow E(b, a)$, whose codomain is the $A'-B'$ bimodule defined by restricting the scalar multiplication in the $A-B$ module E along the ring homomorphisms a and b .

The analogy extends deeper than this: unital rings, ring homomorphisms, bimodules, and module maps define a *proarrow equipment*, in the sense of Wood [64].² Our main result in this chapter is Theorem 11.2.6, which asserts that ∞ -categories, functors, modules, and module maps in any ∞ -cosmos define a *virtual equipment*, in the sense of Cruttwell and Shulman [15].

As a first step, in §11.1 we introduce the double category of two-sided fibrations, which restricts to define a *virtual double category* of modules. A *double category* is a sort of 2-dimensional category with objects; two varieties of 1-morphisms, the “horizontal” and the “vertical”; and 2-dimensional cells fitting

¹In the 1- and ∞ -categorical literature, the names “profunctor,” “correspondence,” and “distributor” are all used as synonyms for “module.”

²This can be seen as a special case of the prototypical equipment comprised of \mathcal{V} -categories, \mathcal{V} -functors, \mathcal{V} -modules, and \mathcal{V} -natural transformations between them, for any closed symmetric monoidal category \mathcal{V} . The equipment for rings is obtained from the case where \mathcal{V} is the category of abelian groups by restricting to abelian group enriched categories with a single object.

into “squares” whose boundaries consist of horizontal and vertical 1-morphisms with compatible domains and codomains. A motivating example from abstract algebra is the double category of modules: objects are rings, vertical morphisms are ring homomorphisms, horizontal morphisms are bimodules, and whose squares are bimodule homomorphisms. In the literature, this sort of structure is sometimes called a *pseudo double category* — morphisms and squares compose strictly in the “vertical” direction but only up to isomorphism in the “horizontal” direction — but we’ll refer to this simply as a “double category” as it is the only variety that we will consider.

Our aim in §11.1 is to describe a similar structure whose objects and vertical morphisms are the ∞ -categories and functors in any fixed ∞ -cosmos, whose horizontal morphisms are modules, and whose squares are module maps, as will be defined in 11.1.6. If the horizontal morphisms are replaced by the larger class of two-sided fibrations, this does define a double category with the horizontal composition operation defined by Proposition 10.2.6. However, on account of Exercise 10.4.ii, the horizontal composition of two-sided fibrations does not preserve the class of modules: the arrow ∞ -category A^2 defines a module from A to A whose horizontal composite with itself is equivalent to the two-sided fibration $(p_2, p_0): A^3 \rightarrowtail A \times A$ of Proposition 10.1.9, which is not discrete in $\mathcal{K}_{/A \times A}$. To define a genuine “tensor product for modules” operation would require a two-stage construction: first forming the pullback that defines a composite two-sided fibration as in Proposition 10.2.6, and then reflecting this into a two-sided *discrete* fibration by means of some sort of “homotopy coinverter” construction. As colimits that are not within the purview of the axioms of an ∞ -cosmos, this presents somewhat of an obstacle.

Rather than leave the comfort of our axiomatic framework in pursuit of a double category of modules, we instead describe the structure that naturally arises within the axiomatization: it turns out to be familiar to category theorists and robust enough for our desired applications. We first demonstrate that ∞ -categories, functors, modules, and module maps assemble into a *virtual double category*, a weaker structure than a double category in which cells are permitted to have a multi horizontal source, as a “virtual” replacement for horizontal composition of modules.

Once the definition of a virtual equipment is given in §11.2, these axioms are very easily checked. The final two sections are devoted to exploring the consequences of this structure, which will be put to full use in Chapter 12, which develops the formal category theory of ∞ -categories by introducing Kan extensions in the virtual equipment of modules. In §11.3, we explain how certain horizontal composites of modules can be recognized in the virtual equipment, even if the general construction of the tensor product of an arbitrary composable pair of modules is not known. The final §11.4 collects together many special properties of the modules $A \xrightarrow{\text{Hom}_B(B, f)} B$ and $B \xrightarrow{\text{Hom}_B(f, B)} A$ represented by a functor $f: A \rightarrow B$ of ∞ -categories, revisiting some of the properties first established in §3.4.

11.1. The double category of two-sided fibrations

Our first task is to define the 2-dimensional morphisms in the double categories that we will introduce.

11.1.1. DEFINITION. Let $A \xleftarrow{q} E \xrightarrow{p} B$ and $A \xleftarrow{s} F \xrightarrow{r} B$ be two-sided isofibrations. A **map of spans** from $A \xleftarrow{q} E \xrightarrow{p} B$ to $A \xleftarrow{s} F \xrightarrow{r} B$ is a fibered isomorphism class of strictly commuting functors

$$\begin{array}{ccc} & E & \\ q \swarrow & \downarrow g & \searrow p \\ A & & B \\ s \nwarrow & \downarrow & \nearrow r \\ & F & \end{array}$$

where two such functors g and g' are considered equivalent if there exists a natural isomorphism $\alpha: g \cong g'$ so that $r\alpha = \text{id}_q$ and $s\alpha = \text{id}_p$.

11.1.2. DEFINITION. Let $A \xleftarrow{q} E \xrightarrow{p} B$ and $A \xleftarrow{s} F \xrightarrow{r} B$ be two-sided fibrations. A **map of two-sided fibrations** from $A \xleftarrow{q} E \xrightarrow{p} B$ to $A \xleftarrow{s} F \xrightarrow{r} B$ is a map of spans in which any and hence every representing map

$$\begin{array}{ccc} & E & \\ q \swarrow & \downarrow g & \searrow p \\ A & & B \\ s \nwarrow & \downarrow & \nearrow r \\ & F & \end{array}$$

defines a cartesian functor of two-sided fibrations defined in Lemma 10.1.10.

11.1.3. DEFINITION. Let $A \xleftarrow{q} E \xrightarrow{p} B$ and $A \xleftarrow{s} F \xrightarrow{r} B$ be modules. A **map of modules** from E to F is just a map of spans from $A \xleftarrow{q} E \xrightarrow{p} B$ to $A \xleftarrow{s} F \xrightarrow{r} B$, that is a fibered isomorphism class of strictly commuting functors

$$\begin{array}{ccc} & E & \\ q \swarrow & \downarrow g & \searrow p \\ A & & B \\ s \nwarrow & \downarrow & \nearrow r \\ & F & \end{array}$$

11.1.4. OBSERVATION (the 1-categories of spans and maps). The 1-category of two-sided isofibrations from A to B and maps of spans may be obtained as a quotient of the quasi-categorically enriched category $\mathcal{K}_{A \times B}$, or of its homotopy 2-category $\mathfrak{h}(\mathcal{K}_{A \times B})$, or of the slice homotopy 2-category $\mathfrak{h}\mathcal{K}_{A \times B}$: it is the 1-category with the same set of objects and in which the morphisms are isomorphism classes of 0-arrows.

Similarly, the 1-category of two-sided fibrations from A to B and maps of two-sided fibrations may be obtained as a quotient of the quasi-categorically enriched category ${}_A\mathcal{Fib}(\mathcal{K})_B$, or of its homotopy 2-category $\mathfrak{h}({}_A\mathcal{Fib}(\mathcal{K})_B)$: it is the 1-category with the same set of objects and in which the morphisms are isomorphism classes of 0-arrows.

By Lemma 10.4.3, the 1-category of modules from A to B and modules maps is a full subcategory of either of the two 1-categories just considered.

The 1-categories of Observation 11.1.4 are of interest because they precisely capture the correct notion of equivalence between two-sided isofibrations, two-sided fibrations, or modules first introduced in Definition 3.2.7.

11.1.5. LEMMA.

- (i) A pair of two-sided isofibrations are equivalent in $\mathcal{K}_{/A \times B}$ if and only if they are isomorphic in the 1-category of spans from A to B .
- (ii) A pair of two-sided fibrations are equivalent in ${}_A \mathcal{Fib}(\mathcal{K})_{/B}$ if and only if they are isomorphic in the 1-category of two-sided fibrations from A to B .
- (iii) A pair of modules are equivalent over A times B if and only if they are isomorphic in the 1-category of modules from A to B . \square

Each of the Definitions 11.1.3 admits a common generalization, which defines the 2-dimensional maps inhabiting squares.

11.1.6. DEFINITION (maps in squares). A **map of modules** or **map of two-sided fibrations** or **map of two-sided isofibration** from $A' \xleftarrow{q'} E' \xrightarrow{p'} B'$ to $A \xleftarrow{q} E \xrightarrow{p} B$ over $a: A' \rightarrow A$ and $b: B' \rightarrow B$ is

$$\begin{array}{ccc} A' & \xrightarrow{E'} & B' \\ a \downarrow & \Downarrow & \downarrow b \\ A & \xrightarrow{E} & B \end{array} \qquad \begin{array}{ccc} E' & \xrightarrow{g} & E \\ (q', p') \downarrow & & \downarrow (q, p) \\ A' \times B' & \xrightarrow{a \times b} & A \times B \end{array}$$

is a fibered isomorphism class of strictly commuting functors g as displayed above-right, which in the case of two-sided fibrations must preserve the cartesian and cocartesian transformations, where two such functors g and g' are considered equivalent if there exists a natural isomorphism $\alpha: g \cong g'$ so that $q\alpha = \text{id}_{aq'}$ and $p\alpha = \text{id}_{bp'}$.

In the case of modules or two-sided isofibrations, the functor-space $\text{Fun}_{a \times b}(E', E)$ of maps from E' to E over $a \times b$ is defined by the pullback

$$\begin{array}{ccc} \text{Fun}_{a \times b}(E', E) & \longrightarrow & \text{Fun}(E', E) \\ \downarrow & \lrcorner & \downarrow (q, p) \\ \mathbb{1} & \xrightarrow{(aq', bp')} & \text{Fun}(E', A \times B) \end{array}$$

In the case of two-sided fibrations, the functor space is taken to be the full sub quasi-category

$$\text{Fun}_{a \times b}^c(E', E) \subset \text{Fun}_{a \times b}(E', E)$$

of all n -simplices whose vertices define cartesian functors.

We occasionally extend the notion of map to allow the domain to be an identity span $C \xleftarrow{\text{id}_C} C \xrightarrow{\text{id}_C} C$, but unless the domain is the identity span, we always require the codomain to be at least a two-sided isofibration.

We now introduce the double categories of isofibrations and of two-sided fibrations. These structures can be viewed either as a collection of data present in the homotopy 2-category $\mathfrak{h}\mathcal{K}$ of an ∞ -cosmos or as a quotient of quasi-categorically enriched structures, presented by a non-unital internal category defined up to natural isomorphism in the category of ∞ -cosmoi and cosmological functors; see Exercise 11.1.i. For economy of language, we adopt the former approach.

11.1.7. PROPOSITION (the double category of two-sided (iso)fibrations). *The homotopy 2-category of an ∞ -cosmos supports a **double category**³ of two-sided isofibrations whose:*

- *objects are ∞ -categories,*
- *vertical arrows are functors,*
- *horizontal arrows $A \xrightarrow{E} B$ are two-sided isofibrations $A \xleftarrow{q} E \xrightarrow{p} B$, and*
- *2-cells with boundary*

$$\begin{array}{ccc} A' & \xrightarrow{E'} & B' \\ a \downarrow & \Downarrow & \downarrow b \\ A & \xrightarrow{E} & B \end{array}$$

are maps of two-sided isofibrations as defined in 11.1.6, or equivalently, are isomorphism classes of objects in the quasi-category $\mathbf{Fun}_{a \times b}(E', E)$.

*Vertical composition of arrows and 2-cells is by composition in \mathcal{K} , while horizontal composition of arrows and 2-cells is by pullback, which is well-defined and associative up to isomorphism. The **double category of two-sided fibrations** is the sub double category that has the same objects and vertical arrows but whose:*

- *horizontal arrows $A \xrightarrow{E} B$ are two-sided fibrations $A \xleftarrow{q} E \xrightarrow{p} B$ and*
- *2-cells with boundary*

$$\begin{array}{ccc} A' & \xrightarrow{E'} & B' \\ a \downarrow & \Downarrow & \downarrow b \\ A & \xrightarrow{E} & B \end{array}$$

are maps of two-sided fibrations as defined in 11.1.6, or equivalently, are isomorphism classes of objects in $\mathbf{Fun}_{a \times b}^c(E', E)$.

PROOF. The composition of horizontal arrows is defined in Proposition 10.2.6, while the horizontal composition of 2-cells is defined in Exercise 10.2.i. By simplicial functoriality of pullback and composition in \mathcal{K} , both constructions are associative up to canonical natural isomorphism. \square

11.1.8. REMARK (why we left out the horizontal unit). We could have formally added the identity span $\Delta: A \rightarrow A \times A$ to serve as a horizontal unit in the double categories of Proposition 11.1.7 but we find it less confusing to leave them out because when we restrict to the structure of greatest interest, the virtual equipment category of modules, we will see that the arrow ∞ -category $A \xrightarrow{\mathrm{Hom}_A} A$ plays the role of the horizontal unit for composition in a sense to be described in Proposition 11.2.4.

11.1.9. DEFINITION (virtual double category). A **virtual double category** consists of

- a category of **objects** and **vertical arrows**
- for any pair of objects A, B , a class of **horizontal arrows** $A \rightarrow B$

³As discussed previously, our double categories support vertical composition laws that are strictly unital and associative but horizontal composition laws that are only associative and unital up to isomorphism. For reasons to be explained in Remarks 11.1.8 and 11.1.13, we choose not to require a horizontal unit arrow or 2-cell.

- **cells**, with boundary depicted as follows

$$\begin{array}{ccccc}
 A_0 & \xrightarrow{E_1} & A_1 & \xrightarrow{E_2} & \cdots & \xrightarrow{E_n} & A_n \\
 f \downarrow & & & \Downarrow & & & \downarrow g \\
 B_0 & \xrightarrow{\quad\quad\quad} & & \xrightarrow{F} & & & B_n
 \end{array} \tag{11.1.10}$$

including those whose horizontal source has length zero, in the case $A_0 = A_n$.

- a **composite cell** as below-right, for any configuration as below-left

$$\begin{array}{ccccc}
 A_0 & \xrightarrow{E_{11}, \dots, E_{1k_1}} & A_1 & \xrightarrow{E_{21}, \dots, E_{2k_2}} & \cdots & \xrightarrow{E_{n1}, \dots, E_{nk_n}} & A_n \\
 f_0 \downarrow & & \Downarrow & \downarrow f_1 & & \Downarrow & \downarrow f_n \\
 B_0 & \xrightarrow{F_1} & B_1 & \xrightarrow{F_2} & \cdots & \xrightarrow{F_n} & B_n \\
 g \downarrow & & & \Downarrow & & & \downarrow h \\
 C_0 & \xrightarrow{\quad\quad\quad} & & \xrightarrow{G} & & & C_n
 \end{array} =: \begin{array}{ccccc}
 A_0 & \xrightarrow{E_{11}} & \cdots & \xrightarrow{E_{12}, \dots, E_{nk_n-1}} & \cdots & \xrightarrow{E_{nk_n}} & A_n \\
 gf_0 \downarrow & & & \Downarrow & & & \downarrow hf_n \\
 C_0 & \xrightarrow{\quad\quad\quad} & & \xrightarrow{G} & & & C_n
 \end{array}$$

- an **identity cell** for every horizontal arrow

$$\begin{array}{ccc}
 A & \xrightarrow{E} & B \\
 \parallel & \Downarrow \text{id}_E & \parallel \\
 A & \xrightarrow{E} & B
 \end{array}$$

so that composition of cells is associative and unital in the usual multi-categorical sense.

11.1.11. LEMMA. *The double category of two-sided isofibrations and the double category of two-sided fibrations extend to a virtual double category in which the*

- *objects are ∞ -categories,*
- *vertical arrows are functors,*
- *horizontal arrows are two-sided isofibrations or two-sided fibrations as appropriate, and*
- *n -ary cells (11.1.10) are 2-cells*

$$\begin{array}{ccccc}
 A_0 & \xrightarrow{E_1 \times \cdots \times E_n} & A_n \\
 f \downarrow & & \Downarrow & & \downarrow g \\
 B_0 & \xrightarrow{\quad\quad\quad} & B_n
 \end{array} \tag{11.1.12}$$

whose single vertical source is the $(n - 1)$ -fold pullback of the sequence of spans comprising the vertical source in (11.1.10).

PROOF. The only thing perhaps worth commenting on is the nullary cells which have an empty sequence as their vertical domain

$$\begin{array}{ccc} A & \xlongequal{\quad} & A \\ f \downarrow & \Downarrow & \downarrow g \\ B & \xrightarrow{F} & C \end{array}$$

which we interpret as a 0-fold pullback, this being the identity span from A to A . So the nullary cells displayed above are fibered isomorphism classes of maps

$$\begin{array}{ccccc} & & A & & \\ f \swarrow & & \downarrow h & & \searrow g \\ B & & & & C \\ s \swarrow & & \downarrow F & & \searrow r \end{array}$$

where h and h' lie in the same equivalence class if there exists a natural isomorphism $\alpha: h \cong h'$ so that $s\alpha = \text{id}_f$ and $r\alpha = \text{id}_g$. \square

11.1.13. REMARK. For instance, the map

$$\begin{array}{ccc} & A & \\ \parallel & \downarrow \Delta & \parallel \\ A & & A \\ q_1 \swarrow & & \searrow q_0 \\ & A^{\mathbb{I}} & \end{array} \quad \rightsquigarrow \quad \begin{array}{ccc} A & \xlongequal{\quad} & A \\ \parallel & \Downarrow & \parallel \\ A & \xrightarrow{A^{\mathbb{I}}} & A \end{array}$$

defines a nullary morphism with codomain $A \xrightarrow{A^{\mathbb{I}}} A$ in the virtual double category of two-sided isofibrations. Note, however, that despite the fact that $\Delta: A \simeq A^{\mathbb{I}}$ defines an equivalence in \mathcal{K} , this cell does not define an isomorphism in the virtual double category of any kind. It is for this sort of reason that we left out the identity horizontal arrows in Proposition 11.1.7.

Our main example of interest is a full sub virtual double category defined by restricting the class of horizontal arrows and taking all cells between them. Since the only operations given in the structure of a virtual double category are vertical sources and targets, vertical identities, and vertical composition, it is clear that this substructure is closed under all of these operations, and thus inherits the structure of a virtual double category:

11.1.14. PROPOSITION. *For any ∞ -cosmos \mathcal{K} , there is a virtual double category of modules $\mathcal{M}od(\mathfrak{h}\mathcal{K})$ defined as a full subcategory of either the virtual double categories of isofibrations or the virtual double category of two-sided fibrations whose*

- *objects are ∞ -categories,*
- *vertical arrows are functors,*
- *horizontal arrows $A \xrightarrow{E} B$ are modules E from A to B ,*

- n -ary cells are fibered isomorphism classes of maps of spans

$$\begin{array}{ccc}
 A_0 & \xrightarrow{E_1} A_1 & \xrightarrow{E_2} \cdots \xrightarrow{E_n} A_n \\
 f \downarrow & & \Downarrow & & \downarrow g \\
 B_0 & \xrightarrow{\quad\quad\quad} & B_n
 \end{array}
 \quad \Leftrightarrow \quad
 \begin{array}{ccc}
 & E_1 \times \cdots \times E_n & \\
 & A_1 \quad A_{n-1} & \\
 A_0 & \swarrow & \searrow A_n \\
 f \downarrow & & \downarrow g \\
 B_0 & \swarrow & \searrow B_n \\
 & F &
 \end{array}
 \quad (11.1.15)$$

These maps, introduced in Definition 11.1.6, can be thought of as special cases of the n -ary cells of Lemma 11.1.11 where E_1, \dots, E_n, F are all required to be modules: the single horizontal source in the diagram (11.1.12) is the two-sided fibration defined by the $(n-1)$ -fold pullback of the sequence of modules comprising the horizontal source in the left-hand diagram. \square

We refer to (11.1.15) as an n -ary **module map**. Note a 1-ary module map is just a module map as in Definition 11.1.6. We refer to the finite sequence of modules occurring as the horizontal domain of an n -ary module map as a **composable sequence of modules**, which just means that their horizontal sources and targets are compatible in the evident way.

A hint at the relevance of this notion of n -ary module map is given by the following special case.

11.1.16. LEMMA. There is a bijection between n -ary module maps whose codomain module $B \xrightarrow{\text{Hom}_D(h,k)} C$ is a comma as displayed below-left and 2-cells in the homotopy 2-category whose boundary is displayed above-right.

$$\begin{array}{ccc}
 A_0 & \xrightarrow{E_1} A_1 & \xrightarrow{E_2} \cdots \xrightarrow{E_n} A_n \\
 f \downarrow & & \Downarrow & & \downarrow g \\
 B & \xrightarrow{\quad\quad\quad} & C \\
 & \text{Hom}_D(h,k) &
 \end{array}
 \quad \Leftrightarrow \quad
 \begin{array}{ccc}
 & E_1 \times \cdots \times E_n & \\
 & A_1 \quad A_{n-1} & \\
 A_0 & \swarrow & \searrow A_n \\
 f \downarrow & & \downarrow g \\
 B & \swarrow & \searrow C \\
 & k & h \\
 & D &
 \end{array}$$

PROOF. Combine Definition 11.1.6 with Proposition 3.3.7. \square

For any pair of objects A and B in the virtual double category of modules, there is a vertical 1-category of modules from A to B and module maps over a pair of identity functors, which coincides with the 1-category of modules from A to B introduced in Observation 11.1.4.

11.1.17. LEMMA. A parallel pair of modules $A \xrightarrow{E} B$ and $A \xrightarrow{F} B$ are isomorphic as objects of vertical 1-category of modules in the virtual double category of modules if and only if the modules E and F are equivalent as spans from A to B .

PROOF. This is a restatement of Lemma 11.1.5(iii). \square

For consistency with the rest of the text, we write $E \simeq F$ or $E \simeq_{A \times B} F$ whenever the modules $A \xrightarrow{E} B$ and $A \xrightarrow{F} B$ are isomorphic as objects of the vertical 1-category of modules from A to B . For instance, Proposition 4.1.1 proves that a functor $f: B \rightarrow A$ is left adjoint to a functor $u: A \rightarrow B$ if and only if $\text{Hom}_A(f, A) \simeq \text{Hom}_B(B, u)$ over $A \times B$, that is, if and only if the modules $B \xrightarrow{\text{Hom}_A(f, A)} A$ and $A \xrightarrow{\text{Hom}_B(B, u)} B$ are isomorphic as objects of the vertical 1-category of modules from A to B .

Exercises.

11.1.i. EXERCISE. Generalize the proof of Proposition 7.4.1 to prove that for any ∞ -cosmos \mathcal{K} , there is an ∞ -cosmos \mathcal{K}^{\bowtie} whose objects are two-sided isofibrations between an arbitrary pair of ∞ -categories. Prove that the domain and codomain define cosmological functors $\mathcal{K}^{\bowtie} \rightrightarrows \mathcal{K}$. Use this to give a second description of the double category of two-sided isofibrations as a quotient of a structure defined at the level of quasi-categorically enriched categories.

11.1.ii. EXERCISE. Prove that any double category defines a virtual double category.⁴

11.2. The virtual equipment of modules

The virtual double category of modules $\mathcal{M}od(\mathfrak{h}\mathcal{K})$ in an ∞ -cosmos \mathcal{K} has two special properties that characterize what Cruttwell and Shulman term a *virtual equipment*. Before stating the definition, we explore each of these in turn.

11.2.1. PROPOSITION (restriction). *Any diagram in $\mathcal{M}od(\mathfrak{h}\mathcal{K})$ as below-left can be completed to a cartesian cell as below-right*

$$\begin{array}{ccc} A' & & B' \\ a \downarrow & & \downarrow b \\ A & \xrightarrow{E} & B \end{array} \rightsquigarrow \begin{array}{ccc} A' & \xrightarrow{E(b,a)} & B' \\ a \downarrow & \Downarrow \rho & \downarrow b \\ A & \xrightarrow{E} & B \end{array}$$

characterized by the universal property that any cell as displayed below-left factors uniquely through ρ as below-right:

$$\begin{array}{ccc} X_0 & \xrightarrow{E_1} & X_1 \xrightarrow{E_2} \cdots \xrightarrow{E_n} X_n \\ af \downarrow & & \Downarrow \\ A & \xrightarrow{E} & B \end{array} = \begin{array}{ccc} X_0 & \xrightarrow{E_1} & X_1 \xrightarrow{E_2} \cdots \xrightarrow{E_n} X_n \\ f \downarrow & & \exists! \Downarrow \\ A' & \xrightarrow{E(b,a)} & B' \\ a \downarrow & \Downarrow \rho & \downarrow b \\ A & \xrightarrow{E} & B \end{array}$$

PROOF. The horizontal source of the cartesian cell is defined by restricting the module $A \xrightarrow{E} B$ along the functors a and b :

$$\begin{array}{ccc} E(b,a) & \xrightarrow{\rho} & E \\ \downarrow & \lrcorner & \downarrow \\ A' \times B' & \xrightarrow{(a,b)} & A \times B \end{array} \quad (11.2.2)$$

⁴If the double category lacks horizontal identity morphisms, the corresponding virtual double category may lack nullary morphisms — unless these can be defined in some other way as we did in the proof of Lemma 11.1.11. Note that if we added identity spans to our double category of two-sided isofibrations, then the corresponding virtual double category would be the correct one, which contains the virtual double category of modules. See Remark 11.1.13 however.

By Proposition 10.4.4, this left-hand isofibration defines a module from A' to B' , while by Definition 11.1.6 the top horizontal functor represents a module map inhabiting the desired square. As in Definition 11.1.6, the simplicial pullback in \mathcal{K} induces an equivalence⁵ of functor spaces:

$$\mathrm{Fun}_{f \times g}(E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n, E(b, a)) \xrightarrow{\rho \circ -} \mathrm{Fun}_{af \times bg}(E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n, E)$$

which descends to a bijection on isomorphism classes of objects. This defines the unique factorization of cells as displayed above left through the cartesian restriction cell ρ . \square

We refer to the module $A' \xrightarrow{E(b,a)} B'$ as the **restriction** of $A \xrightarrow{E} B$ along the functors a and b , because the pullback (11.2.2) is analogous to the restriction of scalars of a bimodule along a pair of ring homomorphisms.

11.2.3. EXAMPLE. The module $C \xrightarrow{\mathrm{Hom}_A(f,g)} B$ is the restriction of the module $A \xrightarrow{A^2} A$ along $g: C \rightarrow A$ and $f: B \rightarrow A$. To make this restriction relationship more transparent, we typically write $A \xrightarrow{\mathrm{Hom}_A} A$ when regarding the arrow ∞ -category as a module. Since the common notation for “homs” places the contravariant variable on the left and the covariant variable on the right, we’ve adopted a similar notation convention for restrictions in Proposition 11.2.1.

11.2.4. PROPOSITION (units). *Any object A in $\mathrm{Mod}(\mathfrak{h}\mathcal{K})$ is equipped with a canonical nullary cocartesian cell as displayed below*

$$\begin{array}{ccc} A & \xlongequal{\quad} & A \\ \parallel & \Downarrow \iota & \parallel \\ A & \xrightarrow{\quad \mathrm{Hom}_A \quad} & A \end{array}$$

characterized by the universal property that any cell in $\mathrm{Mod}(\mathfrak{h}\mathcal{K})$ whose horizontal source includes the object A factors uniquely through ι as below-right:

$$\begin{array}{c} \begin{array}{ccccccc} X & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & A & \xrightarrow{F_1} & \cdots & \xrightarrow{F_m} & Y \\ f \downarrow & & & & \downarrow & & & & \downarrow g \\ B & & & & G & & & & C \end{array} \\ \\ \begin{array}{ccccccc} X & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & A & \xlongequal{\quad} & A & \xrightarrow{F_1} & \cdots & \xrightarrow{F_m} & Y \\ \parallel & \Downarrow \mathrm{id}_{E_1} & \parallel & \cdots & \Downarrow \mathrm{id}_{E_n} & \parallel & \Downarrow \iota & \parallel & \Downarrow \mathrm{id}_{F_1} & \parallel & \cdots & \parallel & \Downarrow \mathrm{id}_{F_m} & \parallel \\ X & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & A & \xrightarrow{\quad \mathrm{Hom}_A \quad} & A & \xrightarrow{F_1} & \cdots & \xrightarrow{F_m} & Y \\ f \downarrow & & & & \downarrow & & \Downarrow \exists! & & & & \downarrow g \\ B & & & & G & & & & & & C \end{array} \end{array}$$

PROOF. The canonical nullary cell is represented by the map of spans

$$\begin{array}{ccc} & A & \\ \swarrow & \downarrow \iota & \searrow \\ A & & A \\ \nwarrow p_1 & & \nearrow p_0 \\ & \mathrm{Hom}_A & \end{array}$$

⁵If the pullbacks are defined strictly, then in fact pullback induces an *isomorphism* of functor spaces, but even if $E(b, a)$ is replaced by an equivalent module, the functor spaces are still equivalent, which enough to induce a bijection on isomorphism classes of objects.

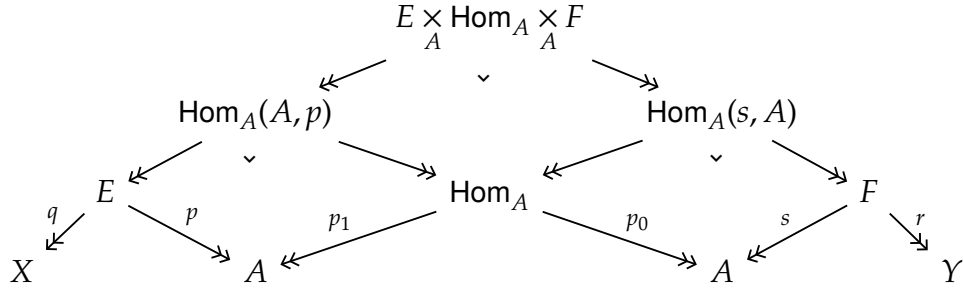
induced by the generic arrow with codomain A (3.2.3); recall from Example 11.2.3 that we write $A \xrightarrow{\text{Hom}_A} A$ for the module encoded by the arrow ∞ -category construction.

In the case where both of the sequences E_i and F_j are empty, the one-sided version of the Yoneda lemma for modules given by Theorem 10.4.9 tells us that restriction along this map induces an equivalence of functor spaces

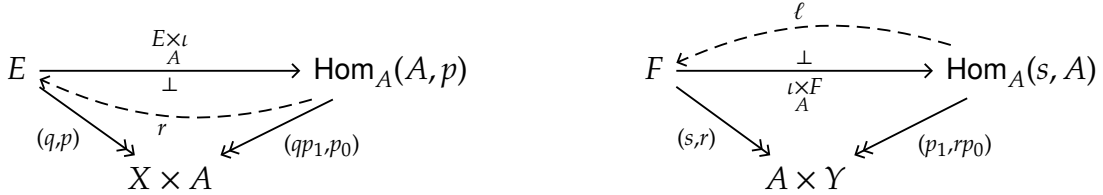
$$\text{Fun}_{A \times A}(\text{Hom}_A, G(g, f)) \simeq \text{Fun}_{A \times A}(A, G(g, f)).$$

Taking isomorphism classes of objects gives the bijection of the statement.

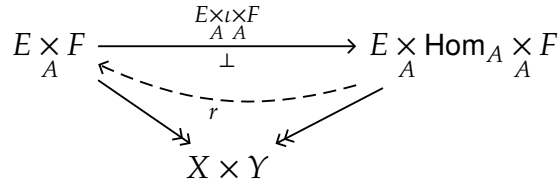
In the case where one or both of the sequences are non-empty, we may form their horizontal composite two-sided fibrations and then form either the horizontal composite $E \times_A \text{Hom}_A$ or the horizontal composite $\text{Hom}_A \times_A F$ of the composable triple below:



In the former case, this constructs the two-sided fibration $(qp_1, p_0): \text{Hom}_A(A, p) \twoheadrightarrow X \times A$, and in the latter case this constructs the two-sided fibration $(p_1, rp_0): \text{Hom}_A(s, A) \twoheadrightarrow A \times Y$. In both cases, by Lemma 10.1.1, the map ι pulls back to define a fibered adjoint functor



We only require one of these adjunctions, so without loss of generality we use the former. This fibered adjunction pulls back along s and pushes forward along r to define a fibered adjunction



between two-sided fibrations. Upon mapping into the discrete object $G(g, f) \twoheadrightarrow X \times Y$, this adjunction becomes an adjoint equivalence. In particular, restriction along ι induces an equivalence of Kan complexes

$$\text{Fun}_{X \times Y}(E \times_A \text{Hom}_A \times_A F, G(g, f)) \xrightarrow[\sim]{-\circ(E \times_A \iota \times_A F)} \text{Fun}_{X \times Y}(E \times_A F, G(g, f)),$$

and once again taking isomorphism classes of objects gives the bijection of the statement. \square

Propositions 11.2.1 and 11.2.4 imply that the virtual double category of modules is a *virtual equipment* in the sense introduced by Cruttwell and Shulman [15, §7].

11.2.5. DEFINITION. A **virtual equipment** is a virtual double category so that

- (i) For any horizontal arrow $A \xrightarrow{E} B$ and pair of vertical arrows $a: A' \rightarrow A$ and $b: B' \rightarrow B$, there exists a horizontal arrow $B' \xrightarrow{E(b,a)} A'$ and unary cartesian cell ρ satisfying the universal property of Proposition 11.2.1.
- (ii) Every object A admits a **unit** horizontal arrow $A \xrightarrow{\text{Hom}_A} A$ equipped with a nullary cocartesian cell ι satisfying the universal property of Proposition 11.2.4.

Thus, Propositions 11.2.1 and 11.2.4 combine to prove:

11.2.6. THEOREM. *The virtual double category $\text{Mod}(\mathbf{h}\mathcal{K})$ of modules in an ∞ -cosmos \mathcal{K} is a virtual equipment.* \square

By abstract nonsense, the relatively simple axioms (i) and (ii) established in Theorem 11.2.6 establish a robust “calculus of modules.” In an effort to familiarize the reader with this little-known categorical structure and expedite the proofs of the formal category theory of ∞ -categories in Chapter 12, we devote the remainder of this chapter to proving a plethora of results that actually follow formally from this axiomatization: namely, Lemmas 11.3.5 and 11.3.11, Proposition 11.4.1, Theorem 11.4.4, Corollary 11.4.6, Proposition 11.4.7, Corollary 11.4.8, and the bijection of Proposition 11.4.10 between unary cells in the virtual equipment of modules. One additional result is left as Exercise 11.4.iii for the reader.

11.2.7. NOTATION. We adopt the following notational conventions to streamline certain virtual equipment diagrams.

- We adopt the convention that an unlabeled unary cell whose vertical boundaries are identities and whose horizontal sources and targets is an identity cell.

$$\begin{array}{ccc} A & \xrightarrow{E} & B \\ \parallel & & \parallel \\ A & \xrightarrow{E} & B \end{array} := \begin{array}{ccc} A & \xrightarrow{E} & B \\ \parallel & \Downarrow \text{id}_E & \parallel \\ A & \xrightarrow{E} & B \end{array}$$

- Cells whose vertical boundary functors are identities and therefore whose source and target spans lie between the same pair of ∞ -categories

$$\mu: E_1 \times \cdots \times E_n \Rightarrow E \quad := \quad \begin{array}{ccccc} A_0 & \xrightarrow{E_1} & A_1 & \xrightarrow{E_2} & \cdots & \xrightarrow{E_n} & A_n \\ \parallel & & & & \Downarrow \mu & & \parallel \\ A_0 & \xrightarrow{\quad\quad\quad} & & & & & A_n \\ & & & & E & & \end{array}$$

may be displayed in line using the notation $\mu: E_1 \times \cdots \times E_n \Rightarrow E$, an expression which implicitly asserts that the modules appearing in the domain define a composable sequence, with the symbol “ \times ” meant to suggest the pullback appearing as the horizontal domain of (11.1.10) rather than a product.

Exercises.

11.2.i. EXERCISE. Prove that unital rings, ring homomorphisms, bimodules, and bimodule maps also define a virtual equipment.

11.3. Composition of modules

In a virtual equipment one cannot define the composite of a generic pair $A \xrightarrow{E} B$ and $B \xrightarrow{F} C$ of horizontal morphisms but there is a mechanism by which a particular horizontal composite $A \xrightarrow{G} C$ that happens to exist can be recognized, in which case we write $E \otimes F \simeq G$ to reinforce the intuition provided by the analogy with bimodules. In the virtual equipment of modules, a composition relation $E \otimes F \simeq G$ does not mean that the module G is equivalent to the horizontal composite two-sided isofibration $E \times F$. Rather, in the notation of 11.2.7 a composition relation is witnessed by a module map $E \times F \Rightarrow G$ that defines a cocartesian cell in a sense analogous to the universal property stated in Proposition 11.2.4.⁶

11.3.1. DEFINITION. A composable sequence of modules

$$A_0 \xrightarrow{E_1} A_1, A_1 \xrightarrow{E_2} A_2, \dots, A_{n-1} \xrightarrow{E_n} A_n$$

admits a composite if there exists a module $A_0 \xrightarrow{E} A_n$ and a cocartesian cell

$$\mu: E_1 \times \dots \times E_n \Rightarrow E$$

characterized by the universal property that any cell of the form

$$\begin{array}{ccccccc} X & \xrightarrow{F_1} & \dots & \xrightarrow{F_m} & A_0 & \xrightarrow{E_1} & \dots & \xrightarrow{E_n} & A_n & \xrightarrow{G_1} & \dots & \xrightarrow{G_k} & Y \\ f \downarrow & & & & & \Downarrow & & & & & & & \downarrow g \\ B & \xrightarrow{\quad\quad\quad} & & & & H & \xrightarrow{\quad\quad\quad} & & & & & & C \end{array}$$

factors uniquely through μ as follows:

$$\begin{array}{ccccccc} X & \xrightarrow{F_1} & \dots & \xrightarrow{F_m} & A_0 & \xrightarrow{E_1} & \dots & \xrightarrow{E_n} & A_n & \xrightarrow{G_1} & \dots & \xrightarrow{G_k} & Y \\ \parallel & & \parallel & \parallel & \parallel & \Downarrow \mu & & \parallel & & \parallel & \parallel & \parallel & \parallel \\ X & \xrightarrow{F_1} & \dots & \xrightarrow{F_m} & A_0 & \xrightarrow{E} & & A_n & \xrightarrow{G_1} & \dots & \xrightarrow{G_k} & & Y \\ f \downarrow & & & & & \Downarrow \exists! & & & & & & & \downarrow g \\ B & \xrightarrow{\quad\quad\quad} & & & & H & \xrightarrow{\quad\quad\quad} & & & & & & C \end{array}$$

A composite $\mu: E_1 \times \dots \times E_n \Rightarrow E$ can be used to reduce the domain of a cell by replacing any occurrence of the composable sequence $E_1 \times \dots \times E_n$ from A_0 to A_n by a single module E . Particularly in the case of binary composites, we write $E_1 \otimes E_2$ to denote the **composite** of the modules

⁶In nearly all cases where $E \otimes F \simeq G$, precomposition with the cocartesian map $\mu: E \times_B F \Rightarrow G$, which by Definition 11.1.1 corresponds to a fibered isomorphism class of maps of spans over $A \times C$, induces an equivalence of Kan complexes $- \circ \mu: \mathbf{Fun}_{A \times C}(G, H) \simeq \mathbf{Fun}_{A \times C}(E \times_B F, H)$ for all modules H , so the module G may be understood as the “reflection” of the two-sided isofibration $E \times_B F$ into the subcategory of modules. Corollary 10.3.5, reappearing as Proposition 11.3.7 below, is one instance of this.

E_1 and E_2 , appearing as the codomain of the cocartesian cell $E_1 \times E_2 \Rightarrow E_1 \otimes E_2$. Lemma 11.1.17 easily implies that composites are unique up to vertical isomorphism, i.e., by Lemma 11.1.17 up to equivalence of modules. Moreover:

11.3.2. LEMMA. Suppose the cells $\mu_i: E_{i1} \times \cdots \times E_{ik_i} \Rightarrow E_i$ exhibit composites for $i = 1, \dots, n$.

(i) If $\mu: E_1 \times \cdots \times E_n \Rightarrow E$ exhibits a composite then the composite cell

$$E_{11} \times \cdots \times E_{nk_n} \xrightarrow{\mu_1 \times \cdots \times \mu_n} E_1 \times \cdots \times E_n \xrightarrow{\mu} E$$

exhibits E as a composite of the sequence $E_{11} \times \cdots \times E_{nk_n}$.

(ii) If the composite cell

$$E_{11} \times \cdots \times E_{nk_n} \xrightarrow{\mu_1 \times \cdots \times \mu_n} E_1 \times \cdots \times E_n \xrightarrow{\mu} E$$

exhibits E as a composite of the sequence $E_{11} \times \cdots \times E_{nk_n}$, then $\mu: E_1 \times \cdots \times E_n \Rightarrow E$ exhibits E as a composite of the sequence $E_1 \times \cdots \times E_n$.

PROOF. For (i), the required bijection factors as a composite of $n + 1$ bijections induced by the maps μ_1, \dots, μ_n and μ . For (ii), the required bijection induced by μ composes with the bijections supplied by the maps μ_1, \dots, μ_n to a bijection and is thus itself a bijection. \square

The trivial instances of composites are easily verified:

11.3.3. LEMMA.

(i) The units $\iota: \emptyset \Rightarrow \text{Hom}_A$ of Proposition 11.2.4 define nullary composites.

(ii) A unary cell $\mu: E \Rightarrow F$ is a composite if and only if it is an isomorphism in the vertical category of modules from A to B and module maps over identity functors, that is, if and only if the modules E and F are equivalent as spans.

PROOF. Exercise 11.3.ii. \square

11.3.4. REMARK. On account of the universal property of restrictions established in Proposition 11.2.1, to prove that a cell $\mu: E_1 \times \cdots \times E_n \Rightarrow E$ exhibits a composite, it suffices to prove the factorization property of Definition 11.3.1 in the case where the vertical functors are identities.

As one might hope, the unit modules $A \xrightarrow{\text{Hom}_A} A$ are units for the composition of Definition 11.3.1: for any module $A \xrightarrow{E} B$, $\text{Hom}_A \otimes E \otimes \text{Hom}_B \simeq E$.

11.3.5. LEMMA (composites with units). For any module $A \xrightarrow{E} B$ the unique cell $\circ: \text{Hom}_A \times E \times \text{Hom}_B \Rightarrow E$ defined using the universal property of the unit cell

$$\begin{array}{ccccc} A & \xrightarrow{\text{Hom}_A} & A & \xrightarrow{E} & B & \xrightarrow{\text{Hom}_B} & B \\ \parallel & \Downarrow \iota & \parallel & & \parallel & \Downarrow \iota & \parallel \\ A & \xrightarrow{\text{Hom}_A} & A & \xrightarrow{E} & B & \xrightarrow{\text{Hom}_B} & B \\ \parallel & & & \Downarrow \circ & & & \parallel \\ A & \xrightarrow{\quad \quad \quad} & & & B & & \end{array} \quad := \quad \begin{array}{ccc} A & \xrightarrow{E} & B \\ \parallel & & \parallel \\ A & \xrightarrow{E} & B \end{array}$$

displays E as the composite $\text{Hom}_A \otimes E \otimes \text{Hom}_B$.

PROOF. The result is immediate from Lemma 11.3.2(ii) and Lemma 11.3.3. \square

The argument used in the proof of Proposition 11.2.4 to demonstrate that units define nullary composites in the virtual equipment of modules applies also to more general composites.

11.3.6. LEMMA. Consider an n -ary module morphism $\mu: E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n \Rightarrow E$ in the virtual equipment of modules whose codomain is a module from A to B . If any representing map of spans

$$\begin{array}{ccc} E_1 \times \cdots \times E_n & \xrightarrow{\quad \ulcorner \mu \urcorner \quad} & E \\ & \searrow \quad \swarrow & \\ & A \times B & \end{array}$$

admits a fibered adjoint over $A \times B$, then μ exhibits E as the composite $E_1 \otimes \cdots \otimes E_n$.

PROOF. To verify the universal property of Definition 11.3.1, consider a composable sequence of modules F_1, \dots, F_m from X to A and a composable sequence of modules G_1, \dots, G_k from B to Y and form the horizontal composite two-sided fibrations

$$\begin{array}{ccc} & F & \\ q \swarrow & & \searrow p \\ X & & A \end{array} \quad \text{and} \quad \begin{array}{ccc} & G & \\ s \swarrow & & \searrow r \\ B & & Y \end{array}$$

The fibered adjunction of the statement pulls back along $p \times s: F \times G \Rightarrow A \times B$ and pushes forward along $q \times r: F \times G \rightarrow X \times Y$ to a fibered adjoint to

$$\begin{array}{ccc} F \times_{A_1} E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n \times_{A_{n-1}} G & \xrightarrow{\quad F \times_{A_1} \ulcorner \mu \urcorner \times_{A_{n-1}} G \quad} & F \times_{A_1} E \times_{A_{n-1}} G \\ & \searrow \quad \swarrow & \\ & X \times Y & \end{array}$$

Via Remark 11.3.4, it suffices to verify the universal property of the composite for modules $X \xrightarrow{H} Y$. Since modules are discrete, applying $\text{Fun}_{X \times Y}(-, H)$ transforms this fibered adjunction into an adjoint equivalence

$$\text{Fun}_{X \times Y}(F \times_{A_1} E \times_{A_{n-1}} G, H) \xrightarrow{\sim} \text{Fun}_{X \times Y}(F \times_{A_1} E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n \times_{A_{n-1}} G, H).$$

Passing to isomorphism classes of objects this now gives the universal property of Definition 11.3.1. \square

For instance:

11.3.7. PROPOSITION. Let $A \xrightarrow{E} B$ be a module encoded by the span $A \xleftarrow{q} E \xrightarrow{p} B$. Then the binary module map

$$\begin{array}{ccccc} A & \xrightarrow{\text{Hom}_A(q, A)} & E & \xrightarrow{\text{Hom}_B(B, p)} & B \\ \parallel & & \Downarrow \mu & & \parallel \\ A & \xrightarrow{\quad E \quad} & & & B \end{array}$$

represented by composite left and right adjoints of Theorem 10.1.4(iii) exhibits $E \simeq \text{Hom}_A(q, A) \otimes \text{Hom}_B(B, p)$ as the composite of the modules representing its legs.

PROOF. Immediate from Theorem 10.1.4(iii) and Lemma 11.3.6 applied twice.⁷ \square

11.3.8. REMARK. Nothing in the proof of Proposition 11.3.7 requires that the span $A \xleftarrow{q} E \xrightarrow{p} B$ is actually a module except for the interpretation that μ is a binary cell in the virtual equipment of modules. For any two-sided fibration $A \xleftarrow{q} E \xrightarrow{p} B$, it is still the case that restriction along μ defines a bijection between n -ary maps whose source includes the span E and whose codomain is a module stand in bijection with $(n + 1)$ -ary maps whose source includes $\mathbf{Hom}_A(q, A) \times \mathbf{Hom}_B(B, p)$. By Theorem 10.4.9, this result can be extended further to mere spans E , not necessarily two-sided fibrations.

11.3.9. REMARK. We provide another description of composition map $\mu: \mathbf{Hom}_A(q, A) \times \mathbf{Hom}_B(B, p) \Rightarrow E$. The comma cones

$$\begin{array}{c}
 \mathbf{Hom}_A(q, A) \times \mathbf{Hom}_B(B, p) \\
 \swarrow \quad \searrow \\
 \mathbf{Hom}_A(q, A) \quad \mathbf{Hom}_B(B, p) \\
 \begin{array}{ccc}
 p_1 \swarrow & \phi & \searrow p_0 \\
 A & \xleftarrow{q} E & \xrightarrow{p} B
 \end{array}
 \end{array}$$

Define a pair of 2-cells to which the premises of Theorem 10.1.4(iv) apply. The conclusion asserts that there is a well-defined fibered isomorphism class of functors $\lceil \mu \rceil: \mathbf{Hom}_A(q, A) \times \mathbf{Hom}_B(B, p) \rightarrow E$ defined by taking the q -cocartesian lift of the left comma cone, composing with the right comma cone, and then taking the codomain of a p -cartesian lift of this composite cell — or by first taking the p -cartesian lift, composing, and then taking the domain of a q -cartesian lift of this composite — this being the functor $\ell r \simeq r \ell$ in the notation of Theorem 10.1.4(iii). In the case where $A \xrightarrow{E} B$ is itself a comma module, the resulting fibered isomorphism class of functors $\lceil \mu \rceil$ is the one that classifies the pasted composite above with the comma cone for E .

Any virtual double category has an identity cell for each horizontal arrow $A \xrightarrow{E} B$ whose vertical boundary arrows are identities. In a virtual equipment, we also have a **unit cell** for each vertical arrow $f: A \rightarrow B$ whose horizontal boundary is given by the unit modules $A \xrightarrow{\mathbf{Hom}_A} A$ and $B \xrightarrow{\mathbf{Hom}_B} B$ of Proposition 11.2.4.

11.3.10. DEFINITION. Using the unit modules in $\mathbf{Mod}(\mathbf{h}\mathcal{K})$, for any functor $f: A \rightarrow B$ we may define a unary **unit cell** as displayed below-left by appealing to the universal property of the nullary unit cell $\iota: \emptyset \Rightarrow \mathbf{Hom}_A$ for A in the equation below-right:

$$\begin{array}{ccc}
 \begin{array}{ccc}
 A & \xrightarrow{\mathbf{Hom}_A} & A \\
 f \downarrow & \Downarrow \mathbf{Hom}_f & \downarrow f \\
 B & \xrightarrow{\mathbf{Hom}_B} & B
 \end{array} & \Leftarrow & \begin{array}{ccc}
 A & \xrightarrow{\quad} & A \\
 \parallel & \Downarrow \iota & \parallel \\
 A & \xrightarrow{\quad} & A \\
 f \downarrow & \Downarrow \mathbf{Hom}_f & \downarrow f \\
 B & \xrightarrow{\quad} & B
 \end{array} \quad := \quad \begin{array}{ccc}
 A & \xrightarrow{\quad} & A \\
 f \downarrow & & \downarrow f \\
 B & \xrightarrow{\quad} & B \\
 \parallel & \Downarrow \iota & \parallel \\
 B & \xrightarrow{\quad} & B
 \end{array}
 \end{array}$$

⁷Of course the composite of a left and a right adjoint is not an adjoint but here we're effectively composing adjoint equivalences in which case the direction does not matter.

In the characterization of Lemma 11.1.16, both sides of the pasting equality defining the unary unit

$$\text{cell correspond to the identity 2-cell } A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \text{id}_f \\ \xrightarrow{f} \end{array} B .$$

As one might hope, the unit cells are units for the vertical composition of cells in the virtual equipment of modules.

11.3.11. LEMMA (composition with unit cells). *Any cell α as below-right equals the pasted composite below-left:*

$$\begin{array}{c} A_0 \rightrightarrows A_0 \xrightarrow{E_1} A_1 \xrightarrow{E_2} \dots \xrightarrow{E_n} A_n \rightrightarrows A_n \\ \Downarrow \iota \quad \Downarrow \quad \Downarrow \quad \Downarrow \quad \Downarrow \iota \\ A_0 \xrightarrow{E_1} A_0 \xrightarrow{E_1} A_1 \xrightarrow{E_2} \dots \xrightarrow{E_n} A_n \xrightarrow{E_n} A_n \\ f \downarrow \quad \Downarrow \text{Hom}_f \quad \downarrow f \quad \quad \quad \Downarrow \alpha \quad \quad \quad g \downarrow \quad \Downarrow \text{Hom}_g \quad \downarrow g \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \xrightarrow{E_n} C \\ \Downarrow \quad \quad \quad \Downarrow \circ \quad \quad \quad \Downarrow \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \end{array} = \begin{array}{c} A_0 \xrightarrow{E_1} A_1 \xrightarrow{E_2} \dots \xrightarrow{E_n} A_n \\ f \downarrow \quad \quad \quad \Downarrow \alpha \quad \quad \quad \downarrow g \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \\ \Downarrow \quad \quad \quad \Downarrow \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \end{array}$$

PROOF. By Definition 11.3.10 and the laws for composition with identity cells in a virtual double category stated in Definition 11.1.9, the left-hand composite of the statement equals the left-hand composite cell displayed below and the right-hand side of the statement equals the right-hand composite cell displayed below:

$$\begin{array}{c} A_0 \rightrightarrows A_0 \xrightarrow{E_1} A_1 \xrightarrow{E_2} \dots \xrightarrow{E_n} A_n \rightrightarrows A_n \\ f \downarrow \quad \quad \quad \downarrow f \quad \quad \quad \Downarrow \alpha \quad \quad \quad g \downarrow \quad \quad \quad \downarrow g \\ B \rightrightarrows B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \rightrightarrows C \\ \Downarrow \iota \quad \quad \quad \Downarrow \quad \quad \quad \Downarrow \iota \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \xrightarrow{E_n} C \\ \Downarrow \quad \quad \quad \Downarrow \circ \quad \quad \quad \Downarrow \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \end{array} = \begin{array}{c} A_0 \xrightarrow{E_1} A_1 \xrightarrow{E_2} \dots \xrightarrow{E_n} A_n \\ f \downarrow \quad \quad \quad \Downarrow \alpha \quad \quad \quad \downarrow g \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \\ \Downarrow \quad \quad \quad \Downarrow \\ B \xrightarrow{E_1} B \xrightarrow{E_2} \dots \xrightarrow{E_n} C \end{array}$$

By Lemma 11.3.5, the left-hand side equals the right-hand side. \square

11.3.12. DEFINITION (horizontal composition of cells). If given a horizontally composable sequence of unary cells

$$\begin{array}{c} A_0 \xrightarrow{E_1} A_1 \xrightarrow{E_2} \dots \xrightarrow{E_n} A_n \\ f_0 \downarrow \quad \Downarrow \alpha_1 \quad f_1 \downarrow \quad \Downarrow \alpha_2 \quad \dots \quad \Downarrow \alpha_n \quad f_n \downarrow \\ B_0 \xrightarrow{F_1} B_1 \xrightarrow{F_2} \dots \xrightarrow{F_n} B_n \end{array}$$

for which the composable sequences $E_1 \times \cdots \times E_n$ and $F_1 \times \cdots \times F_n$ both admit composites, then there exists a **horizontal composite unary cell** $\alpha_1 * \cdots * \alpha_n$ that is uniquely determined up to the specification of the composites $\circ: E_1 \times \cdots \times E_n \Rightarrow E$ and $F_1 \times \cdots \times F_n \Rightarrow F$ by the pasting identity:

$$\begin{array}{ccc}
 \begin{array}{ccc}
 A_0 & \xrightarrow{E_1} & A_1 & \xrightarrow{E_2} & \cdots & \xrightarrow{E_n} & A_n \\
 \parallel & & \Downarrow \circ & & & & \parallel \\
 A_0 & \xrightarrow{E} & & & & & A_n \\
 f_0 \downarrow & & \Downarrow \alpha_1 * \cdots * \alpha_n & & & & \downarrow f_n \\
 B_0 & \xrightarrow{F} & & & & & B_n
 \end{array}
 & = &
 \begin{array}{ccc}
 \begin{array}{ccc}
 A_0 & \xrightarrow{E_1} & A_1 & \xrightarrow{E_2} & \cdots & \xrightarrow{E_n} & A_n \\
 f_0 \downarrow & \Downarrow \alpha_1 & f_1 \downarrow & \Downarrow \alpha_2 & \cdots & \Downarrow \alpha_n & \downarrow f_n \\
 B_0 & \xrightarrow{F_1} & B_1 & \xrightarrow{F_2} & \cdots & \xrightarrow{F_n} & B_n \\
 \parallel & & \Downarrow \circ & & & & \parallel \\
 B_0 & \xrightarrow{F} & & & & & B_n
 \end{array}
 \end{array}
 \end{array}$$

By an argument very similar to the proof of Lemma 11.3.11 using the composites of Lemma 11.3.5, the horizontal composite $\text{Hom}_f * \alpha * \text{Hom}_g$ of a unary cell α with the unit cells Hom_f and Hom_g at its vertical boundary functors recovers α . The upshot of Definition 11.3.12 is that $\text{Mod}(\mathfrak{h}\mathcal{K})$ can be understood to contain various “vertical” and “horizontal” bicategories.

11.3.13. PROPOSITION (the vertical 2-category in the virtual equipment). *Any virtual equipment contains a vertical 2-category whose objects are the objects of the virtual equipment, whose arrows are the vertical arrows, and whose 2-cells are those unary cells*

$$\begin{array}{ccc}
 A & \xrightarrow{\text{Hom}_A} & A \\
 g \downarrow & \Downarrow & \downarrow f \\
 B & \xrightarrow{\text{Hom}_B} & B
 \end{array}$$

whose horizontal boundary arrows are given by the unit modules.

PROOF. To prove that these structures define a 2-category we must define “horizontal” composition of 2-cells (composing along a boundary 0-cell) and “vertical” composition of 2-cells (composing along a boundary 1-cell). The “horizontal” composition in the 2-category is defined via the vertical composition in the virtual double category described in Definition 11.1.9. The “vertical” composition in the 2-category is defined by Definition 11.3.12. To see that this yields a 2-category and not a bicategory note that any bicategory in which the composition of 1-cells is strictly associative and unital is a 2-category; in this case, the 1-cells are the vertical arrows of the virtual double category, which do indeed compose strictly. \square

Proposition 11.4.10 will prove that the vertical 2-category in the virtual equipment $\text{Mod}(\mathfrak{h}\mathcal{K})$ is isomorphic to the homotopy 2-category $\mathfrak{h}\mathcal{K}$.

11.3.14. REMARK (horizontal bicategories in the virtual equipment). Via Definition 11.3.12, a virtual equipment can also be understood to contain various “horizontal” bicategories, defined by taking the 1-cells to be composable modules and the 2-cells to be unary module maps whose vertical boundary functors are identities. Particular horizontal bicategories of interest are described in Definition 11.4.11.

Exercises.

11.3.i. EXERCISE. Extending Exercise 11.1.ii, prove that in a virtual double category arising from an actual double category that every composable sequence of horizontal morphisms admits a composite in the sense of Definition 11.3.1.

11.3.ii. EXERCISE. Prove Lemma 11.3.3.

11.4. Representable modules

Any vertical arrow $f: A \rightarrow B$ in a virtual equipment has a pair of associated horizontal arrows $B \xrightarrow{\text{Hom}_B(f,B)} A$ and $A \xrightarrow{\text{Hom}_B(B,f)} B$ — defined as restrictions of the horizontal unit arrows — that have universal properties similar to companions and conjoinants in an ordinary double category. In the virtual equipment of modules, these are sensibly referred to as the *left* and *right representations* of a functor as a module and coincide exactly with the left and right representable first introduced in §3.4 and reappearing in Definition 10.4.8.

11.4.1. PROPOSITION (companion and conjoint relations for representables). *To any functor $f: A \rightarrow B$ in the virtual equipment of modules, there exist canonical restriction cells displayed below-left and application cells displayed below-right*

$$\begin{array}{ccc}
 \begin{array}{ccc} B & \xrightarrow{\text{Hom}_B(f,B)} & A \\ \parallel & \Downarrow \rho & \downarrow f \\ B & \xrightarrow{\quad} & B \\ & \text{Hom}_B & \end{array} &
 \begin{array}{ccc} A & \xrightarrow{\text{Hom}_B(B,f)} & B \\ f \downarrow & \Downarrow \rho & \parallel \\ B & \xrightarrow{\quad} & B \\ & \text{Hom}_B & \end{array} &
 \begin{array}{ccc} A & \xrightarrow{\text{Hom}_A} & A \\ f \downarrow & \Downarrow \kappa & \parallel \\ B & \xrightarrow{\quad} & A \\ & \text{Hom}_B(f,B) & \end{array} &
 \begin{array}{ccc} A & \xrightarrow{\text{Hom}_A} & A \\ \parallel & \Downarrow \kappa & \downarrow f \\ A & \xrightarrow{\quad} & B \\ & \text{Hom}_B(B,f) & \end{array}
 \end{array}$$

defining unary module maps between the unit modules $A \xrightarrow{\text{Hom}_A} A$ and $B \xrightarrow{\text{Hom}_B} B$ and the left and right representable modules $B \xrightarrow{\text{Hom}_B(f,B)} A$ and $A \xrightarrow{\text{Hom}_B(B,f)} B$. These satisfy the identities:

$$\begin{array}{ccc}
 \begin{array}{ccc} A & \xrightarrow{\text{Hom}_A} & A \\ f \downarrow & \Downarrow \kappa & \parallel \\ B & \xrightarrow{\text{Hom}_B(f,B)} & A \\ \parallel & \Downarrow \rho & \downarrow f \\ B & \xrightarrow{\quad} & B \\ & \text{Hom}_B & \end{array} & = & \begin{array}{ccc} A & \xrightarrow{\text{Hom}_A} & A \\ f \downarrow & \Downarrow \text{Hom}_f & \downarrow f \\ B & \xrightarrow{\quad} & B \\ & \text{Hom}_B & \end{array} & = & \begin{array}{ccc} A & \xrightarrow{\text{Hom}_A} & A \\ \parallel & \Downarrow \kappa & \downarrow f \\ A & \xrightarrow{\quad} & B \\ f \downarrow & \Downarrow \rho & \parallel \\ B & \xrightarrow{\quad} & B \\ & \text{Hom}_B & \end{array}
 \end{array} \quad (11.4.2)$$

and

$$\begin{array}{ccc}
 \begin{array}{ccc} B & \xrightarrow{\text{Hom}_B(f,B)} & A \\ \parallel & \Downarrow \rho & \downarrow f \\ B & \xrightarrow{\quad} & B \\ \parallel & \Downarrow \rho & \parallel \\ B & \xrightarrow{\quad} & B \\ & \text{Hom}_B & \end{array} & = & \begin{array}{ccc} B & \xrightarrow{\text{Hom}_B(f,B)} & A \\ \parallel & \Downarrow \circ & \parallel \\ B & \xrightarrow{\quad} & A \\ & \text{Hom}_B(f,B) & \end{array} & = & \begin{array}{ccc} A & \xrightarrow{\text{Hom}_A} & A \\ \parallel & \Downarrow \kappa & \downarrow f \\ A & \xrightarrow{\quad} & B \\ \parallel & \Downarrow \rho & \parallel \\ A & \xrightarrow{\quad} & B \\ & \text{Hom}_B(B,f) & \end{array}
 \end{array} \quad (11.4.3)$$

PROOF. The unary module maps κ are defined by the equations (11.4.2) by appealing to the universal property of the restriction cells in Proposition 11.2.1. The relations (11.4.3) could also be verified directly from the axioms of Theorem 11.2.6 via Propositions 11.2.4 and Lemmas 11.3.5 and 11.3.5. Instead, we appeal to Lemma 11.1.16 to characterize each of the cells in the virtual equipment as 2-cells in the homotopy 2-category.

We prove this for the right representables; the co-dual then proves this for the left representables. The binary module morphism on the left-hand side of the equality of (11.4.3) represents the 2-cell below-left, while the right-hand composite is below-right:

$$\begin{array}{c}
 \begin{array}{ccc}
 & A^2 \times \text{Hom}_B(B, f) & \\
 & \swarrow \quad \searrow & \\
 A^2 & & \text{Hom}_B(B, f) \\
 \swarrow p_1 \quad \searrow p_0 & & \swarrow p_1 \quad \searrow p_0 \\
 A & \xrightarrow{\kappa} & A \\
 & \xrightarrow{f} & B
 \end{array} \\
 = & \begin{array}{ccccc}
 & A^2 \times \text{Hom}_B(B, f) & & & \\
 & \swarrow \quad \searrow & & & \\
 & A^2 & & \text{Hom}_B(B, f) & \\
 \swarrow p_1 \quad \searrow p_0 & & \swarrow p_1 \quad \searrow p_0 & & \\
 A & \xrightarrow{f} & B & \xrightarrow{f} & B
 \end{array}
 \end{array}$$

By the definition of the induced functor $k: A^2 \rightarrow \text{Hom}_B(B, f)$, $\phi k = f\kappa$ and by the definition of the comma cone ϕ for $\text{Hom}_B(B, f)$, $\phi = \kappa\rho$. Thus, the left-hand side equals the right-hand side. \square

11.4.4. THEOREM. *In the virtual equipment of modules there are bijections between cells of the following four forms*

$$\begin{array}{ccc}
 \begin{array}{ccccc}
 C & \xrightarrow{\text{Hom}_C(f, C)} & A & \xrightarrow{E} & B \\
 \parallel & & \Downarrow & & \downarrow g \\
 C & \xrightarrow{F} & D & &
 \end{array} & \rightsquigarrow & \begin{array}{ccccc}
 A & \xrightarrow{E} & B & & \\
 \downarrow f & & \downarrow & & \downarrow g \\
 C & \xrightarrow{F} & D & &
 \end{array} \\
 & & & & \\
 & & \begin{array}{ccccc}
 C & \xrightarrow{\text{Hom}_C(f, C)} & A & \xrightarrow{E} & B & \xrightarrow{\text{Hom}_D(D, g)} & D \\
 \parallel & & \Downarrow & & \parallel & & \\
 C & \xrightarrow{F} & D & & & &
 \end{array}
 \end{array}$$

implemented by composing with the canonical cells κ and ρ of Proposition 11.4.1 and with the composition and nullary cells associated to the units.

PROOF. The composite bijection carries cells α and β to the cells displayed below-left and below-right respectively:

$$\hat{\alpha} := \begin{array}{ccccc} & \text{Hom}_C(f,C) & & E & \text{Hom}_D(D,g) \\ C & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & D \\ \parallel & \Downarrow \rho & \downarrow f & \Downarrow \alpha & \downarrow g & \Downarrow \rho & \parallel \\ C & \xrightarrow{\quad} & C & \xrightarrow{\quad} & D & \xrightarrow{\quad} & D \\ \parallel & & & \Downarrow \circ & & & \parallel \\ C & \xrightarrow{\quad} & & & & & D \\ & & & F & & & \end{array} \quad \text{and} \quad \check{\beta} := \begin{array}{ccccccc} A & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & B \\ \parallel & \Downarrow \iota & \parallel & & \parallel & \Downarrow \iota & \parallel \\ A & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & B \\ \downarrow f & \Downarrow \kappa & \parallel & & \parallel & \Downarrow \kappa & \downarrow g \\ C & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & D \\ \parallel & & & \Downarrow \beta & & & \parallel \\ C & \xrightarrow{\quad} & & & & & D \\ & & & F & & & \end{array}$$

By Proposition 11.4.1 and Lemma 11.3.11

$$\check{\alpha} := \begin{array}{ccccccc} A & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & B \\ \parallel & \Downarrow \iota & \parallel & & \parallel & \Downarrow \iota & \parallel \\ A & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & B \\ \downarrow f & \Downarrow \kappa & \parallel & & \parallel & \Downarrow \kappa & \downarrow g \\ C & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & D \\ \parallel & \Downarrow \rho & \downarrow f & \Downarrow \alpha & \downarrow g & \Downarrow \rho & \parallel \\ C & \xrightarrow{\quad} & C & \xrightarrow{\quad} & D & \xrightarrow{\quad} & D \\ \parallel & & & \Downarrow \circ & & & \parallel \\ C & \xrightarrow{\quad} & & & & & D \\ & & & F & & & \end{array} = \begin{array}{ccccccc} A & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & B \\ \parallel & \Downarrow \iota & \parallel & & \parallel & \Downarrow \iota & \parallel \\ A & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & B \\ \downarrow f & \Downarrow \text{Hom}_f f & \downarrow f & \Downarrow \alpha & \downarrow g & \Downarrow \text{Hom}_g g & \downarrow g \\ C & \xrightarrow{\quad} & C & \xrightarrow{\quad} & D & \xrightarrow{\quad} & D \\ \parallel & & & \Downarrow \circ & & & \parallel \\ C & \xrightarrow{\quad} & & & & & D \\ & & & F & & & \end{array} = \begin{array}{ccc} A & \xrightarrow{\quad} & B \\ \downarrow f & \Downarrow \alpha & \downarrow g \\ C & \xrightarrow{\quad} & D \\ & F & \end{array}$$

The other composite is:

$$\hat{\beta} := \begin{array}{ccccccc} & \text{Hom}_C(f,C) & & E & & \text{Hom}_D(D,g) & \\ C & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & D \\ \parallel & \text{Hom}_C(f,C) & \parallel & \Downarrow \iota & \parallel & \Downarrow \iota & \parallel \\ C & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & D \\ \parallel & \Downarrow \rho & \downarrow f & \Downarrow \kappa & \parallel & \Downarrow \kappa & \downarrow g & \Downarrow \rho & \parallel \\ C & \xrightarrow{\quad} & C & \xrightarrow{\quad} & A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & D \\ \parallel & & & \Downarrow \beta & & & & & \parallel \\ C & \xrightarrow{\quad} & C & \xrightarrow{\quad} & & & D & \xrightarrow{\quad} & D \\ \parallel & & & & & & & & \parallel \\ C & \xrightarrow{\quad} & & & & & & & D \\ & & & F & & & & & \end{array} \quad (11.4.5)$$

By Lemma 11.3.5, we have

$$\begin{array}{ccc}
\begin{array}{c}
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \iota \parallel \text{Hom}_C(f,C) \parallel \downarrow \iota \parallel \\
C \xrightarrow{\text{Hom}_C} C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \beta \parallel \\
C \xrightarrow{\text{Hom}_C} C \xrightarrow{F} D \\
\parallel \downarrow \circ \parallel \\
C \xrightarrow{F} D
\end{array}
& = &
\begin{array}{c}
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \iota \parallel \text{Hom}_C(f,C) \parallel \downarrow \iota \parallel \\
C \xrightarrow{\text{Hom}_C} C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \circ \parallel \text{Hom}_C(f,C) \parallel \downarrow \circ \parallel \\
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \beta \parallel \\
C \xrightarrow{F} D
\end{array}
\end{array}$$

since both composites equal β . By the universal property of the unit cells in Proposition 11.2.4, the bottom two rows of these diagrams are equal, so we may substitute the bottom two rows of the right-hand diagram for the bottom two rows of (11.4.5) to obtain:

$$\begin{array}{c}
\begin{array}{c}
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \iota \parallel \text{Hom}_C(f,C) \parallel \downarrow \iota \parallel \\
C \xrightarrow{\text{Hom}_C} C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \rho \parallel f \parallel \downarrow \kappa \parallel \\
C \xrightarrow{\text{Hom}_C} C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \circ \parallel \text{Hom}_C(f,C) \parallel \downarrow \circ \parallel \\
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \beta \parallel \\
C \xrightarrow{F} D
\end{array}
\end{array}$$

By Proposition 11.4.1 and Lemma 11.3.5 this reduces to β .

$$\begin{array}{ccc}
\begin{array}{c}
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \iota \parallel \text{Hom}_C(f,C) \parallel \downarrow \iota \parallel \\
C \xrightarrow{\text{Hom}_C} C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \circ \parallel \text{Hom}_C(f,C) \parallel \downarrow \circ \parallel \\
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \beta \parallel \\
C \xrightarrow{F} D
\end{array}
& = &
\begin{array}{c}
C \xrightarrow{\text{Hom}_C(f,C)} A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D,g)} D \\
\parallel \downarrow \beta \parallel \\
C \xrightarrow{F} D
\end{array}
\end{array}$$

By vertically bisecting this construction, one obtains the one-sided bijections of the statement. \square

We frequently apply this result in the following form:

11.4.6. COROLLARY. Given modules $A \xrightarrow{E} B$ and $C \xrightarrow{F} D$ and functor $f: A \rightarrow C$ and $g: B \rightarrow D$, there is a bijection between ternary module maps $\text{Hom}_C(f, C) \times E \times \text{Hom}_D(D, g) \Rightarrow F$ and unary module maps $E \Rightarrow F(g, f)$, i.e., between cells

$$\begin{array}{ccc} C & \xrightarrow{\text{Hom}_C(f, C)} & A \xrightarrow{E} B \xrightarrow{\text{Hom}_D(D, g)} D \\ \parallel & & \downarrow \\ C & \xrightarrow{\quad\quad\quad} & D \end{array} \quad \rightsquigarrow \quad \begin{array}{ccc} A & \xrightarrow{E} & B \\ \parallel & & \downarrow \\ A & \xrightarrow{F(g, f)} & B \end{array}$$

PROOF. Combine Theorem 11.4.4 with Proposition 11.2.1. \square

11.4.7. PROPOSITION. For any module $A \xrightarrow{E} B$ and pair of functors $a: X \rightarrow A$ and $b: Y \rightarrow B$, the composite $\text{Hom}_A(A, a) \otimes E \otimes \text{Hom}_B(b, B)$ exists and is given by the restriction $E(b, a)$, with the ternary composite map $\mu: \text{Hom}_A(A, a) \times E \times \text{Hom}_B(b, B) \Rightarrow E(b, a)$ defined by the universal property of the restriction by the pasting diagram:

$$\begin{array}{ccc} \begin{array}{ccc} X & \xrightarrow{\text{Hom}_A(A, a)} & A \xrightarrow{E} B \xrightarrow{\text{Hom}_B(b, B)} Y \\ \parallel & & \downarrow \mu \\ X & \xrightarrow{\quad\quad\quad} & Y \\ a \downarrow & & \downarrow \rho \\ A & \xrightarrow{\quad\quad\quad} & B \\ & & E \end{array} & := & \begin{array}{ccc} \begin{array}{ccc} X & \xrightarrow{\text{Hom}_A(A, a)} & A \xrightarrow{E} B \xrightarrow{\text{Hom}_B(b, B)} Y \\ a \downarrow & \downarrow \rho & \parallel \\ A & \xrightarrow{\text{Hom}_A} & A \xrightarrow{E} B \xrightarrow{\text{Hom}_B} B \\ \parallel & & \downarrow \circ \\ A & \xrightarrow{\quad\quad\quad} & B \\ & & E \end{array} \end{array} \end{array}$$

PROOF. The horizontal composite two-sided fibration of the composable sequence is

$$\begin{array}{ccccccc} & & \text{Hom}_A(A, a) \times E \times \text{Hom}_B(b, B) & & & & \\ & \swarrow & \downarrow & \searrow & & & \\ & \text{Hom}_A(q, a) & & \text{Hom}_B(b, p) & & & \\ & \swarrow & & \searrow & & & \\ \text{Hom}_A(A, a) & & E & & \text{Hom}_B(b, B) & & \\ p_1 \swarrow & & \downarrow q & & \downarrow p & & \searrow p_1 \\ X & \xrightarrow{\quad\quad\quad} & A & \xrightarrow{\quad\quad\quad} & B & \xrightarrow{\quad\quad\quad} & Y \\ & & p_0 & & & & \end{array}$$

from which we see that the binary composite cell

$$\begin{array}{ccc} \text{Hom}_A(q, A) \times_E \text{Hom}_B(B, p) & \xrightarrow{\quad\quad\quad} & E \\ & \searrow & \downarrow (q, p) \\ & & A \times B \end{array}$$

of Proposition 11.3.7 pulls back along $a \times b: X \times Y \rightarrow A \times B$ to define the map μ . By Lemma 11.3.6, we conclude that $\mu: \text{Hom}_A(A, a) \times E \times \text{Hom}_B(b, B) \Rightarrow E(b, a)$ is a composite. \square

As a special case, right representable modules can always be composed with each other and dually left representable modules can always be composed with each other:

11.4.8. COROLLARY. Any composable pair of functors $A \xrightarrow{f} B \xrightarrow{g} C$ defines a composable pair of right-represented modules and a composable pair of left-represented modules

$$A \xrightarrow{\text{Hom}_B(B,f)} B \xrightarrow{\text{Hom}_C(C,g)} C \quad C \xrightarrow{\text{Hom}_C(g,C)} B \xrightarrow{\text{Hom}_B(f,B)} A$$

and moreover:

$$\text{Hom}_B(B, f) \otimes \text{Hom}_C(C, g) \simeq \text{Hom}_C(C, gf) \quad \text{and} \quad \text{Hom}_C(g, C) \otimes \text{Hom}_B(f, B) \simeq \text{Hom}_C(gf, C). \quad \square$$

Combining this result with Proposition 11.3.7 provides a generalization of Theorem 3.4.11, which allows us to detect representable modules.

11.4.9. PROPOSITION. Let $A \xleftarrow{q} E \xrightarrow{p} B$ encode a module.

- (i) The module $A \xrightarrow{E} B$ is right representable if and only if its left leg $q: E \rightarrow A$ has a right adjoint $r: A \rightarrow E$ in which case $E \simeq \text{Hom}_B(B, pr)$.
- (ii) The module $A \xrightarrow{E} B$ is left representable if and only if its right leg $p: E \rightarrow B$ has a left adjoint $\ell: B \rightarrow E$ in which case $E \simeq \text{Hom}_A(q\ell, A)$.

PROOF. Lemma 3.4.8 proves that the claimed adjoints to the legs $p_1: \text{Hom}_B(B, f) \rightarrow A$ and $p_0: \text{Hom}_B(f, B) \rightarrow A$ of left or right representable modules exist, so it remains only to prove the converse. By Proposition 11.3.7, any module $A \xrightarrow{E} B$ can be expressed as a composite $E \simeq \text{Hom}_A(q, A) \otimes \text{Hom}_B(B, p)$ of the left representation of its left leg followed by the right right representation of its right leg. If $q \dashv r$, then by Proposition 4.1.1 $\text{Hom}_A(q, A) \simeq \text{Hom}_E(E, r)$, so $E \simeq \text{Hom}_E(E, r) \otimes \text{Hom}_B(B, p)$. By Corollary 11.4.8, $\text{Hom}_E(E, r) \otimes \text{Hom}_B(B, p) \simeq \text{Hom}_B(B, pr)$ so it follows that $E \simeq \text{Hom}_B(B, pr)$. The case of left representability is dual. \square

Finally, we revisit the “cheap” version of the Yoneda lemma presented in Corollary 3.4.10, which encodes natural transformations in the homotopy 2-category as maps of represented modules.

11.4.10. PROPOSITION. For any parallel pair of functors there are natural bijections between 2-cells in the homotopy 2-category

$$A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \\ \xrightarrow{g} \end{array} B$$

and cells in the virtual equipment of modules:

$$\begin{array}{ccc} \begin{array}{c} A \xrightarrow{\text{Hom}_B(B,f)} B \\ \parallel \quad \Downarrow \quad \parallel \\ A \xrightarrow{\text{Hom}_B(B,g)} B \end{array} & \Leftrightarrow & \begin{array}{c} A \xrightarrow{\text{Hom}_A} A \\ g \downarrow \quad \Downarrow \quad \downarrow f \\ B \xrightarrow{\text{Hom}_B} B \end{array} & \Leftrightarrow & \begin{array}{c} B \xrightarrow{\text{Hom}_B(g,B)} A \\ \parallel \quad \Downarrow \quad \parallel \\ B \xrightarrow{\text{Hom}_B(f,B)} A \end{array} \end{array}$$

PROOF. The bijection between 2-cells in the homotopy 2-category and unary module maps between left or right representables is simply a restatement of Corollary 3.4.10. Alternatively, the bijection between 2-cells in the homotopy 2-category and the cells displayed in the center follows from Lemma 11.1.16 and Proposition 11.2.4. The bijections in $\text{Mod}(\mathbf{h}\mathcal{K})$ can then be derived from Theorem 11.4.4 and Corollary 11.4.6. \square

11.4.11. DEFINITION (the covariant and contravariant embeddings). Proposition 11.4.10 defines the action on 2-cells of two identity-on-objects locally fully faithful homomorphisms

$$\begin{aligned} \mathbf{h}\mathcal{K} &\hookrightarrow \mathcal{M}od(\mathbf{h}\mathcal{K}) & \mathbf{h}\mathcal{K}^{\text{coop}} &\hookrightarrow \mathcal{M}od(\mathbf{h}\mathcal{K}) \\ A \xrightarrow{f} B &\longmapsto A \xrightarrow{\text{Hom}_B(B,f)} B & A \xrightarrow{f} B &\longmapsto B \xrightarrow{\text{Hom}_B(f,B)} A \end{aligned}$$

that embed the homotopy 2-category fully faithfully into the sub “bicategory” of $\mathcal{M}od(\mathbf{h}\mathcal{K})$ containing only those unary cells whose vertical boundaries are identities.

This substructure of $\mathcal{M}od(\mathbf{h}\mathcal{K})$ isn’t quite a bicategory because not all horizontally composable modules can be composed, but if we restrict only to the right representable modules or only to the left representable modules, then by Corollary 11.4.8 the composites do exist and moreover the embeddings are horizontally as well as vertically pseudofunctorial: given $A \xrightarrow{f} B \xrightarrow{g} C$ we have $\text{Hom}_B(B, f) \otimes \text{Hom}_C(C, g) \simeq \text{Hom}_C(C, gf)$ and $\text{Hom}_C(g, C) \otimes \text{Hom}_B(f, B) \simeq \text{Hom}_C(gf, C)$. We refer to these as the **covariant** and **contravariant** embeddings respectively.

As described in Remark 11.3.14, $\mathcal{M}od(\mathbf{h}\mathcal{K})$ can be understood to contain genuine bicategories whose 2-cells are unary cells between right-represented modules (or between left-represented modules) whose vertical boundaries are identities. In this way, the covariant and contravariant embeddings can be understood to define genuine bicategorical homomorphisms.

There is a third locally fully faithful embedding of the homotopy 2-category $\mathbf{h}\mathcal{K}$ into $\mathcal{M}od(\mathbf{h}\mathcal{K})$ that is identity on objects, sends $f: A \rightarrow B$ to the corresponding vertical 1-cell, and uses the third bijection of Proposition 11.4.10 to define the action on 2-cells. Since $\text{Hom}_A \otimes \text{Hom}_A \simeq \text{Hom}_A$, the unary cells in this image of this embedding can be composed horizontally as well as vertically, and this embedding is functorial in both directions: vertical composites of natural transformations in $\mathbf{h}\mathcal{K}$ coincide with horizontal composites of unary cells and horizontal composites of natural transformations in $\mathbf{h}\mathcal{K}$ coincide with vertical composites of unary cells. The image is precisely the vertical 2-category of Proposition 11.3.13. We will make much greater use of the covariant and contravariant embeddings of Definition 11.4.11 however.

Exercises.

11.4.i. EXERCISE. Prove Proposition 11.4.1 in any virtual equipment, without appealing to Lemma 11.1.16.

11.4.ii. EXERCISE. Prove Proposition 11.4.7 in any virtual equipment, without appealing to Lemma 11.3.6.

11.4.iii. EXERCISE. For any functor $f: A \rightarrow B$, define a unary cell $\eta: \text{Hom}_A \Rightarrow \text{Hom}_B(f, f) \cong \text{Hom}_B(B, f) \otimes \text{Hom}_B(f, B)$ and a binary cell $\epsilon: \text{Hom}_B(f, B) \times \text{Hom}_B(B, f) \Rightarrow \text{Hom}_B$. Use this data to demonstrate that the modules $A \xrightarrow{\text{Hom}_B(B,f)} B$ and $B \xrightarrow{\text{Hom}_B(f,B)} A$ are “adjoint” in a suitable sense.

Formal category theory in a virtual equipment

Mac Lane famously asserted that “all concepts are Kan extensions” [38, §X.7] — at least in category theory. Kelly later amended this to assert that the *pointwise Kan extensions*, which he calls simply “Kan extensions” are the important ones, writing “Our present choice of nomenclature is based on our failure to find a single instance where a [non-pointwise] Kan extension plays any mathematical role whatsoever” [31, §4]. Using the calculus of modules we can now add the theory of pointwise Kan extensions of functors between ∞ -categories to the basic ∞ -category theory developed in Part I.

Right and left extensions of a functor $f: A \rightarrow C$ along a functor $k: A \rightarrow B$ can be defined internally to any 2-category — at this level of generality the eponym “Kan” is typically dropped. We review this notion in Definition 12.2.1. However, in the homotopy 2-category of an ∞ -cosmos, the universal property defining left and right extensions is not strong enough, and indeed the correct universal property is associated to the stronger notion of a *pointwise extension*, for which the values of a right or left extension at an element of B can be computed as limits or colimits indexed by the appropriate comma ∞ -category; see Corollary 12.4.3 for a precise statement.

Our aim in this chapter is to define and study pointwise extensions for functors between ∞ -categories. In fact, we give multiple definitions of pointwise extension. One is fundamentally 2-categorical: a pointwise extension is an ordinary 2-categorical extension in the homotopy 2-category that is stable under pasting with comma squares. Another definition is that a 2-cell defines a pointwise right extension if and only if its image under the covariant embedding into the virtual equipment of modules defines a right extension there. Theorem 12.2.7 proves that these two notions coincide.

Before turning our attention to pointwise extensions, we first introduce exact squares in §12.1, a class of squares in the homotopy 2-category that include comma squares and which will be used to characterize the pointwise extensions internally to the homotopy 2-category. Pointwise extensions are introduced in a variety of equivalent ways in §12.2 and applied in §12.3 to develop a few aspects of the formal theory of ∞ -categories. In §12.4, we conclude with a discussion of pointwise extensions in a cartesian closed ∞ -cosmos, in which context these relate to the absolute lifting diagrams and limits and colimits studied in §2.3-2.4.

12.1. Exact squares

By Proposition 11.4.10, natural transformations in the homotopy 2-category of an ∞ -cosmos correspond bijectively to unary squares in the virtual equipment of modules of various forms. By this result, Theorem 11.4.4, Proposition 11.2.4, and Proposition 11.2.1, we have bijections:

$$\begin{array}{ccccc}
 \begin{array}{ccc} & D & \\ k \swarrow & & \searrow h \\ C & \xleftarrow{\alpha} & B \\ g \searrow & & \swarrow f \\ & A & \end{array} & \rightsquigarrow & \begin{array}{ccc} D & \xrightarrow{\text{Hom}_D} & D \\ gk \downarrow & \Downarrow & \downarrow fh \\ A & \xrightarrow{\text{Hom}_A} & A \end{array} & \rightsquigarrow & \begin{array}{ccc} C & \xrightarrow{\text{Hom}_C(k,C)} D & \xrightarrow{\text{Hom}_B(B,h)} B \\ \parallel & \Downarrow \hat{\alpha} & \parallel \\ C & \xrightarrow{\text{Hom}_A(f,g)} & B \end{array}
 \end{array}$$

12.1.1. DEFINITION (exact squares). A square in the homotopy 2-category of an ∞ -cosmos

$$\begin{array}{ccc} & D & \\ k \swarrow & & \searrow h \\ C & \xRightarrow{\alpha} & B \\ g \searrow & & \swarrow f \\ & A & \end{array}$$

is **exact** if and only if the corresponding cell below-left, which under the bijection of Lemma 11.1.16 encodes the below-right pasted composite

$$\begin{array}{ccc} \begin{array}{ccc} C & \xrightarrow{\text{Hom}_C(k,C)} D & \xrightarrow{\text{Hom}_B(B,h)} B \\ \parallel & \Downarrow \hat{\alpha} & \parallel \\ C & \xrightarrow{\text{Hom}_A(f,g)} B \end{array} & \rightsquigarrow & \begin{array}{c} \text{Hom}_C(k,C) \times \text{Hom}_B(B,h) \\ \downarrow D \\ \begin{array}{ccc} \text{Hom}_C(k,C) & & \text{Hom}_B(B,h) \\ \downarrow p_0 & & \downarrow p_1 \\ \begin{array}{ccc} \phi \swarrow & D & \nwarrow \phi \\ p_1 \swarrow & & \searrow p_0 \\ C & \xRightarrow{\alpha} & B \\ g \searrow & & \swarrow f \\ & A & \end{array} \end{array} \end{array} \quad (12.1.2)$$

displays $\text{Hom}_A(f,g)$ as the composite $\text{Hom}_C(k,C) \otimes \text{Hom}_B(B,h)$ as defined in Definition 11.3.1.

When the boundary square is clear from context, for economy of language we may write that “ $\alpha: fh \Rightarrow gk$ is an exact square” but note that the definition of exactness requires the specification of the four boundary components of the square inhabited by the 2-cell α .¹

12.1.3. REMARK (exactness as a Beck-Chevalley condition). By Proposition 11.4.7, the canonical cell $\mu_{\text{Hom}_A(A,g) \times \text{Hom}_A(f,A)}: \text{Hom}_A(A,g) \times \text{Hom}_A(f,A) \Rightarrow \text{Hom}_A(f,g)$ encoded by the map of spans defined by 1-cell induction

$$\begin{array}{ccc} \begin{array}{ccc} \text{Hom}_A(A,g) \times \text{Hom}_A(f,A) & & \\ \downarrow A & & \\ \begin{array}{ccc} \text{Hom}_A(A,g) & & \text{Hom}_A(f,A) \\ \downarrow p_1 & \Downarrow \phi & \downarrow p_0 \\ C & \xrightarrow{g} & A \end{array} & & \begin{array}{ccc} \text{Hom}_A(f,A) & & B \\ \downarrow p_1 & \Downarrow \phi & \downarrow p_0 \\ A & \xleftarrow{f} & B \end{array} \end{array} \\ = & & \begin{array}{ccc} \text{Hom}_A(A,g) \times \text{Hom}_A(f,A) & & \\ \downarrow \mu & & \\ \text{Hom}_A(f,g) & & \\ \downarrow p_1 & \Downarrow \phi & \downarrow p_0 \\ C & \xrightarrow{g} & A \end{array} \end{array}$$

is a composite. Exactness says that α induces an isomorphism

$$\hat{\alpha}: \text{Hom}_C(k,C) \otimes \text{Hom}_B(B,h) \simeq \text{Hom}_A(A,g) \otimes \text{Hom}_A(f,A)$$

of modules from C to B .

The remainder of this section is devoted to examples of exact squares.

¹For instance, compare the statements of Exercise 12.1.i and Lemma 12.3.3.

12.1.4. LEMMA (comma squares are exact). *For any cospan $C \xrightarrow{g} A \xleftarrow{f} B$, the comma cone defines an exact square:*

$$\begin{array}{ccc}
 & \text{Hom}_A(f, g) & \\
 p_1 \swarrow & \phi & \searrow p_0 \\
 C & & B \\
 g \searrow & & \swarrow f \\
 & A &
 \end{array}$$

PROOF. By Proposition 11.3.7, the module $C \xrightarrow{\text{Hom}_A(f, g)} B$ is the composite of the left representation of its left leg followed by the right representation of its right leg: $\text{Hom}_C(p_1, C) \otimes \text{Hom}_B(B, p_0) \simeq \text{Hom}_A(f, g)$. By Remark 11.3.9, the composition map $\text{Hom}_C(p_1, C) \times \text{Hom}_B(B, p_0) \Rightarrow \text{Hom}_A(f, g)$ classifies the pasted composite

$$\begin{array}{ccccc}
 & & \text{Hom}_C(p_1, C) \times \text{Hom}_B(B, p_0) & & \\
 & \swarrow & \downarrow \vee & \searrow & \\
 \text{Hom}_C(p_1, C) & & & & \text{Hom}_B(B, p_0) \\
 \downarrow p_1 & \swarrow p_0 & \phi & \swarrow p_1 & \downarrow p_0 \\
 C & & \text{Hom}_A(f, g) & & B \\
 g \searrow & \phi & & \swarrow f & \\
 & A & & &
 \end{array}$$

which recovers the cell $\hat{\phi}$ defined by (12.1.2) that tests the exactness of comma square $\phi: fp_0 \Rightarrow gp_1$. \square

12.1.5. LEMMA. *If $g: C \rightarrow A$ is a cartesian fibration or $f: B \rightarrow A$ is a cocartesian fibration, then the pullback square*

$$\begin{array}{ccc}
 & P & \\
 \pi_1 \swarrow & \downarrow \vee & \searrow \pi_0 \\
 C & & B \\
 g \searrow & & \swarrow f \\
 & A &
 \end{array}$$

is exact.

PROOF. The two statements are dual though the positions of the cocartesian and cartesian fibrations cannot be interchanged, as the proof will reveal. If $f: B \rightarrow A$ is a cocartesian fibration, observe that the functor $i: P \rightarrow \text{Hom}_A(f, g)$ induced by the identity 2-cell $f\pi_0 = g\pi_1$ is a pullback of the

functor $i: B \rightarrow \text{Hom}_A(f, A)$ induced by the identity 2-cell id_f .

$$\begin{array}{ccccc}
 P & \xleftarrow{\pi_0} & B & \xleftarrow{\ell} & \\
 \downarrow \pi_1 & \searrow i & \downarrow i & \searrow i & \\
 & \text{Hom}_A(f, g) & \xrightarrow{\quad} & \text{Hom}_A(f, A) & \\
 \downarrow p_1 & & \downarrow f & & \downarrow p_1 \\
 C & \xrightarrow{g} & A & &
 \end{array}$$

ℓ (dashed) from P to $\text{Hom}_A(f, g)$, ℓ (dashed) from B to $\text{Hom}_A(f, A)$, \perp (dashed) from P to $\text{Hom}_A(f, g)$, \perp (dashed) from B to $\text{Hom}_A(f, A)$.

Since f is a cocartesian fibration, Theorem 5.1.11(ii) tells us that $i: B \rightarrow \text{Hom}_A(f, A)$ has a fibered left adjoint over A . This fibered adjunction pulls back via the cosmological functor $g^*: \mathcal{K}_A \rightarrow \mathcal{K}_C$ to define a fibered left adjoint to $i: P \rightarrow \text{Hom}_A(f, g)$.

Since $\pi_0 = p_0 i$, Corollary 11.4.8 implies that the canonical cell

$$\text{Hom}_{\text{Hom}_A(f, g)}(\text{Hom}_A(f, g), i) \times \text{Hom}_B(B, p_0) \Rightarrow \text{Hom}_B(B, \pi_0)$$

is a composite. Since $\ell \dashv i$, $\text{Hom}_P(\ell, P) \simeq \text{Hom}_{\text{Hom}_A(f, g)}(\text{Hom}_A(f, g), i)$ by Proposition 4.1.1. And since $p_1 = \pi_1 \ell$, Corollary 11.4.8 again implies that the canonical cell

$$\text{Hom}_C(\pi_1, C) \times \text{Hom}_P(\ell, P) \Rightarrow \text{Hom}_C(p_1, C)$$

is a composite. Composing these bijections, we see that cells with domain $\text{Hom}_C(\pi_1, C) \times \text{Hom}_B(B, \pi_0)$ correspond bijectively to cells with domain $\text{Hom}_C(p_1, C) \times \text{Hom}_B(B, p_0)$.

The equation $\text{id} = \phi i: f \pi_0 = f p_0 i \Rightarrow g p_1 i = g \pi_1$ asserts that the identity is the transpose along $\ell \dashv i$ of the cell $\phi: f p_0 \Rightarrow g p_1 = g \pi_1 \ell$, which tells us that the cells

$$\hat{\text{id}}: \text{Hom}_C(\pi_1, C) \times \text{Hom}_B(B, \pi_0) \Rightarrow \text{Hom}_A(f, g) \quad \text{and}$$

$$\hat{\phi}: \text{Hom}_C(p_1, C) \times \text{Hom}_B(B, p_0) \Rightarrow \text{Hom}_A(f, g)$$

correspond under the bijection just described. Since Lemma 12.1.4 proves that $\hat{\phi}$ is a composite, by Lemma 11.3.2 so is $\hat{\text{id}}$. \square

12.1.6. LEMMA. For any pair of functors $f: A \rightarrow B$ and $g: C \rightarrow D$ the square

$$\begin{array}{ccc}
 A \times C & \xrightarrow{f \times C} & B \times C \\
 A \times g \downarrow & & \downarrow B \times g \\
 A \times D & \xrightarrow{f \times D} & B \times D
 \end{array}$$

is exact.

PROOF. Exercise 12.1.ii. \square

12.1.7. LEMMA. The product of a comma square $\phi: fp_0 \Rightarrow gp_1$ with any ∞ -category K defines an exact square

$$\begin{array}{ccc}
 & \text{Hom}_A(f, g) \times K & \\
 p_1 \times K \swarrow & & \searrow p_0 \times K \\
 C \times K & \xleftarrow{\phi \times K} & B \times K \\
 g \times K \searrow & & \swarrow f \times K \\
 & A \times K &
 \end{array}$$

PROOF. Exercise 12.1.iii. □

Finally, the plethora of examples of exact squares just established can be composed to yield further comma squares:

12.1.8. LEMMA (composites of exact squares). Given a diagram of squares in the homotopy 2-category

$$\begin{array}{ccccc}
 & H & & G & \\
 s \swarrow & & r \searrow & q \swarrow & p \searrow \\
 F & \xleftarrow{\gamma} & D & \xleftarrow{\beta} & E \\
 c \searrow & & k \swarrow & h \searrow & b \swarrow \\
 & C & \xleftarrow{\alpha} & B & \\
 & g \searrow & & f \swarrow & \\
 & A & & &
 \end{array}$$

if $\alpha: fh \Rightarrow hk$, $\beta: bp \Rightarrow hq$, and $\gamma: kr \Rightarrow cs$ are all exact squares then so are the composite rectangles $\alpha q \cdot f\beta$ and $g\gamma \cdot \alpha r$. Consequently, arbitrary “double categorical” composites of exact squares define exact squares.

PROOF. The two cases are co-duals, so it suffices to prove that the rectangle $\alpha q \cdot f\beta: g(kq) \Rightarrow (fb)p$ is exact. The corresponding cell $\widehat{\alpha q \cdot f\beta}$ displayed below-left factors as below-right:

$$\begin{array}{ccc}
 C \xrightarrow{\text{Hom}_C(k, C)} D \xrightarrow{\text{Hom}_D(q, D)} G \xrightarrow{\text{Hom}_E(E, p)} E \\
 \parallel \quad \Downarrow \widehat{\alpha q \cdot f\beta} \quad \parallel \\
 C \xrightarrow{\quad \quad \quad} E \\
 \text{Hom}_A(fb, g)
 \end{array}
 =
 \begin{array}{ccc}
 C \xrightarrow{\text{Hom}_C(k, C)} D \xrightarrow{\text{Hom}_D(q, D)} G \xrightarrow{\text{Hom}_E(E, p)} E \\
 \parallel \quad \parallel \quad \Downarrow \hat{\beta} \quad \parallel \\
 C \xrightarrow{\text{Hom}_C(k, C)} D \xrightarrow{\quad \quad \quad} E \\
 \parallel \quad \Downarrow \hat{\alpha} \quad \parallel \\
 C \xrightarrow{\quad \quad \quad} E \\
 \text{Hom}_A(fb, g)
 \end{array}$$

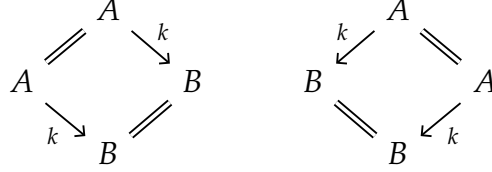
through a cell $\hat{\alpha}$ defined by the universal property of the composite $\text{Hom}_B(B, h) \otimes \text{Hom}_B(b, B) \simeq \text{Hom}_B(b, h)$ of Proposition 11.4.7 by the pasting equality:

$$\begin{array}{ccc}
 C \xrightarrow{\text{Hom}_C(k, C)} D \xrightarrow{\text{Hom}_B(B, h)} B \xrightarrow{\text{Hom}_B(b, B)} E \\
 \parallel \quad \parallel \quad \Downarrow \circ \\
 C \xrightarrow{\text{Hom}_C(k, C)} D \xrightarrow{\quad \quad \quad} E \\
 \parallel \quad \Downarrow \hat{\alpha} \quad \parallel \\
 C \xrightarrow{\quad \quad \quad} E \\
 \text{Hom}_A(fb, g)
 \end{array}
 :=
 \begin{array}{ccc}
 C \xrightarrow{\text{Hom}_C(k, C)} D \xrightarrow{\text{Hom}_B(B, h)} B \xrightarrow{\text{Hom}_B(b, B)} E \\
 \parallel \quad \Downarrow \hat{\alpha} \quad \parallel \quad \text{Hom}_B(b, B) \parallel \\
 C \xrightarrow{\quad \quad \quad} B \xrightarrow{\quad \quad \quad} E \\
 \parallel \quad \text{Hom}_A(f, g) \quad \Downarrow \circ \quad \parallel \\
 C \xrightarrow{\quad \quad \quad} E \\
 \text{Hom}_A(fb, g)
 \end{array}$$

By exactness of α , $\hat{\alpha}$ and both cells named \circ are composites, so by Lemma 11.3.2 $\bar{\alpha}$ is a composite as well. By exactness of β and Lemma 11.3.2 again it now follows that $\widehat{\alpha q \cdot f \beta}$ is also a composite, proving exactness of the rectangle $\alpha q \cdot f \beta: g(kq) \Rightarrow (fb)p$. \square

Exercises.

12.1.i. EXERCISE. Prove that the identity cells



define exact squares.

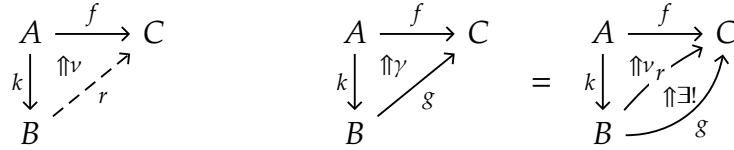
12.1.ii. EXERCISE. Prove Lemma 12.1.6.

12.1.iii. EXERCISE. Prove Lemma 12.1.7.

12.2. Pointwise right and left extensions

In this section we give four definitions of pointwise extension and prove they are equivalent. We begin with a general categorical notion that on its own is too weak.

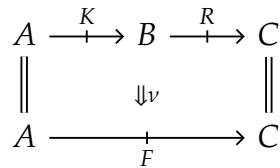
12.2.1. DEFINITION. A **right extension** of a 1-cell $f: A \rightarrow C$ along a 1-cell $k: A \rightarrow B$ is given by a pair $(r: B \rightarrow C, \nu: rk \Rightarrow f)$ as below-left



so that any similar pair as above-center factors uniquely through ν as above right. The co-dual defines a **left extension** of a 1-cell $f: A \rightarrow C$ along a 1-cell $k: A \rightarrow B$.

The op-dual of Definition 12.2.1 defines a notion of right lifting in any 2-category. Analogous notions of right extension and right lifting can be defined for horizontal morphisms in a virtual double equipment, where in the presence of restrictions of modules it suffices to consider cells whose vertical functors are identities. We specialize our language to the virtual equipment of modules, as this will be the one case of interest:

12.2.2. DEFINITION. A **right extension** of a module $A \xrightarrow{F} C$ along a module $A \xrightarrow{K} B$ consists of a pair given by a module $B \xrightarrow{R} C$ together with a binary cell



with the property that every $n + 1$ -ary cell of the form displayed below-left factors uniquely through $\nu: K \times R \Rightarrow F$ as below-right:

$$\begin{array}{ccc}
 A & \xrightarrow{K} B & \xrightarrow{E_1} \cdots \xrightarrow{E_n} C \\
 \parallel & & \downarrow \\
 A & \xrightarrow{\quad\quad\quad} & C \\
 & & F
 \end{array}
 =
 \begin{array}{ccccc}
 A & \xrightarrow{K} B & \xrightarrow{E_1} \cdots \xrightarrow{E_n} C & & \\
 \parallel & & \parallel & \Downarrow \exists! & \parallel \\
 A & \xrightarrow{K} B & \xrightarrow{\quad\quad\quad} C & & \\
 \parallel & & \parallel & \Downarrow \nu & \parallel \\
 A & \xrightarrow{\quad\quad\quad} & C & & \\
 & & F & &
 \end{array}$$

Dually, a **right lifting** of $A \xrightarrow{F} C$ through $B \xrightarrow{H} C$ consists of a pair given by a module $A \xrightarrow{L} B$ together with a binary cell

$$\begin{array}{ccc}
 A & \xrightarrow{L} B & \xrightarrow{H} C \\
 \parallel & & \parallel \\
 A & \xrightarrow{\quad\quad\quad} & C \\
 & & F
 \end{array}$$

with the property that every $n + 1$ -ary cell of the form displayed below-left factors uniquely through $\lambda: L \times H \Rightarrow F$ as below-right:

$$\begin{array}{ccc}
 A & \xrightarrow{E_1} \cdots \xrightarrow{E_n} B & \xrightarrow{H} C \\
 \parallel & & \parallel \\
 A & \xrightarrow{\quad\quad\quad} & C \\
 & & F
 \end{array}
 =
 \begin{array}{ccccc}
 A & \xrightarrow{E_1} \cdots \xrightarrow{E_n} B & \xrightarrow{H} C & & \\
 \parallel & & \parallel & \Downarrow \exists! & \parallel \\
 A & \xrightarrow{\quad\quad\quad} B & \xrightarrow{H} C & & \\
 \parallel & & \parallel & \Downarrow \lambda & \parallel \\
 A & \xrightarrow{\quad\quad\quad} & C & & \\
 & & F & &
 \end{array}$$

Because of the asymmetry in Definition 11.1.9, there is no corresponding notion of *left* extension or *left* lifting.

12.2.3. LEMMA. For any functor $f: A \rightarrow B$, the binary cell

$$\begin{array}{ccc}
 B & \xrightarrow{\text{Hom}_B(f,B)} A & \xrightarrow{\text{Hom}_B(B,f)} B \\
 \parallel & & \parallel \\
 B & \xrightarrow{\quad\quad\quad} & B \\
 & & \text{Hom}_B
 \end{array}$$

defined in Exercise 11.4.iii defines a right extension of $B \xrightarrow{\text{Hom}_B} B$ through $B \xrightarrow{\text{Hom}_B(f,B)} A$ and a right lifting of $B \xrightarrow{\text{Hom}_B} B$ through $A \xrightarrow{\text{Hom}_B(B,f)} B$.

PROOF. Exercise 12.2.i. □

We now explain how Definition 12.2.2 relates to Definition 12.2.1 via the covariant and contravariant embeddings of Definition 11.4.11.

12.2.4. LEMMA. If

$$\begin{array}{ccccc} A & \xrightarrow{\text{Hom}_B(B,k)} & B & \xrightarrow{\text{Hom}_C(C,r)} & C \\ \parallel & & \Downarrow \nu & & \parallel \\ A & \xrightarrow{\text{Hom}_C(C,f)} & & & C \end{array}$$

defines a right extension in the virtual equipment of modules, then $\nu: rk \Rightarrow f$ defines a right extension in the homotopy 2-category. Dually if

$$\begin{array}{ccccc} A & \xrightarrow{\text{Hom}_A(\ell,A)} & B & \xrightarrow{\text{Hom}_B(h,B)} & C \\ \parallel & & \Downarrow \lambda & & \parallel \\ A & \xrightarrow{\text{Hom}_A(g,A)} & & & C \end{array}$$

defines a right lifting in the virtual equipment of modules, then $\lambda: g \Rightarrow \ell h$ is a left extension in the homotopy 2-category.

PROOF. By Corollary 11.4.8 binary cells $\nu: \text{Hom}_B(B,k) \times \text{Hom}_C(C,r) \Rightarrow \text{Hom}_C(C,f)$ correspond to unary cells $\nu: \text{Hom}_C(C,rk) \Rightarrow \text{Hom}_C(C,f)$, which by Proposition 11.4.10 correspond to natural transformations $\nu: rk \Rightarrow f$ in the homotopy 2-category. Via this correspondence the universal property of Definition 12.2.2 clearly subsumes that of Definition 12.2.1. The left extension case is similar, via the contravariant embedding of Definition 11.4.11. \square

12.2.5. DEFINITION (stability of extensions under pasting). A right extension diagram $\nu: rk \Rightarrow f$ in a 2-category is said to be **stable under pasting with a square α**

$$\begin{array}{ccc} A & \xrightarrow{f} & C \\ k \downarrow & \Uparrow \nu & \nearrow r \\ B & & \end{array} \quad \begin{array}{ccccc} & & D & & \\ & g \swarrow & & \searrow h & \\ A & & \alpha & & E \\ & k \searrow & & \swarrow b & \\ & & B & & \end{array}$$

if the pasted composite

$$\begin{array}{ccccc} D & \xrightarrow{g} & A & \xrightarrow{f} & C \\ h \downarrow & \nearrow \alpha & k \downarrow & \Uparrow \nu & \nearrow r \\ E & \xrightarrow{b} & B & & \end{array} \quad (12.2.6)$$

defines a right extension $rb: E \rightarrow C$ of $fg: D \rightarrow C$ along $h: D \rightarrow E$. The co-dual of this statement defines what it means for a left extension diagram to be stable under pasting with a square.

12.2.7. THEOREM (pointwise right extensions). For a diagram

$$\begin{array}{ccc} A & \xrightarrow{f} & C \\ k \downarrow & \Uparrow \nu & \nearrow r \\ B & & \end{array}$$

in the homotopy 2-category of an ∞ -cosmos \mathcal{K} the following are equivalent:

- (i) $v: rk \Rightarrow f$ defines a right extension in $\mathfrak{h}\mathcal{K}$ that is stable under pasting with exact squares.
- (ii) $v: rk \Rightarrow f$ defines a right extension in $\mathfrak{h}\mathcal{K}$ that is stable under pasting with comma squares.
- (iii) $v: \text{Hom}_B(B, k) \times \text{Hom}_C(C, r) \Rightarrow \text{Hom}_C(C, f)$ defines a right extension in $\text{Mod}(\mathfrak{h}\mathcal{K})$.
- (iv) For any exact square $\alpha: bh \Rightarrow kg, vg \cdot r\alpha: \text{Hom}_E(E, h) \times \text{Hom}_C(C, rb) \Rightarrow \text{Hom}_C(C, fg)$ defines a right extension in $\text{Mod}(\mathfrak{h}\mathcal{K})$.

When these conditions hold, we say $r: B \rightarrow C$ defines a *pointwise right extension* of $f: A \rightarrow C$ along $k: A \rightarrow B$.

PROOF. Lemma 12.1.4 proves (i) \Rightarrow (ii).

To show (ii) \Rightarrow (iii), suppose $v: rk \Rightarrow f$ defines a right extension in $\mathfrak{h}\mathcal{K}$ that is stable under pasting with comma squares and consider a cell in $\text{Mod}(\mathfrak{h}\mathcal{K})$:

$$\begin{array}{ccccc}
 A & \xrightarrow{\text{Hom}_B(B, k)} & B & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & C \\
 \parallel & & & \Downarrow & & & \parallel \\
 A & \xrightarrow{\quad\quad\quad} & & & & & C \\
 & & & \text{Hom}_C(C, f) & & &
 \end{array}$$

Let $B \xleftarrow{q} E \xrightarrow{p} C$ denote the composite two-sided fibration $E_1 \times \cdots \times E_n$. By Remark 11.3.8 applied to $B \xleftarrow{q} E \xrightarrow{p} C$, module maps $\text{Hom}_B(B, k) \times E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, f)$ stand in bijection with module maps $\text{Hom}_B(B, k) \times \text{Hom}_B(q, B) \times \text{Hom}_C(C, p) \Rightarrow \text{Hom}_C(C, f)$. By Corollary 11.4.6 and Proposition 11.4.7, such module maps stand in bijection with module maps $\text{Hom}_B(q, k) \Rightarrow \text{Hom}_C(p, f)$. By Lemma 11.1.16, these module maps correspond bijectively to 2-cells

$$\begin{array}{ccccc}
 & & \text{Hom}_B(q, k) & & \\
 & \swarrow p_1 & & \searrow p_0 & \\
 A & & \alpha & & E \\
 & \searrow f & \Leftarrow & \swarrow p & \\
 & & C & &
 \end{array}$$

in the homotopy 2-category. By the hypothesis (ii),

$$\begin{array}{ccccc}
 \text{Hom}_B(q, k) & \xrightarrow{p_1} & A & \xrightarrow{f} & C \\
 p_0 \downarrow & \nearrow \phi & k \downarrow & \Uparrow v & \nearrow r \\
 E & \xrightarrow{q} & B & &
 \end{array}$$

defines a right extension in $\mathfrak{h}\mathcal{K}$, so α factors uniquely through this pasted composite via a map $\gamma: p \Rightarrow rq$. By Proposition 11.4.10, this defines a cell $\gamma: \text{Hom}_C(C, p) \Rightarrow \text{Hom}_C(C, rq)$, which by Corollary 11.4.6 gives rise to a canonical cell $\hat{\gamma}: \text{Hom}_B(q, B) \times \text{Hom}_C(C, p) \Rightarrow \text{Hom}_C(C, r)$. By Remark 11.3.8

again, this produces the desired unique factorization

$$\begin{array}{ccc}
 A & \xrightarrow{\text{Hom}_B(B,k)} B & \xrightarrow{E_1} \cdots \xrightarrow{E_n} C \\
 \parallel & \downarrow & \\
 A & \xrightarrow{\text{Hom}_C(C,f)} C &
 \end{array}
 =
 \begin{array}{ccccc}
 A & \xrightarrow{\text{Hom}_B(B,k)} B & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} C \\
 \parallel & \parallel & & & \parallel \\
 A & \xrightarrow{\text{Hom}_B(B,k)} B & \xrightarrow{\text{Hom}_C(C,r)} & & C \\
 \parallel & \parallel & \downarrow \nu & & \parallel \\
 A & \xrightarrow{\text{Hom}_C(C,f)} C & & &
 \end{array}$$

To show (iii) \Rightarrow (iv), consider a diagram (12.2.6) in which $\alpha: bh \Rightarrow kg$ is exact and $\nu: \text{Hom}_B(B, k) \times \text{Hom}_C(C, r) \Rightarrow \text{Hom}_C(C, f)$ defines a right extension diagram in $\text{Mod}(\mathfrak{h}\mathcal{K})$. Now by Corollary 11.4.6, a cell

$$\text{Hom}_E(E, h) \times E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, fg)$$

corresponds to a cell

$$\text{Hom}_A(g, A) \times \text{Hom}_E(E, h) \times E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, f).$$

By exactness of α , this corresponds to a cell

$$\text{Hom}_B(b, k) \times E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, f),$$

or equivalently, upon restricting along the composite map $\text{Hom}_B(B, k) \times \text{Hom}_B(b, B) \Rightarrow \text{Hom}_B(b, k)$ to a cell

$$\text{Hom}_B(B, k) \times \text{Hom}_B(b, B) \times E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, f).$$

Since $B \xrightarrow{\text{Hom}_C(C, r)} C$ is the right extension of $A \xrightarrow{\text{Hom}_C(C, f)} C$ along $A \xrightarrow{\text{Hom}_B(B, k)} B$, this corresponds to a cell

$$\text{Hom}_B(b, B) \times E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, r),$$

which transposes via Corollary 11.4.6 to a cell

$$E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, rb),$$

which gives the factorization required to prove that $E \xrightarrow{\text{Hom}_C(C, rb)} C$ is the right extension of $D \xrightarrow{\text{Hom}_C(C, fg)} C$ along $D \xrightarrow{\text{Hom}_E(E, h)} E$. A slightly more delicate argument is required to see that this bijection is implemented by composing with the map of modules $\text{Hom}_E(E, h) \times \text{Hom}_C(C, rb) \Rightarrow \text{Hom}_C(C, fg)$ corresponding to the pasted composite (12.2.6), but for this it suffices by the Yoneda lemma to start with the identity cell $\text{id}_{\text{Hom}_C(C, rb)}$ and trace back up through the bijection just described. By Lemma 11.1.16 this is straightforward.

Finally Lemma 12.2.4 and the trivial example of Exercise 12.1.i prove that (iv) \Rightarrow (i). \square

12.2.8. COROLLARY. *The pasted composite (12.2.6) of a pointwise right extension with an exact square is a pointwise right extension.*

PROOF. Lemma 12.1.8, the pasted composite of two exact squares remains an exact square, so by Theorem 12.2.7(i), the pasted composite of a pointwise right extension remains stable under pasting with exact squares. \square

Exercises.

12.2.i. EXERCISE. Prove Lemma 12.2.3.

12.2.ii. EXERCISE. Using Lemma 12.2.4 as a hint, state and prove a dual version of Theorem 12.2.7 defining pointwise left extensions in the homotopy 2-category of an ∞ -cosmos.

12.3. Formal category theory in a virtual equipment

12.3.1. PROPOSITION. For any pair of functors $u: A \rightarrow B$ the following are equivalent:

- (i) The natural transformation $\epsilon: fu \Rightarrow \text{id}_A$ is the counit of an adjunction $f \dashv u$.
- (ii) There is a pointwise right extension diagram in $\mathbf{h}\mathcal{K}$

$$\begin{array}{ccc} A & \xlongequal{\quad} & A \\ u \downarrow & \nearrow f & \uparrow \epsilon \\ B & & \end{array} \quad (12.3.2)$$

that is *absolute*, preserved by any functor $h: A \rightarrow C$.

- (iii) The square

$$\begin{array}{ccc} & A & \\ \swarrow & & \searrow u \\ A & \xlongequal{\quad} & B \\ \nwarrow & \epsilon & \nearrow f \\ & A & \end{array}$$

is exact.

PROOF. Without the adjective “pointwise” the equivalence (i) \Leftrightarrow (ii) is the op-dual of Lemma 2.3.6, whose proof works in any 2-category and in particular in $\mathbf{h}\mathcal{K}^{\text{op}}$. It remains only to demonstrate that the right extension produced by (i) \Rightarrow (ii) is pointwise. To see this, recall that for any $f: B \rightarrow A$, Lemma 12.2.3 provides a right lifting in $\mathbf{Mod}(\mathbf{h}\mathcal{K})$ as below left

$$\begin{array}{ccc} A & \xrightarrow{\text{Hom}_A(f,A)} B & \xrightarrow{\text{Hom}_A(A,f)} A \\ \parallel & \Downarrow \epsilon & \parallel \\ A & \xrightarrow{\text{Hom}_A} & A \end{array} \cong \begin{array}{ccc} A & \xrightarrow{\text{Hom}_B(B,u)} B & \xrightarrow{\text{Hom}_A(A,f)} A \\ \parallel & \Downarrow \epsilon & \parallel \\ A & \xrightarrow{\text{Hom}_A} & A \end{array}$$

If $f \dashv u$, then by Proposition 4.1.1, the counit induces an equivalence $\text{Hom}_B(B, u) \simeq \text{Hom}_A(f, A)$, so we have an isomorphic right lifting diagram above right. By Proposition 11.4.10 and Theorem 12.2.7 this supplies a natural transformation $\epsilon: fu \Rightarrow \text{id}_A$ that defines a pointwise right extension (12.3.2).

Proposition 4.1.1, which demonstrates that $\epsilon: fu \Rightarrow \text{id}_A$ is a counit if and only if it induces an equivalence $\text{Hom}_B(B, u) \simeq \text{Hom}_A(f, A)$ also proves (i) \Leftrightarrow (iii), via Lemma 11.3.5 which tells us that $\text{Hom}_A \otimes \text{Hom}_B(B, u) \simeq \text{Hom}_B(B, u)$. \square

12.3.3. LEMMA. A functor $k: A \rightarrow B$ is *fully faithful* when any of the following equivalent conditions hold:

(i) The square

$$\begin{array}{ccc} & A & \\ \lrcorner & & \lrcorner \\ A & & A \\ \searrow_k & & \swarrow_k \\ & B & \end{array}$$

is exact.

(ii) The unary cell $\hat{\text{id}}_k: \mathbf{Hom}_A \Rightarrow \mathbf{Hom}_B(k, k)$ is a composite.

(iii) The module map $\hat{\text{id}}_k$ defines an equivalence of modules $\mathbf{Hom}_A \simeq \mathbf{Hom}_B(k, k)$ from A to A .

PROOF. The equivalence follows from Definition 12.1.1 and Lemma 11.3.3. \square

12.3.4. PROPOSITION (extensions along fully faithful functors). If

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

is a pointwise right extension and k is fully faithful, then v is an isomorphism.

PROOF. Pasting the pointwise right extension with the exact square of Lemma 12.3.3 yields a pointwise right extension diagram

$$\begin{array}{ccc} A & \xrightarrow{f} & C \\ \parallel & \nearrow \uparrow v & \\ A & & \end{array}$$

By Lemma 11.3.5 and Theorem 12.2.7(iii), $f: A \rightarrow C$ also defines a pointwise right extension of itself along the identity. The universal property of these extension diagrams in \mathbf{hK} described in Definition 12.2.1 now suffices to construct an inverse isomorphism to v . \square

The dual result, that the 2-cell in a pointwise left extension along a fully faithful functor is invertible, is left to Exercise 12.3.i.

12.3.5. PROPOSITION. A right adjoint $u: A \rightarrow B$ is fully faithful if and only if the counit $\epsilon: fu \Rightarrow \text{id}_A$ is an isomorphism.

PROOF. If $f \dashv u$ with counit $\epsilon: fu \Rightarrow \text{id}_A$, then Proposition 4.1.1 reveals that pasting with ϵ induces an equivalence of modules $\mathbf{Hom}_B(B, u) \simeq \mathbf{Hom}_A(f, A)$. Equivalently, by Proposition 12.3.1, the counit $\epsilon: fu \Rightarrow \text{id}_A$ is exact. If u is fully faithful, then by Lemma 12.1.8 the composite rectangle is also exact.

$$\begin{array}{ccccc} & & A & & \\ & \lrcorner & & \lrcorner & \\ & A & & A & \\ & \searrow u & & \swarrow u & \\ A & & B & & A \\ \lrcorner & \epsilon & & & \lrcorner \\ A & & & & A \\ \lrcorner & & \lrcorner & & \\ & A & & A & \end{array}$$

which by Lemma 11.3.3 is to say that ϵ induces an equivalence of modules $\mathbf{Hom}_A(A, A) \simeq \mathbf{Hom}_A(fu, A)$ under the contravariant embedding of Definition 11.4.11. By Proposition 11.4.10, which says this embedding is fully faithful, it follows that $\epsilon: fu \Rightarrow \mathrm{id}_A$ is an isomorphism.

Conversely, assume $f \dashv u$ with invertible counit $\epsilon: fu \cong \mathrm{id}_A$. By Proposition 11.4.7 we have a composite $\mathbf{Hom}_B(B, u) \otimes \mathbf{Hom}_B(u, B) \simeq \mathbf{Hom}_B(u, u)$. Substituting the equivalence $\mathbf{Hom}_A(f, A) \simeq \mathbf{Hom}_B(B, u)$ gives another composite $\mathbf{Hom}_A(f, A) \otimes \mathbf{Hom}_B(u, B) \simeq \mathbf{Hom}_B(u, u)$, but now Corollary 11.4.8 gives a third composite $\mathbf{Hom}_A(f, A) \otimes \mathbf{Hom}_B(u, B) \simeq \mathbf{Hom}_A(fu, A)$. Factoring one composite through the other we obtain an equivalence $\mathbf{Hom}_A(fu, A) \simeq \mathbf{Hom}_B(u, u)$ which composes with the equivalence $\mathbf{Hom}_A \simeq \mathbf{Hom}_A(fu, A)$ induced by the invertible counit cell to define a composite $\mathbf{Hom}_A \simeq \mathbf{Hom}_A(fu, A) \simeq \mathbf{Hom}_B(u, u)$, proving, by Lemma 12.3.3, that $u: A \rightarrow B$ is fully faithful. \square

Exercises.

12.3.i. EXERCISE. Prove that if

$$\begin{array}{ccc} A & \xrightarrow{f} & C \\ k \downarrow & \Downarrow \lambda & \nearrow \ell \\ B & & \end{array}$$

is a pointwise left extension and k is fully faithful, then λ is an isomorphism.

12.4. Limits and colimits in cartesian closed ∞ -cosmoi

In this section we work in an ∞ -cosmos \mathcal{K} that is *cartesian closed*, satisfying the extra assumption of Definition 1.2.18. In a cartesian closed ∞ -cosmos a functor $f: A \rightarrow C$ transposes to define an element $f: 1 \rightarrow C^A$ of the ∞ -category of functors from A to C and a family of diagrams $f: A \times D \rightarrow C$ of shape A parametrized by an ∞ -category D transposes to a generalized element $f: D \rightarrow C^A$. The aim is to reinterpret the limits and colimits of §2.3 as pointwise right and left extensions.

12.4.1. PROPOSITION. Suppose the diagram below-left is a pointwise right extension diagram in a cartesian closed ∞ -cosmos.

$$\begin{array}{ccc} A \times D & \xrightarrow{f} & C \\ k \times D \downarrow & \Uparrow v & \nearrow r \\ B \times D & & \end{array} \quad \Leftrightarrow \quad \begin{array}{ccc} & & C^B \\ & \nearrow r & \downarrow C^k \\ D & \xrightarrow{f} & C^A \end{array}$$

Then its transpose above-right defines an absolute right lifting diagram in the homotopy 2-category which moreover is stable under pasting with the square C^ϕ induced from any exact square ϕ .

PROOF. The universal property that characterizes the absolute right lifting diagram

$$\begin{array}{ccc} X & \xrightarrow{e} & C^B \\ d \downarrow & \Downarrow \chi & \downarrow C^k \\ D & \xrightarrow{f} & C^A \end{array} = \begin{array}{ccc} X & \xrightarrow{e} & C^B \\ d \downarrow & \Downarrow \exists! \zeta & \nearrow r \\ D & \xrightarrow{f} & C^A \end{array} \quad \begin{array}{ccc} & & C^B \\ & \nearrow r & \downarrow C^k \end{array}$$

transposes to

$$\begin{array}{ccc}
 A \times X & \xrightarrow{A \times d} & A \times D \xrightarrow{f} C \\
 k \times X \downarrow & \Uparrow \chi & \\
 B \times X & \xrightarrow{e} &
 \end{array}
 =
 \begin{array}{ccc}
 A \times X & \xrightarrow{A \times d} & A \times D \xrightarrow{f} C \\
 k \times X \downarrow & k \times D \downarrow & \Uparrow \nu \\
 B \times X & \xrightarrow{B \times d} & B \times D \xrightarrow{\exists ! \zeta} C \\
 & \Uparrow \exists ! \zeta & \\
 & e &
 \end{array}$$

Similarly, the pasted composite of the absolute right lifting diagram with an exponentiated exact square transposes below-left to the diagram below-right

$$\begin{array}{ccc}
 & C^B & \xrightarrow{C^h} C^E \\
 r \nearrow & \downarrow C^k & \Downarrow C^\phi \downarrow C^q \\
 D & \xrightarrow{f} C^A & \xrightarrow{C^p} C^F
 \end{array}
 \iff
 \begin{array}{ccc}
 F \times D & \xrightarrow{p \times D} & A \times D \xrightarrow{f} C \\
 q \times D \downarrow & \Downarrow \phi \times D & k \times D \downarrow \Uparrow \nu \\
 E \times D & \xrightarrow{h \times D} & B \times D \xrightarrow{r} C
 \end{array}$$

Lemma 12.1.6 and Lemma 12.1.7 prove that the square defining the product $k \times d$ and the square $\phi \times D$ are exact.

Now if ν is a pointwise right extension, then by Lemma 12.1.6 and Corollary 12.2.8 so is $\nu \cdot (A \times d)$. The transposed universal property of this right extension diagram proves that ν defines an absolute right lifting. Since by Corollary 12.2.8, the pasted composite of ν with the exact square $\phi \times D$ gives another pointwise right extension, the same argument shows that the pasted composite of ν with E^ϕ is again an absolute right lifting diagram. \square

12.4.2. PROPOSITION. *In a cartesian closed ∞ -cosmos any limit as encoded by the absolute right lifting diagram below-right transposes to define a pointwise right extension diagram as below-left:*

$$\begin{array}{ccc}
 A & \xrightarrow{f} & C \\
 ! \downarrow & \Uparrow \nu \nearrow & \\
 1 & &
 \end{array}
 \iff
 \begin{array}{ccc}
 & C & \\
 \ell \nearrow & \downarrow \Delta & \\
 1 & \xrightarrow{f} & C^A
 \end{array}$$

Conversely, any pointwise right extension diagram of this form transposes to define a limit in C .

PROOF. The converse is a special case of Proposition 12.4.1, so it remains only to demonstrate that absolute right lifting diagrams of the form displayed above-right transpose to pointwise right extension diagrams as above-left. Comma squares over $! : A \rightarrow 1$ have the form

$$\begin{array}{ccccc}
 & & A \times X & & \\
 & \swarrow \pi & \downarrow \vee & \searrow \pi & \\
 A & & & & X \\
 & \searrow ! & & \swarrow ! & \\
 & & 1 & &
 \end{array}$$

We can show that the pasted composite of $v: \ell! \Rightarrow f$ with this square defines a right extension diagram in \mathbf{hK} by proving that the transposed diagram

$$\begin{array}{ccccc} & & C & \xrightarrow{\Delta} & C^X \\ & \nearrow \ell & \downarrow \Delta & & \downarrow C^\pi \\ 1 & \xrightarrow{f} & C^A & \xrightarrow{C^\pi} & C^{A \times X} \end{array}$$

defines a right lifting diagram. In fact, by transposing across the 2-adjunction $(-) \times X \dashv (-)^X$ on \mathbf{hK} of Proposition 1.4.5 this is easily seen to define an absolute right lifting diagram since $v: \Delta \ell \Rightarrow f$ is an absolute right lifting diagram. \square

12.4.3. COROLLARY. *For any pointwise right extension in a cartesian closed ∞ -cosmos*

$$\begin{array}{ccc} A & \xrightarrow{f} & C \\ k \downarrow & \nearrow \uparrow v & \uparrow r \\ B & & \end{array}$$

and any element $b: 1 \rightarrow B$, the element $rb: 1 \rightarrow C$ is the limit of the diagram

$$\mathrm{Hom}_B(b, k) \xrightarrow{p_1} A \xrightarrow{f} C$$

PROOF. By Theorem 12.2.7(ii), the composite

$$\begin{array}{ccccc} \mathrm{Hom}_B(b, k) & \xrightarrow{p_1} & A & \xrightarrow{f} & C \\ \downarrow ! & \nearrow \phi & \downarrow k & \nearrow \uparrow v & \uparrow r \\ 1 & \xrightarrow{b} & B & & \end{array}$$

is a pointwise right extension. By Proposition 12.4.2 this can be interpreted as saying that $rb: 1 \rightarrow C$ defines the limit of the restriction of the diagram $f: A \rightarrow C$ along $p_1: \mathrm{Hom}_B(b, k) \rightarrow A$. \square

Recall from Definition 2.4.6 that a functor $k: I \rightarrow J$ is **final** if and only if for any ∞ -category A , the square

$$\begin{array}{ccc} A & \xlongequal{\quad} & A \\ \Delta \downarrow & & \downarrow \Delta \\ A^J & \xrightarrow{A^k} & A^I \end{array}$$

preserves and reflects all absolute left lifting diagrams. Dually a functor $k: I \rightarrow J$ is **initial** if this square preserves and reflects all absolute right lifting diagrams. We can now give a more concise formulation of these notions.

12.4.4. DEFINITION. A functor $k: I \rightarrow J$ is **final** if and only if the square below-left is exact and **initial** if and only if the square below-right is exact.

$$\begin{array}{ccc} & I & \\ \downarrow ! & \searrow k & \\ 1 & & J \\ \parallel & \swarrow ! & \\ & 1 & \end{array} \quad \begin{array}{ccc} & I & \\ \swarrow k & \searrow ! & \\ J & & 1 \\ \downarrow ! & \swarrow ! & \\ & 1 & \end{array}$$

Note that the functor $!: J \rightarrow 1$ is represented on the right and on the left by the modules $J \xrightarrow{J} 1$ and $1 \xrightarrow{J} J$. So we see that $k: I \rightarrow J$ is **final** if and only if $p_0: \mathbf{Hom}_J(J, k) \rightrightarrows J$ is a trivial fibration, and $k: I \rightarrow J$ is **initial** if and only if $p_1: \mathbf{Hom}_J(k, J) \rightrightarrows J$ is a trivial fibration.

To reconcile Definition 12.4.4 with Definition 2.4.6 we must prove:

12.4.5. PROPOSITION. In a cartesian closed ∞ -cosmos, if $k: I \rightarrow J$ is initial and $f: J \rightarrow C$ is any diagram, then a limit of f also defines a limit of $fk: I \rightarrow C$ and conversely if the limit of $fk: I \rightarrow C$ exists, then it also defines a limit of $f: J \rightarrow C$.

PROOF. By Proposition 12.4.2, a limit of f defines a pointwise right extension as below left, which by Corollary 12.2.8 and Definition 12.4.4 gives rise to another pointwise right extension below-right.

$$\begin{array}{ccc} J & \xrightarrow{f} & C \\ \downarrow ! & \nearrow \ell & \\ 1 & & \end{array} \quad \begin{array}{ccccc} I & \xrightarrow{k} & J & \xrightarrow{f} & C \\ \downarrow ! & & \downarrow ! & \nearrow \ell & \\ 1 & = & 1 & & \end{array}$$

By Proposition 12.4.2 again, this tells us that ℓ is the limit of fk .

For the converse, suppose we are given a pointwise right extension diagram

$$\begin{array}{ccc} I & \xrightarrow{fk} & C \\ \downarrow ! & \nearrow \ell & \\ 1 & & \end{array}$$

By Theorem 12.2.7(iii), this universal property tells us that for any composable sequence of modules $E_1 \times \cdots \times E_n$ from 1 to C , composing with $\mu: \mathbf{Hom}_1(1, !) \times \mathbf{Hom}_C(C, \ell) \Rightarrow \mathbf{Hom}_C(C, fk)$ defines a bijection between cells $E_1 \times \cdots \times E_n \Rightarrow \mathbf{Hom}_C(C, \ell)$ and the cells below-left:

$$\begin{array}{ccc} I & \xrightarrow{\mathbf{Hom}_1(1, !)} 1 & \xrightarrow{E_1} \cdots \xrightarrow{E_n} C \\ \parallel & \Downarrow & \parallel \\ I & \xrightarrow{\mathbf{Hom}_C(C, fk)} & C \end{array} \quad \begin{array}{ccccccc} J & \xrightarrow{\mathbf{Hom}_J(k, J)} I & \xrightarrow{\mathbf{Hom}_1(1, !)} 1 & \xrightarrow{E_1} \cdots \xrightarrow{E_n} C \\ \parallel & & \Downarrow & & \parallel \\ J & \xrightarrow{\mathbf{Hom}_C(C, f)} & & & C \end{array}$$

By Corollary 11.4.6, composing with $\mu: \mathbf{Hom}_1(1, !) \times \mathbf{Hom}_C(C, \ell) \Rightarrow \mathbf{Hom}_C(C, fk)$ also defines a bijection between cells $E_1 \times \cdots \times E_n \Rightarrow \mathbf{Hom}_C(C, \ell)$ and the cells above-right.

To say that $k: I \rightarrow J$ is initial means, by Definition 12.4.4, that the map $\mathbf{Hom}_J(k, J) \times \mathbf{Hom}_1(1, !) \Rightarrow \mathbf{Hom}_1(1, !)$ of modules from J to 1 induced by the identity is a composite. Thus composing with

$\mu: \text{Hom}_1(1,!) \times \text{Hom}_C(C, \ell) \Rightarrow \text{Hom}_C(C, fk)$ also defines a bijection between cells $E_1 \times \cdots \times E_n \Rightarrow \text{Hom}_C(C, \ell)$ and the cells

$$\begin{array}{ccccc} J & \xrightarrow{\text{Hom}_1(1,!)} & 1 & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & C \\ \parallel & & & \Downarrow & & & \parallel \\ J & \xrightarrow{\text{Hom}_C(C, f)} & & & & & C \end{array}$$

But this says exactly that the cell $\nu: \text{Hom}_1(1,!) \times \text{Hom}_C(C, \ell) \Rightarrow \text{Hom}_C(C, f)$ that corresponds to μ under this series of bijections displays $1 \xrightarrow{\text{Hom}_C(C, \ell)} C$ as the right extension of $J \xrightarrow{\text{Hom}_C(C, f)} C$ along $J \xrightarrow{\text{Hom}_1(1,!)} 1$; unpacking this definition, we see that $\nu k = \mu$. Thus $\nu: \ell! \Rightarrow f$ is a pointwise right extension and by Proposition 12.4.2 we conclude that $\ell: 1 \rightarrow C$ also defines a limit of $f: J \rightarrow C$ as claimed. \square

12.4.6. DEFINITION. In a cartesian closed ∞ -cosmos \mathcal{K} , an ∞ -category E admits functorial pointwise right extensions along $k: A \rightarrow B$ if there is a pointwise right extension

$$\begin{array}{ccc} A \times E^A & \xrightarrow{\text{ev}} & E \\ k \times E^A \downarrow & \nearrow \text{rank} & \uparrow \epsilon \\ B \times E^A & & \end{array}$$

of the evaluation functor along $k \times E^A$.

By Proposition 12.4.1 if E admits functorial pointwise right extensions along $k: A \rightarrow B$, there is an absolute right lifting diagram

$$\begin{array}{ccc} & E^B & \\ \text{rank} \nearrow & & \downarrow \text{res} \\ E^A & \xlongequal{\quad} & E^A \end{array}$$

that is stable under pasting with E^ϕ for any exact square ϕ .

12.4.7. PROPOSITION (Beck-Chevalley condition). For any exact square

$$\begin{array}{ccc} & D & \\ q \swarrow & & \searrow p \\ C & \xleftarrow{\phi} & B \\ g \searrow & & \swarrow f \\ & A & \end{array}$$

in a cartesian closed ∞ -cosmos and any ∞ -category E , whenever E admits functorial pointwise left and right extensions, the Beck-Chevalley condition is satisfied for the induced 2-cell ϕ^* below-left: the mates of ϕ^* below

center and below right are both isomorphisms.

$$\begin{array}{ccccc}
 & E^A & & E^A & \\
 g^* \swarrow & & f^* \searrow & \text{rang} \nearrow & \nwarrow f^* \\
 E^C & \xleftarrow{\phi^*} & E^B & E^C & \xrightarrow{\phi^!} E^B \\
 q^* \searrow & & p^* \swarrow & q^* \searrow & \nearrow \text{ran}_p \\
 & E^D & & E^D &
 \end{array}
 \qquad
 \begin{array}{ccccc}
 & E^A & & E^A & \\
 g^* \swarrow & & \text{lan}_f \nwarrow & \text{rang} \nearrow & \nwarrow f^* \\
 E^C & \xleftarrow{\phi^!} & E^B & E^C & \xrightarrow{\phi^!} E^B \\
 \text{lan}_q \nwarrow & & p^* \swarrow & \text{lan}_q \nwarrow & \nearrow \text{ran}_p \\
 & E^D & & E^D &
 \end{array}$$

PROOF. By Proposition 12.4.1, the pointwise right extensions defining rang_g and ran_p transpose to define absolute right lifting diagrams

$$\begin{array}{ccc}
 & E^A & \xrightarrow{f^*} E^B \\
 \text{rang} \nearrow & \downarrow g^* & \downarrow \phi^* \downarrow p^* \\
 E^C & \xrightarrow{\epsilon} E^C & \xrightarrow{q^*} E^D
 \end{array}
 \qquad
 \begin{array}{ccc}
 & E^B & \\
 \text{ran}_p \nearrow & \downarrow p^* & \\
 E^C & \xrightarrow{q^*} E^D & \xrightarrow{\epsilon} E^D
 \end{array}$$

Moreover, the mate $\phi^!$ of ϕ^* defines a factorization of the left-hand diagram through the right-hand diagram:

$$\begin{array}{ccc}
 & E^A & \xrightarrow{f^*} E^B \\
 \text{rang} \nearrow & \downarrow g^* & \downarrow \phi^* \downarrow p^* \\
 E^C & \xrightarrow{\epsilon} E^C & \xrightarrow{q^*} E^D
 \end{array}
 =
 \begin{array}{ccc}
 & E^A & \xrightarrow{f^*} E^B \\
 \text{rang} \nearrow & \downarrow \phi^! & \nearrow \text{ran}_p \downarrow p^* \\
 E^C & \xrightarrow{q^*} E^D & \xrightarrow{\epsilon} E^D
 \end{array}$$

Immediately from the universal property of the absolute right liftings of q^* through p^* we have that $\phi^!$ is an isomorphism. The proof for $\phi_!$ is similar using the absolute left lifting diagrams arising from the pointwise left extensions defining lan_f and lan_q \square

Part IV

Change of model and model independence

CHAPTER 13

Cosmological biequivalences

In this chapter we study a certain class of cosmological functors between ∞ -cosmoi that do not merely preserve ∞ -categorical structure but also reflect and create it. We refer to these functors as *biequivalences* because the 2-functors they induce between homotopy 2-categories are biequivalences: surjective on objects up to equivalence and defining a local equivalence of hom-categories. Informally, we refer to cosmological biequivalences as “change-of-model functors.” For example, the four ∞ -cosmoi introduced in Example 1.2.19 whose objects model $(\infty, 1)$ -categories are connected by the following biequivalences briefly described in Example 1.3.7:

$$\begin{array}{ccc}
 CSS & \xrightarrow{\text{discretization}} & Segal \\
 \swarrow \text{row}_0 & & \searrow \text{row}_0 \\
 & \text{cylinder} \quad \text{prism} & \\
 & \searrow \quad \swarrow & \\
 & QCat & \\
 \uparrow U & \downarrow \downarrow & \\
 & 1-Comp &
 \end{array} \tag{13.0.1}$$

In §13.1, we collect together a number of results about cosmological functors that are scattered throughout the text. In §13.2, we introduce the special class of biequivalences and discuss several examples. Then in §13.3 we establish the basic 2-categorical properties of biequivalences, which will provide the essential ingredient in the proof of the model-independence results. We preview this line of reasoning in §13.4 before developing a more systematic approach to model-invariance in Chapter 14.

13.1. Cosmological functors

Recall from Definition 1.3.1 that a **cosmological functor** is a simplicial functor $F: \mathcal{K} \rightarrow \mathcal{L}$ between ∞ -cosmoi that preserves

- the specified classes of isofibrations and
- all of the simplicial limits enumerated in 1.2.1(i).

By Lemma 1.3.2, it follows that cosmological functors also preserve the equivalences and the trivial fibrations. By Corollary 7.3.3, cosmological functors preserve all flexible weighted limits, since Proposition 7.3.1 reveals that these can be constructed out of simplicial limits of diagrams of isofibrations of the form listed in 1.2.1(i).

Our aim in this section is to show that cosmological functors preserve all of the ∞ -categorical structures we have introduced. In many cases this will not be evident from the original 2-categorical definitions (eg of cartesian fibrations in Definition 5.1.6) but can be deduced rather easier from the accompanying “internal characterization” of each categorical notion (such as given in Theorem 5.1.11(iii)).

First, we orient ourselves to the main examples. Recall Proposition 1.3.3:

13.1.1. EXAMPLE (cosmological functors).

- (i) The nerve embedding defines a cosmological functor $Cat \hookrightarrow QCat$.
- (ii) For any object A in an ∞ -cosmos \mathcal{K} ,

$$\mathrm{Fun}(A, -): \mathcal{K} \rightarrow QCat$$

defines a cosmological functor.

- (iii) In particular, each ∞ -cosmos has an **underlying quasi-category** functor

$$(-)_0 := \mathrm{Fun}(1, -): \mathcal{K} \rightarrow QCat,$$

defined by mapping out of the terminal ∞ -category. We use the notation “ $(-)_0$ ” for this functor because the underlying quasi-categories of a complete Segal space or Segal category displayed in (13.0.1) are defined by evaluating these simplicial objects at 0 and because this notation for an “underlying category” is commonly used in enriched category theory (see Definition A.1.5).

- (iv) For any ∞ -cosmos \mathcal{K} and any simplicial set U , the simplicial cotensor defines a cosmological functor

$$(-)^U: \mathcal{K} \rightarrow \mathcal{K}.$$

- (v) For any object A in a cartesian closed ∞ -cosmos \mathcal{K} , exponentiation defines a cosmological functor

$$(-)^A: \mathcal{K} \rightarrow \mathcal{K}.$$

- (vi) For any map $f: A \rightarrow B$ in an ∞ -cosmos \mathcal{K} , pullback defines a cosmological functor

$$f^*: \mathcal{K}_{/B} \rightarrow \mathcal{K}_{/A}.$$

In the special case of the map $!: A \rightarrow 1$, the pullback cosmological functor has the form

$$- \times A: \mathcal{K} \rightarrow \mathcal{K}_{/A}.$$

- (vii) For any cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ and any $A \in \mathcal{K}$, the induced map on slices

$$F: \mathcal{K}_{/A} \rightarrow \mathcal{L}_{/FA}$$

defines a cosmological functor.

13.1.2. EXAMPLE. The inclusion of a replete sub ∞ -cosmos described in Proposition 7.4.6 is a cosmological functor. Examples include:

- (i) The full subcategory of discrete objects

$$\mathrm{Disc}(\mathcal{K}) \hookrightarrow \mathcal{K}$$

defines a replete sub ∞ -cosmos; see Proposition 1.2.22.

- (ii) The inclusions

$$\mathcal{K}_{\top} \hookrightarrow \mathcal{K} \leftarrow \mathcal{K}_{\perp}$$

of the ∞ -cosmoi of ∞ -categories possessing and functors preserving a terminal or initial element. More generally, the inclusions

$$\mathcal{K}_{\top, J} \hookrightarrow \mathcal{K} \leftarrow \mathcal{K}_{\perp, J}$$

of the ∞ -cosmoi of ∞ -categories possessing and functors preserving limits or colimits of shape J ; see Propositions 7.4.7 and 7.4.14.

(iii) The inclusions

$$\mathcal{R}ari(\mathcal{K})_{/B} \hookrightarrow \mathcal{K}_{/B} \hookleftarrow \mathcal{L}ari(\mathcal{K})_{/B}$$

or

$$\mathcal{R}ari(\mathcal{K}) \hookrightarrow \mathcal{K}^2 \hookleftarrow \mathcal{L}ari(\mathcal{K})$$

of ∞ -cosmoi whose objects are isofibrations admitting a right or left adjoint right inverse; see Corollary 7.4.10 and Proposition 7.4.12.

(iv) The inclusions

$$Cart(\mathcal{K})_{/B} \hookrightarrow \mathcal{K}_{/B} \hookleftarrow coCart(\mathcal{K})_{/B}$$

or

$$Cart(\mathcal{K}) \hookrightarrow \mathcal{K}^2 \hookleftarrow coCart(\mathcal{K})$$

of the ∞ -cosmoi of cartesian or cartesian fibrations and cartesian functors between them; see Proposition 7.4.15.

13.1.3. OBSERVATION. Inclusions $\mathcal{K}' \hookrightarrow \mathcal{K}$ and $\mathcal{L}' \hookrightarrow \mathcal{L}$ of replete sub ∞ -cosmoi create isofibrations and the simplicial limits of axiom 1.2.1(i). As these inclusions are full on positive-dimensional arrows, a simplicial functor

$$\begin{array}{ccc} \mathcal{K} & \xrightarrow{F} & \mathcal{L} \\ \uparrow & & \uparrow \\ \mathcal{K}' & \xrightarrow{F} & \mathcal{L}' \end{array}$$

restricts to a simplicial functor on the subcategories if and only if it carries the objects and 0-arrows of the subcategory \mathcal{K}' into the objects and 0-arrows of \mathcal{L}' , as will be the case whenever the replete sub ∞ -cosmoi are “naturally defined” by the same ∞ -categorical property. Whenever this is the case, the restricted functor is cosmological.

For example, by Proposition 5.1.20 and Exercise 5.1.iv, pullback $f^*: \mathcal{K}_{/B} \rightarrow \mathcal{K}_{/A}$ preserves cartesian fibrations and cartesian functors. Thus, pullback along any functor $f: A \rightarrow B$ in \mathcal{K} restricts to define a cosmological functor:

$$\begin{array}{ccc} \mathcal{K}_{/B} & \xrightarrow{f^*} & \mathcal{K}_{/A} \\ \uparrow & & \uparrow \\ Cart(\mathcal{K})_{/B} & \xrightarrow{f^*} & Cart(\mathcal{K})_{/A} \end{array}$$

13.1.4. EXAMPLE. There are also cosmological functors connecting the ∞ -cosmoi of “Reedy fibrant diagrams.”

(i) By Proposition 7.4.1, the domain, codomain, and identity functors

$$\mathcal{K}^2 \begin{array}{c} \xrightarrow{\text{dom}} \\ \xleftarrow{\text{id}} \\ \xrightarrow{\text{cod}} \end{array} \mathcal{K}$$

are all cosmological.

(ii) By Exercise 11.1.i, the domain and codomain functors

$$\mathcal{K}^{\bowtie} \begin{array}{c} \xrightarrow{\text{dom}} \\ \xrightarrow{\text{cod}} \end{array} \mathcal{K}$$

from the ∞ -cosmos of two-sided isofibrations are cosmological.

Cosmological functors may fail dramatically to be surjective on objects — $\text{id}: \mathcal{K} \rightarrow \mathcal{K}^2$ comes to mind. Thus a 2-categorical property involving a universal quantifier is not obviously preserved. For instance, by Definition 1.2.21 an object $E \in \mathcal{K}$ is **discrete** just when for all $X \in \mathcal{K}$, $\text{Fun}(X, E)$ is a Kan complex. However, by Exercise 1.2.iv, which we belatedly solve, discrete objects admit an internal characterization given in (iv) below:

13.1.5. PROPOSITION. *An object E in an ∞ -cosmos \mathcal{K} is discrete if the following equivalent conditions are satisfied:*

- (i) E is a discrete object in the homotopy 2-category $\mathbf{h}\mathcal{K}$, that is, every 2-cell with codomain E is invertible.
- (ii) For each $X \in \mathcal{K}$, the hom-category $\mathbf{h}\text{Fun}(X, E)$ is a groupoid.
- (iii) For each $X \in \mathcal{K}$, the mapping quasi-category $\text{Fun}(X, E)$ is a Kan complex.
- (iv) The isofibration $E^{\mathbb{I}} \twoheadrightarrow E^2$, induced by the inclusion of simplicial sets $\mathbb{2} \hookrightarrow \mathbb{I}$, is a trivial fibration.

PROOF. Here (ii) is an unpacking of (i). The equivalence of (ii) and (iii) is a well-known result of Joyal [24, 1.4] reproduced in Corollary 1.1.15. Condition (iv) is equivalent to the assertion that $\text{Fun}(X, E)^{\mathbb{I}} \twoheadrightarrow \text{Fun}(X, E)^2$ is a trivial fibration between quasi-categories for all X . If this is a trivial fibration, then surjectivity on vertices implies that every 1-simplex in $\text{Fun}(X, E)$ is an isomorphism, proving (iii). By Exercise 1.1.iv, $\mathbb{2} \hookrightarrow \mathbb{I}$ is in the class of maps cellularly generated by the outer horn inclusions, so (iii) implies (iv). \square

Note that if E is discrete, then any equivalent object E' is also discrete. Now the result we want is easy to establish.

13.1.6. COROLLARY. *Cosmological functors preserve discrete objects.*

PROOF. If $E \in \mathcal{K}$ is discrete and $F: \mathcal{K} \rightarrow \mathcal{L}$ is cosmological, then

$$F(E^{\mathbb{I}} \twoheadrightarrow E^2) \cong (FE)^{\mathbb{I}} \twoheadrightarrow (FE)^2$$

is a trivial fibration in \mathcal{L} , proving that FE is discrete by Proposition 13.1.5(iv). \square

Importantly:

13.1.7. PROPOSITION. *Cosmological functors preserve comma ∞ -categories: if $F: \mathcal{K} \rightarrow \mathcal{L}$ is a cosmological functor and the diagram below-left*

$$\begin{array}{ccc} & E & \\ e_1 \swarrow & & \searrow e_0 \\ C & \xleftarrow{\epsilon} & B \\ g \searrow & & \swarrow f \\ & A & \end{array} \quad \xrightarrow{F} \quad \begin{array}{ccc} & FE & \\ Fe_1 \swarrow & & \searrow Fe_0 \\ FC & \xleftarrow{F\epsilon} & FB \\ Fg \searrow & & \swarrow Ff \\ & FA & \end{array} \quad (13.1.8)$$

is a comma cone in \mathcal{K} , then the diagram above-right is a comma cone in \mathcal{L} .

PROOF. The simplicial pullback (3.3.2) that constructs the comma cone is preserved by any cosmological functor. By Proposition 3.3.11, any comma cone as above left arises from a fibered equivalence $e: E \simeq \text{Hom}_A(f, g)$ where $\epsilon = \phi e$, and any fibered equivalence of this form defines a comma cone. Since $Fe: FE \simeq F(\text{Hom}_A(f, g)) \cong \text{Hom}_{FA}(Ff, Fg)$, we conclude that the right-hand data again defines a comma cone. \square

Using Proposition 13.1.7, we can quickly establish the following preservation properties of cosmological functors by arguing along similar lines to Corollary 13.1.6. For ease of reference, we include on this list the preservation properties that have been previously established.

13.1.9. PROPOSITION. *Cosmological functors preserve:*

- (i) *Equivalences between ∞ -categories.*
- (ii) *Adjunctions between ∞ -categories, including right adjoint right inverse adjunctions and left adjoint right inverse adjunctions.*
- (iii) *Invertible 2-cells and mates.*
- (iv) *Homotopy coherent adjunctions and monads.*
- (v) *Trivial fibrations and discrete objects.*
- (vi) *Flexible weighted limits.*
- (vii) *Comma spans and comma cones.*
- (viii) *Absolute right and left lifting diagrams.*
- (ix) *Limits or colimits of diagrams indexed by a simplicial set J inside an ∞ -category.*
- (x) *Cartesian and cocartesian fibrations and cartesian functors between them.*
- (xi) *Discrete cartesian fibrations and discrete cocartesian fibrations.*
- (xii) *Two-sided fibrations and cartesian functors between them and also modules.*
- (xiii) *Modules and represented modules.*

PROOF. Lemma 1.3.2 proves that cosmological functors preserve equivalences between ∞ -categories since these can be characterized as 2-categorical equivalences, which are preserved by any 2-functor. Similarly, as observed in Lemma 2.1.3, adjunctions are preserved by any 2-functor, as are invertible 2-cells and mates. In the same way, homotopy coherent adjunctions are preserved by any simplicial functor. So the preservation properties (ii), (iii) and (iv) hold under much weaker hypotheses.

The preservation of trivial fibrations was also established in Lemma 1.3.2 and Corollary 13.1.6 uses this to prove that discrete objects are also preserved, proving (v). Corollary 7.3.3 proves that cosmological functors preserve all flexible weighted limits as stated in (vi). Proposition 13.1.7 proves that cosmological functors preserve comma spans in the ∞ -cosmos and comma cones in the homotopy 2-category as stated in (vii).

The preservation property (viii) follows from Theorem 3.4.3, which characterizes absolute lifting diagrams as fibered equivalences of comma ∞ -categories, Proposition 13.1.7, which says that cosmological functors preserve commas, and the fact that cosmological functors preserve equivalences. Now (ix) follows from this by Definition 2.3.7 and the fact that cosmological functors preserve simplicial tensors.

The preservation properties (x) and (xi) also follow from Proposition 13.1.7 and the fact that cosmological functors preserve right or left adjoint right inverse adjunctions, mates, and trivial fibrations via the characterizations of Theorem 5.1.11(iii), Theorem 5.1.19(iii), and Proposition 5.4.6. More details are given in the proof of Corollary 5.1.16, which also observes that cartesian natural transformations are preserved by cosmological functors.

Directly from the internal characterization of Theorem 10.1.4 and the preservation of adjunctions and invertible 2-cells, cartesian functors preserve two-sided fibrations; preservation of cartesian functors between them is left to Exercise 13.1.i. This establishes (xii). By Proposition 1.3.3(vi), a cosmological functor induces a direct image cosmological functor between sliced ∞ -cosmoi, which then preserves discrete objects by Corollary 13.1.6. Thus, modules are also preserved. By specializing Proposition 13.1.7 to cospans involving identities, it becomes clear that left and right representable commas

are preserved. Since a module is representable if and only if it is fibered equivalent to one of these, representable modules are preserved as well, completing the proof of (xiii). \square

13.1.10. NON-EXAMPLE. The composite of the underlying quasi-category functor with the homotopy category functor

$$\mathcal{K} \xrightarrow{(-)_0} \mathcal{QCat} \xrightarrow{\mathbf{h}} \mathcal{Cat}$$

defines a simplicial functor that carries an ∞ -category A to its homotopy category $\mathbf{h}A$ first introduced in Definition 1.4.12. This functor does preserve isofibrations but does not preserve simplicial cotensors and so is not cosmological. This is a good thing because if it were Proposition 13.1.9(ix) would imply that limits in an ∞ -category would also define limits in its homotopy category, which is not generally true.

Exercises.

13.1.i. EXERCISE. Prove that any cosmological functor preserves cartesian functors between two-sided fibrations. Conclude that any cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ induces a cosmological functor $F: {}_{A\backslash} \mathcal{Fib}(\mathcal{K})_{/B} \rightarrow {}_{FA\backslash} \mathcal{Fib}(\mathcal{L})_{/FB}$.

13.2. Biequivalences of ∞ -cosmoi as change-of-model functors

Special cosmological functors, called *biequivalences*, preserve and also reflect the category theory developed in this text. Recall Definition 1.3.5:

13.2.1. DEFINITION (cosmological biequivalences). A cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ is a **biequivalence** when it is:

- (i) surjective on objects up to equivalence: i.e., if for all $C \in \mathcal{L}$ there exists $A \in \mathcal{K}$ so that $FA \simeq C$; and
- (ii) a local equivalence of quasi-categories: i.e., if for every pair $A, B \in \mathcal{K}$, the map

$$\mathrm{Fun}(A, B) \xrightarrow{\sim} \mathrm{Fun}(FA, FB)$$

is an equivalence of quasi-categories.

More generally, two ∞ -cosmoi are **biequivalent** if there exists a finite zig-zag of biequivalences connecting them.

13.2.2. EXAMPLE (biequivalences between ∞ -cosmoi of $(\infty, 1)$ -categories). In Appendix E, we will show that the functors (13.0.1) are all biequivalences. Except for the functor $\mathfrak{h}: \mathcal{QCat} \rightarrow 1\text{-Comp}$, each of the functors (13.0.1) arises from a simplicially enriched right Quillen equivalence between model categories enriched over the Joyal model structure with all objects cofibrant. Functors of this form are easily seen to encode cosmological biequivalences.

Recall that any ∞ -cosmos has an **underlying quasi-category functor**

$$\mathcal{K} \xrightarrow{(-)_0 := \mathrm{Fun}(1, -)} \mathcal{QCat}$$

defined by mapping out of the terminal ∞ -category. We now show that for every ∞ -cosmos that is biequivalent to \mathcal{QCat} , its underlying quasi-category functor is a biequivalence.

13.2.3. PROPOSITION. *If an ∞ -cosmos \mathcal{K} is biequivalent to \mathcal{QCat} , then the underlying quasi-category functor $(-)_0: \mathcal{K} \rightarrow \mathcal{QCat}$ is a cosmological biequivalence.*

PROOF. We will show that in the presence of cosmological biequivalences

$$\mathcal{K} \xleftarrow[\sim]{G} \mathcal{L} \xrightarrow[\sim]{F} \mathcal{QCat}$$

the underlying quasi-category functor $(-)_0: \mathcal{K} \rightarrow \mathcal{QCat}$ is a cosmological biequivalence. By induction, perhaps taking one of these functors to be the identity, the same conclusion holds for any ∞ -cosmos connected by a finite zig-zag of biequivalences to \mathcal{QCat} .

As F is a biequivalence, for each quasi-category Q , there exists an ∞ -category $B \in \mathcal{L}$ so that $FB \simeq Q$. Because F and G are both local equivalences preserving the terminal ∞ -category 1 (for which we adopt the same notation in each of \mathcal{K} , \mathcal{L} , and \mathcal{QCat}), there is then a zig-zag of equivalences of quasi-categories

$$(GB)_0 = \text{Fun}(1, GB) \xleftarrow{\sim} \text{Fun}(1, B) \xrightarrow{\sim} \text{Fun}(1, FB) \cong FB \simeq Q.$$

This proves that there exists an ∞ -category $GB \in \mathcal{K}$ whose underlying quasi-category is equivalent to Q .

To show that the underlying quasi-category functor $(-)_0: \mathcal{K} \rightarrow \mathcal{QCat}$ is a local equivalence, consider a pair of ∞ -categories $A, B \in \mathcal{K}$. By essential surjectivity of G , there exist ∞ -categories $X, Y \in \mathcal{L}$ so that $GX \simeq A$ and $B \simeq GY$. By pre- and post-composing with these equivalences, Corollary 1.4.9 implies that $\text{Fun}(A, B) \rightarrow \text{Fun}(A_0, B_0)$ is equivalent to $\text{Fun}(GX, GY) \rightarrow \text{Fun}((GX)_0, (GY)_0)$, so it suffices to prove that the latter map is an equivalence of quasi-categories.

By simplicial functoriality of the local equivalences F and G , there is a commutative diagram whose vertical maps are equivalences

$$\begin{array}{ccc} \text{Fun}(GX, GY) & \longrightarrow & \text{Fun}(\text{Fun}(1, GX), \text{Fun}(1, GY)) \\ \uparrow \wr & & \downarrow \wr \\ & & \text{Fun}(\text{Fun}(1, X), \text{Fun}(1, GY)) \\ & & \uparrow \wr \\ \text{Fun}(X, Y) & \longrightarrow & \text{Fun}(\text{Fun}(1, X), \text{Fun}(1, Y)) \\ \downarrow \wr & & \downarrow \wr \\ & & \text{Fun}(\text{Fun}(1, X), \text{Fun}(1, FY)) \\ & & \uparrow \wr \\ \text{Fun}(FX, FY) & \xrightarrow{\cong} & \text{Fun}(\text{Fun}(1, FX), \text{Fun}(1, FY)) \end{array}$$

Any quasi-category is isomorphic to its underlying quasi-category, so the bottom horizontal map is an isomorphism. By the 2-of-3 property, it follows that the top horizontal map is an equivalence, which is what we wanted to show. \square

Recall from Proposition 1.3.3(vi) that a cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ induces a cosmological functor $F: \mathcal{K}_B \rightarrow \mathcal{L}_{FB}$ for any $B \in \mathcal{K}$.

13.2.4. PROPOSITION. *If $F: \mathcal{K} \rightarrow \mathcal{L}$ is a cosmological biequivalence, then for any $B \in \mathcal{K}$ the induced functor $F: \mathcal{K}_B \rightarrow \mathcal{L}_{FB}$ is also a cosmological biequivalence.*

PROOF. We first argue that the F defines a local equivalence of sliced mapping quasi-categories, as defined in Proposition 1.2.17(ii). Given a pair of isofibration $p: E \twoheadrightarrow B$ and $p': E' \twoheadrightarrow B$ in \mathcal{K} , the

induced functor on mapping quasi-categories is defined by

$$\begin{array}{ccccc}
 \text{Fun}_B(p, p') & \xrightarrow{\quad} & \text{Fun}(E, E') & & \\
 \downarrow & \dashrightarrow & \downarrow & \searrow & \\
 & \text{Fun}_{FB}(Fp, Fp') & \xrightarrow{\quad} & \text{Fun}(FE, FE') & \\
 & \downarrow & \downarrow & \downarrow & \\
 1 & \xrightarrow{\quad} & \text{Fun}(E, B) & \xrightarrow{\quad} & \text{Fun}(FE, FB) \\
 & \searrow & \searrow & & \\
 & 1 & & &
 \end{array}$$

As the maps between the cospans in \mathcal{QCat} are equivalences, so is the induced map between the pull-backs.

For surjectivity up to equivalence, consider an isofibration $q: L \twoheadrightarrow FB$ in \mathcal{L} . As F is surjective on objects up to equivalence, there exists some $A \in \mathcal{K}$ together with an equivalence $i: FA \xrightarrow{\sim} L \in \mathcal{L}$. As F defines a local equivalence of mapping quasi-categories, there is moreover a functor $f: A \rightarrow B$ in \mathcal{L} so that $Ff: FA \rightarrow FB$ is isomorphic to qi in $\mathfrak{h}\mathcal{L}$. The map f need not be an isofibration, but Lemma 1.2.12 allows us to factor f as $A \xrightarrow{p} K \xrightarrow{j} B$. Choosing an equivalence inverse $j: K \xrightarrow{\sim} A$, this data defines a diagram in $\mathfrak{h}\mathcal{L}$ that commutes up to isomorphism:

$$\begin{array}{ccccc}
 FK & \xrightarrow{Fj} & FA & \xrightarrow{i} & L \\
 \searrow & \cong & \downarrow & \cong & \swarrow \\
 & Fp & Ff & q & \\
 & & FB & &
 \end{array}$$

Proposition 1.4.10 tells us that isofibrations in ∞ -cosmoi define isofibrations in the homotopy 2-category. In particular, we may lift the displayed isomorphism along the isofibration $q: L \twoheadrightarrow FB$ to define a commutative triangle:

$$\begin{array}{ccccc}
 FK & \xrightarrow{Fj} & FA & \xrightarrow{i} & L \\
 \searrow & \cong & \downarrow & \cong & \swarrow \\
 & Fp & Ff & q & \\
 & & FB & &
 \end{array}
 =
 \begin{array}{ccc}
 & i \cdot Fj & \\
 FK & \xrightarrow{\quad} & L \\
 \searrow & \cong & \swarrow \\
 & e & \\
 FK & \xrightarrow{Fp} & FB & \xrightarrow{q} & L
 \end{array}$$

As noted in the proof of Theorem 1.4.7, since e is isomorphic to an equivalence $i \cdot Fj$, it must also define an equivalence. Thus, by Proposition 1.2.17(vii), we have shown that the isofibration $p: K \twoheadrightarrow B$ maps under F to an isofibration that is equivalent to our chosen $q: L \twoheadrightarrow FB$. \square

A similar argument proves that a cosmological biequivalence induces a biequivalence between the corresponding ∞ -cosmoi of isofibrations of Proposition 7.4.1.

13.2.5. PROPOSITION. *If $F: \mathcal{K} \rightarrow \mathcal{L}$ is a cosmological biequivalence then the induced functor $F: \mathcal{K}^2 \rightarrow \mathcal{L}^2$ is a biequivalence.*

PROOF. Exercise 13.2.i. \square

To establish another family of biequivalences of sliced ∞ -cosmoi, we require a general lemma:

13.2.6. LEMMA. *In any ∞ -cosmos, the pullback of an equivalence along an isofibration is an equivalence.*

$$\begin{array}{ccc} P & \xrightarrow{g} & E \\ q \downarrow & \lrcorner & \downarrow p \\ A & \xrightarrow[\sim]{f} & B \end{array}$$

PROOF. The map $g: P \rightarrow E$ is an equivalence if and only if $g_*: \mathbf{Fun}(X, P) \rightarrow \mathbf{Fun}(X, E)$ is an equivalence of quasi-categories for all X . By the simplicial universal property of the pullback P , this map g_* is the pullback of the equivalence $f_*: \mathbf{Fun}(X, A) \xrightarrow{\sim} \mathbf{Fun}(X, B)$ along the isofibration $p_*: \mathbf{Fun}(X, E) \rightarrow \mathbf{Fun}(X, B)$. Thus, it suffices to prove this result for quasi-categories, where a number of proofs are available. One invokes a standard bit of model category theory: in any model category, the pullback of any weak equivalence between fibrant objects along a fibration is a weak equivalence (see for instance [41, 15.4.2]). An alternate approach, left to the reader is to use Lemma 3.1.5 and the isomorphism lifting property to directly lift the data of an equivalence from f to g . \square

13.2.7. PROPOSITION. *If $f: A \xrightarrow{\sim} B$ is an equivalence in \mathcal{K} , then the pullback functor $f^*: \mathcal{K}_B \rightarrow \mathcal{K}_A$ is a cosmological biequivalence.*

PROOF. To see that $f^*: \mathcal{K}_B \rightarrow \mathcal{K}_A$ is essentially surjective, consider an object $r: D \twoheadrightarrow A$, factor the composite map $fr: D \rightarrow B$ as an equivalence followed by an isofibration, and pull the result back along f .

$$\begin{array}{ccccc} & & D & \xrightarrow{\sim} & E \\ & \searrow & \downarrow & & \downarrow \\ & & P & \xrightarrow{\sim} & E \\ & \searrow & q \downarrow & \lrcorner & \downarrow p \\ & & A & \xrightarrow[\sim]{f} & B \end{array}$$

(Note: In the original image, there is a dashed arrow from D to P and a curved arrow from D to A labeled r. The diagram above captures the essential structure with a curved arrow from D to A labeled r.)

By Lemma 13.2.6, the pullback of f is an equivalence, so by the 2-of-3 property, r is equivalent to the isofibration $q: P \twoheadrightarrow A$, which is in the image of $f^*: \mathcal{K}_B \rightarrow \mathcal{K}_A$.

To show that this simplicial functor is a local equivalence, consider a pair of isofibrations $p: E \twoheadrightarrow B$ and $q: F \twoheadrightarrow B$. We will show that the quasi-category of functors over B is equivalent to the quasi-category of functors over A between their pullbacks

$$\begin{array}{ccccc} f^*E & \xrightarrow[\sim]{h} & E \\ \downarrow r & \lrcorner & \downarrow p \\ f^*F & \xrightarrow[\sim]{k} & F \\ \downarrow s & \lrcorner & \downarrow q \\ A & \xrightarrow[\sim]{\tilde{f}} & B \end{array}$$

To define the comparison map $\text{Fun}_B(E, F) \rightarrow \text{Fun}_A(f^*E, f^*F)$ consider the following commutative prism

$$\begin{array}{ccccc}
 & \text{Fun}_B(E, F) & \xrightarrow{\quad} & \text{Fun}(E, F) & \\
 & \downarrow \lrcorner & & \downarrow q_* & \\
 \text{Fun}_A(f^*E, f^*F) & \xrightarrow{\quad} & \text{Fun}(f^*E, f^*F) & \xrightarrow{k_*} & \text{Fun}(f^*E, F) \\
 \downarrow & \lrcorner & \downarrow s_* & \lrcorner & \downarrow q_* \\
 \mathbb{1} & \xrightarrow{r} & \text{Fun}(f^*E, A) & \xrightarrow{f_*} & \text{Fun}(f^*E, B) \\
 & \lrcorner & & \lrcorner & \downarrow h^* \\
 & & & & \text{Fun}(E, B)
 \end{array}$$

The front-right square is a pullback by the simplicial universal property of f^*F , while the front-left square and back face are the pullbacks that define $\text{Fun}_A(f^*E, f^*F)$ and $\text{Fun}_B(E, F)$. The universal property of the composite front pullback rectangle induces the map $\text{Fun}_B(E, F) \rightarrow \text{Fun}_A(f^*E, f^*F)$. As this functor is the pullback of the equivalences h^* of Corollary 1.4.9, the induced map defines an equivalence of quasi-categories. \square

Exercises.

13.2.i. EXERCISE. Prove Proposition 13.2.5.

13.2.ii. EXERCISE. Give a second proof of Lemma 13.2.6 that directly constructs an inverse equivalence to the pullback of an equivalence in any ∞ -cosmos.

13.2.iii. EXERCISE. If $F: \mathcal{K} \rightleftarrows \mathcal{L}$ is a biequivalence and $A \in \mathcal{K}$ and $B \in \mathcal{L}$ are so that $FA \simeq B$ prove that the slice ∞ -cosmoi $\mathcal{K}_{/A}$ and $\mathcal{L}_{/B}$ are biequivalent.

13.3. Properties of change-of-model functors

We refer to biequivalence between ∞ -cosmoi as *change-of-model functors*. In this section, we enumerate their basic properties. First, we observe that cosmological biequivalences descend to biequivalences between homotopy 2-categories, hence the name:

13.3.1. PROPOSITION. A cosmological biequivalence $F: \mathcal{K} \rightarrow \mathcal{L}$ induces a biequivalence $F: \mathfrak{h}\mathcal{K} \rightarrow \mathfrak{h}\mathcal{L}$ of homotopy 2-categories: i.e., the 2-functor F is

- (i) surjective on objects up to equivalence and
- (ii) defines a local equivalence of categories $\mathfrak{h}\text{Fun}(A, B) \rightleftarrows \mathfrak{h}\text{Fun}(FA, FB)$ for all $A, B \in \mathcal{K}$.

PROOF. This is immediate from the definition: Theorem 1.4.7 observed that ∞ -cosmos-level equivalences coincide with 2-categorical equivalences, and by Lemma 1.2.15 the homotopy category functor $\mathfrak{h}: \mathcal{QCat} \rightarrow \mathcal{Cat}$ carries equivalences of quasi-categories to equivalences of categories. \square

Any biequivalence between 2-categories induces a variety of local and global bijections, as enumerated below, which can be put to use to solve Exercise 13.3.i.

13.3.2. COROLLARY. Consider any cosmological biequivalence $F: \mathcal{K} \rightarrow \mathcal{L}$.

- (i) The biequivalence F preserves, reflects, and creates equivalences between ∞ -categories, and induces a bijection between equivalence classes of objects.

- (ii) The biequivalence F induces local bijections between isomorphism classes of functors extending the bijection of (i): choosing any pairs of objects $A, B \in \mathcal{K}$ and $A', B' \in \mathcal{L}$ and equivalences $FA \simeq A'$ and $FB \simeq B'$, the map

$$\mathbf{hFun}(A, B) \simeq \mathbf{hFun}(FA, FB) \simeq \mathbf{hFun}(A', B') \quad (13.3.3)$$

defines a bijection between isomorphism classes of functors $A \rightarrow B$ in \mathcal{K} and isomorphism classes of functors $A' \rightarrow B'$ in \mathcal{L} .

- (iii) The biequivalence F induces local bijections between 2-cells with specified boundary extending the bijections of (i) and (ii): choosing any pairs of objects $A, B \in \mathcal{K}$ and $A', B' \in \mathcal{L}$, equivalences $FA \simeq A'$ and $FB \simeq B'$, functors $f, g: A \rightrightarrows B$ and $f', g': A' \rightrightarrows B'$, and natural isomorphisms

$$\begin{array}{ccc} FA & \xrightarrow{Ff} & FB \\ \wr \downarrow & \cong \alpha & \downarrow \wr \\ A' & \xrightarrow{f'} & B' \end{array} \quad \begin{array}{ccc} FA & \xrightarrow{Fg} & FB \\ \wr \downarrow & \cong \beta & \downarrow \wr \\ A' & \xrightarrow{g'} & B' \end{array}$$

the map (13.3.3) induces a bijection between 2-cells $f \Rightarrow g$ in \mathcal{K} and 2-cells $f' \Rightarrow g'$ in \mathcal{L} .

PROOF. For (i), any 2-functor preserves equivalences, so our first take is to show that equivalences are also reflected. If $f: A \rightarrow B$ is a morphism so that $Ff: FA \rightrightarrows FB$ is an equivalence then by the 2-of-3 property and the commutative diagram

$$\begin{array}{ccc} \mathbf{Fun}(X, A) & \xrightarrow{f_*} & \mathbf{Fun}(X, B) \\ \wr \downarrow & & \downarrow \wr \\ \mathbf{Fun}(FX, FA) & \xrightarrow[\sim]{Ff_*} & \mathbf{Fun}(FX, FB) \end{array}$$

f_* is an equivalence for all X , proving that $f: A \rightarrow B$ is an equivalence.

To prove that equivalences are also created — meaning that if $FA \simeq FB$ then $A \simeq B$ — note that the equivalence $\mathbf{Fun}(A, B) \simeq \mathbf{Fun}(FA, FB)$ implies that any morphism $FA \rightarrow FB$ has a lift $A \rightarrow B$ up to isomorphism. In this way, the morphisms of an equivalence $f: FA \rightrightarrows FB$ and $g: FB \rightrightarrows FA$ can be lifted to morphisms $\tilde{f}: A \rightarrow B$ and $\tilde{g}: B \rightarrow A$ so that $\tilde{g}\tilde{f}$ and id_A have isomorphic images under the equivalence $\mathbf{Fun}(A, A) \simeq \mathbf{Fun}(FA, FA)$. Since an equivalence of quasi-categories induces a bijection on isomorphism classes of vertices, we conclude that $\tilde{g}\tilde{f} \cong \mathrm{id}_A \in \mathbf{Fun}(A, A)$. Similarly, $\tilde{f}\tilde{g}$ and id_B have isomorphic images under $\mathbf{Fun}(B, B) \simeq \mathbf{Fun}(FB, FB)$ and thus $\tilde{f}\tilde{g} \cong \mathrm{id}_B$, proving that $A \simeq B$.

Finally, the preservation, reflection, and creation of equivalences together with essential surjectivity of a cosmological biequivalence implies that such functors induces a bijection on equivalence classes of objects.

For (ii), by Corollary 1.4.9, the chosen equivalences $FA \simeq A'$ and $FB \simeq B'$ induce an equivalence of quasi-categories

$$\mathbf{Fun}(A, B) \xrightarrow{\sim} \mathbf{Fun}(FA, FB) \xrightarrow{\sim} \mathbf{Fun}(A', B')$$

which descends to the equivalence of homotopy categories (13.3.3). Since equivalences of quasi-categories induce bijections between isomorphism classes of vertices, this yields in particular a bijection between isomorphism classes of functors.

For (iii), the equivalence (13.3.3) is full and faithful, inducing a bijection between cells $f \Rightarrow g$ and $Ff \Rightarrow Fg$. This bijection can be transported along any chosen isomorphisms α and β to yield a bijection between natural transformations $f \Rightarrow g$ in $\mathbf{hFun}(A, B)$ in \mathcal{K} and natural transformations $f' \Rightarrow g'$ in $\mathbf{hFun}(A', B')$ in \mathcal{L} . \square

As an application of Corollary 13.3.2, we now show that the internal hom B^A between ∞ -categories A and B in a cartesian closed ∞ -cosmos \mathcal{K} that is biequivalent to \mathbf{QCat} is equivalent to the simplicial cotensor B^{A_0} of B with the underlying quasi-category of A . Even if \mathcal{K} is not cartesian closed as an ∞ -cosmos, on account of the biequivalence $(-)_0: \mathcal{K} \rightarrow \mathbf{QCat}$ of Proposition 13.2.3, its homotopy 2-category $\mathbf{h}\mathcal{K}$ is cartesian closed in the bicategorical sense, replacing the natural isomorphisms of Proposition 1.4.5(ii) with natural equivalences: we define $B^A \in \mathcal{K}$ to be any ∞ -category whose underlying quasi-category is $B_0^{A_0}$. By the 2-of-3 property for equivalences

$$\begin{array}{ccc} \mathrm{Fun}(X, B^A) & \xrightarrow{\sim} & \mathrm{Fun}(X_0, B_0^{A_0}) \\ \downarrow \wr & & \downarrow \wr \\ \mathrm{Fun}(X \times A, B) & \xrightarrow{\sim} & \mathrm{Fun}(X_0 \times A_0, B_0) \end{array}$$

we see that $\mathrm{Fun}(X, B^A) \simeq \mathrm{Fun}(X \times A, B)$ for any X . For this reason, the statement of Proposition 13.3.4 does not require that \mathcal{K} is cartesian closed as an ∞ -cosmos; the exponentials can be inferred to exist a posteriori.

13.3.4. PROPOSITION. *Suppose \mathcal{K} is an ∞ -cosmos that is biequivalent to \mathbf{QCat} . Then for any ∞ -categories $A, B \in \mathcal{K}$, the exponential $B^A \simeq B^{A_0}$ is equivalent to the cotensor of B with the underlying quasi-category of A .*

PROOF. By Corollary 13.3.2(i), cosmological biequivalences reflect equivalences of ∞ -categories. Thus, to prove $B^A \simeq B^{A_0}$, it suffices by Proposition 13.2.3 and Corollary 13.3.2 to prove that B^A and B^{A_0} have equivalent underlying quasi-categories. The defining universal properties of the exponential and cotensor provide equivalences

$$\mathrm{Fun}(1, B^A) \simeq \mathrm{Fun}(A, B) \xrightarrow{\sim} \mathrm{Fun}(A_0, B_0) \cong \mathrm{Fun}(1, B^{A_0})$$

which compose with the local equivalence of the underlying quasi-category functor to provide the desired equivalence. \square

We now prove that biequivalences reflect and create, as well as preserve, the ∞ -categorical structures considered in Section 13.1.

13.3.5. PROPOSITION. *A biequivalence $F: \mathcal{K} \rightarrow \mathcal{L}$ between ∞ -cosmoi:*

- (i) *Preserves and reflects invertibility of 2-cells.*
- (ii) *Preserves, reflects, and creates adjunctions between ∞ -categories, including right adjoint right inverse adjunctions and left adjoint right inverse adjunctions.*
- (iii) *Preserves and reflects discreteness.*
- (iv) *Preserves, reflects, and creates fibered equivalences.*
- (v) *Preserves and reflects comma and arrow ∞ -categories: a cell as on the left of (13.1.8) is a comma cone in \mathcal{K} if and only if its image is a comma cone in \mathcal{L} .*
- (vi) *Preserves and reflects cartesian and cocartesian fibrations and cartesian functors between them.*

- (vii) Preserves and reflects discrete cartesian fibrations and discrete cocartesian fibrations.
- (viii) Preserves and reflects two-sided fibrations and cartesian functors between them.
- (ix) Preserves and reflects modules and represented modules and induces a bijection on equivalence classes of modules between a fixed pair of ∞ -categories.
- (x) Preserves, reflects, and creates absolute right and left lifting diagrams over a given cospan.
- (xi) Preserves and reflects limits or colimits of diagrams indexed by a simplicial set J inside an ∞ -category and creates the property of an ∞ -category in \mathcal{K} admitting a limit or colimit of a given diagram.

PROOF. Properties (i) and (ii) hold for any biequivalence between 2-categories, such as $F: \mathbf{h}\mathcal{K} \rightarrow \mathbf{h}\mathcal{L}$ and are left to Exercise 13.3.i as a useful exercise to familiarize oneself with the 2-categorical notion of biequivalence.

Property (iii) follows from (i) and Proposition 13.1.5(i): if FE is discrete, then the image under F of any 2-cell in \mathcal{K} with codomain E is invertible, which implies that that 2-cell is invertible in E .

Property (iv) is a special case of Corollary 13.3.2(i) applied to the induced biequivalence of Proposition 13.2.4. Since both \mathcal{K} and \mathcal{L} admit comma ∞ -categories and Proposition 3.3.11 shows that comma spans are characterized by a fibered equivalence class of two-sided isofibrations, (v) follows from (iv).

Proposition (vi) follows from (ii) and (i) and (vii) follows from Corollary 13.3.2(ii) which shows that invertibility of the morphism considered in Proposition 5.4.6 is reflected. Property (viii) follows similarly from Theorem 10.1.4(iii) and (ii) and (i). Preservation and reflection of modules now follows from (iii) and the bijection between equivalence classes follows from (iv); we defer full details until Proposition 14.1.1. The final statement of (ix), on representability, combines (iv) with (v), as will be elaborated upon in Proposition 14.1.2.

The reflection properties of (x) and (xi) follow from Theorem 3.4.3 and the creation properties follow from Theorem 3.4.11 and (ix). The precise steps are spelled out further in Theorem 13.4.1. \square

13.3.6. COROLLARY. *If $F: \mathcal{K} \rightarrow \mathcal{L}$ is a cosmological biequivalence then the following induced cosmological functors are all biequivalences:*

- (i) $F: \mathcal{D}\text{isc}(\mathcal{K}) \rightarrow \mathcal{D}\text{isc}(\mathcal{L})$
- (ii) $F: \mathcal{K}_{\top, J} \rightarrow \mathcal{L}_{\top, J}$ and $F: \mathcal{K}_{\perp, J} \rightarrow \mathcal{L}_{\perp, J}$
- (iii) $F: \mathcal{R}\text{ari}(\mathcal{K})_{/B} \rightarrow \mathcal{R}\text{ari}(\mathcal{L})_{/FB}$ and $F: \mathcal{L}\text{ari}(\mathcal{K})_{/B} \rightarrow \mathcal{L}\text{ari}(\mathcal{L})_{/FB}$
- (iv) $F: \mathcal{R}\text{ari}(\mathcal{K}) \rightarrow \mathcal{R}\text{ari}(\mathcal{L})$ and $F: \mathcal{L}\text{ari}(\mathcal{K}) \rightarrow \mathcal{L}\text{ari}(\mathcal{L})$
- (v) $F: \mathcal{C}\text{art}(\mathcal{K})_{/B} \rightarrow \mathcal{C}\text{art}(\mathcal{L})_{/FB}$ and $F: \mathcal{c}\text{oC}\text{art}(\mathcal{K})_{/B} \rightarrow \mathcal{c}\text{oC}\text{art}(\mathcal{L})_{/FB}$
- (vi) $F: \mathcal{C}\text{art}(\mathcal{K}) \rightarrow \mathcal{C}\text{art}(\mathcal{L})$ and $F: \mathcal{c}\text{oC}\text{art}(\mathcal{K}) \rightarrow \mathcal{c}\text{oC}\text{art}(\mathcal{L})$
- (vii) $F: {}_{A\backslash}\mathcal{F}\text{ib}(\mathcal{K})_{/B} \rightarrow {}_{FA\backslash}\mathcal{F}\text{ib}(\mathcal{L})_{/FB}$
- (viii) $F: {}_{A\backslash}\mathcal{M}\text{od}(\mathcal{K})_{/B} \rightarrow {}_{FA\backslash}\mathcal{M}\text{od}(\mathcal{L})_{/FB}$

PROOF. In each case we start with a cosmological biequivalence — perhaps $\mathcal{K}_{/B} \rightarrow \mathcal{L}_{/FB}$ or $\mathcal{K}^2 \rightarrow \mathcal{L}^2$ — and must show that the restricted cosmological functor of Observation 13.1.3 is again a biequivalence between the replete sub ∞ -cosmoi. Each of the arguments is similar: we know that $F: \mathcal{K} \rightarrow \mathcal{L}$ induces a bijection between equivalence classes of objects. Since the sub ∞ -cosmoi are replete, the equivalence classes of objects of the replete sub ∞ -cosmos are given by a subset of the equivalence classes of objects of \mathcal{K} . Since, moreover, Proposition 13.3.5 proves that the property that characterizes the objects of the sub ∞ -cosmos is preserved, reflected, and created by any biequivalence, it is clear that the bijection between equivalence classes of objects in \mathcal{K} and \mathcal{L} restricts to define a bijection between equivalence classes of objects in the sub ∞ -cosmoi.

Now suppose $A, B \in \mathcal{K}$ are objects of its replete sub ∞ -cosmoi. We must show the local equivalence

$$\mathrm{Fun}(A, B) \xrightarrow{\sim} \mathrm{Fun}(FA, FB)$$

restricts to a local equivalence of the functor spaces of the sub ∞ -cosmoi. Since we know that the biequivalence defines a bijection between isomorphism classes of 0-arrows in the sub ∞ -cosmoi, the proof is completed by the following lemma. \square

13.3.7. LEMMA. *Let $f: K \xrightarrow{\sim} L$ be an equivalence of quasi-categories. Let $K' \subset K$ and $L' \subset L$ be **replete sub quasi-categories** — that is, full and replete up to isomorphism on some collection of vertices — and suppose further that f restricts to define a simplicial functor*

$$\begin{array}{ccc} K & \xrightarrow[\sim]{f} & L \\ \uparrow & & \uparrow \\ K' & \dashrightarrow & L' \end{array}$$

that is bijective on isomorphism classes of vertices. Then $f: K' \xrightarrow{\sim} L'$ is an equivalence of quasi-categories.

PROOF. Choose any inverse equivalence $g: L \xrightarrow{\sim} K$. Since $K' \subset K$ is replete and full on some subset of vertices and $f: K \rightarrow L$ is bijective on isomorphism classes of vertices, g restricts to define a functor $g: L' \rightarrow K'$: for each $y \in L'$, $fg(y') \cong y' \in L$ so $g(y')$ must lie in K' . By repleteness and fullness again, the simplicial natural isomorphisms $K \rightarrow K^{\mathbb{I}}$ and $L \rightarrow L^{\mathbb{I}}$ that witness $gf \cong \mathrm{id}_K$ and $fg \cong \mathrm{id}_L$ restrict to L' and K' to define the desired equivalence. \square

Exercise.

13.3.i. EXERCISE. Consider a 2-functor $F: \mathcal{C} \rightarrow \mathcal{D}$ that defines a biequivalence in the sense of Proposition 13.3.1. Prove that:

- (i) A 2-cell $A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B$ in \mathcal{C} is invertible if and only if $F\alpha$ is invertible in \mathcal{D} .
- (ii) $u: A \rightarrow B$ admits a left adjoint in \mathcal{C} if and only if $Fu: FA \rightarrow FB$ admits a left adjoint in \mathcal{D} in which case F preserve the adjunction.

13.3.ii. EXERCISE. Prove that cosmological biequivalences between cartesian closed ∞ -cosmoi preserve exponential objects up to equivalence.

13.4. Ad hoc model invariance

An ad hoc approach to proving the model-independence of the basic category theory of ∞ -categories is given by elaborations of Proposition 13.3.5, as described for instance in the following theorem:

13.4.1. THEOREM (model independence of basic category theory I). *The following notions are preserved, reflected, and created by any cosmological biequivalence:*

- (i) A left or right adjoint to a functor $u: A \rightarrow B$.
- (ii) A limit or a colimit for a J -indexed diagram $d: \mathbf{1} \rightarrow A^J$ in an ∞ -category A .

PROOF. For (i), if $u: A \rightarrow B$ admits a left adjoint $f: B \rightarrow A$, then this adjunction is preserved by any 2-functor, and hence by any cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$. If there merely exists $f: B \rightarrow A$ in \mathcal{K} so that $Ff \dashv Fu$ in \mathcal{L} , then in the case where F is a biequivalence, Corollary 13.3.2(iii) can be

used to lift the unit and counit from \mathcal{L} to define 2-cells $\eta: \text{id}_B \Rightarrow uf$ and $\epsilon: fu \Rightarrow \text{id}_A$ in \mathcal{K} . A priori the composites $\epsilon f \cdot f\eta$ and $u\epsilon \cdot \eta u$ need not be identities, but they will be invertible and the standard 2-categorical argument appearing in the proof of Proposition 2.1.11 can be used to modify one of these 2-cells to produce a genuine adjunction $f \dashv u$. A similar line of reasoning can be used in the absence of a candidate left adjoint using Corollary 13.3.2(ii) to lift the left adjoint from \mathcal{L} to a functor $f: B \rightarrow A$ in \mathcal{K} whose image is isomorphic to the left adjoint to Fu . The rest of the argument proceeds as before.

For (ii), given an absolute lifting diagram in $\mathfrak{h}\mathcal{L}$ as displayed on the right

$$\begin{array}{ccc} & FA & \\ \nearrow \bar{\ell} & \downarrow \Delta & \\ 1 & \xrightarrow{Fd} FA^J & \end{array} \quad \begin{array}{ccc} & A & \\ \nearrow \ell & \downarrow \Delta & \\ 1 & \xrightarrow{d} A^J & \end{array}$$

Corollary 13.3.2(ii) and (iii) yield a 1-cell $\ell: 1 \rightarrow A$ with $F\ell \cong \bar{\ell}$ and a 2-cell $\lambda: \Delta\ell \Rightarrow d$, as displayed on the right, so that $F\lambda$ composes with the isomorphism $F\ell \cong \bar{\ell}$ to $\bar{\lambda}$. Our task is to show that that this data defines an absolute right lifting diagram in \mathcal{K} , which amounts to showing for all objects X and for all maps $a: X \rightarrow A$ that the composition operation with λ induces a bijection

$$\begin{array}{ccc} \text{hFun}(X, A)(a, \ell) & \xrightarrow{\lambda \circ -} & \text{hFun}(X, A^J)(\Delta a, d!) \\ \parallel & & \parallel \\ \text{hFun}(FX, FA)(Fa, F\ell) & \xrightarrow{F\lambda \circ -} & \text{hFun}(FX, FA^J)(\Delta Fa, Fd!) \\ \parallel & & \parallel \\ \text{hFun}(FX, FA)(Fa, \bar{\ell}) & \xrightarrow{\bar{\lambda} \circ -} & \text{hFun}(FX, FA^J)(\Delta Fa, Fd!) \end{array}$$

On account of the isomorphisms of Corollary 13.3.2(ii) and (iii), this follows from the corresponding encoding of the universal property of $\bar{\lambda}$ in \mathcal{L} .

This argument also shows that the universal property of absolute lifting diagrams is reflected. To see that absolute lifting diagrams are also preserved, Corollary 13.3.2(i) must be invoked to lift any cone in \mathcal{L} with summit Y over the 2-cell $F\lambda$ to an equivalent one in \mathcal{K} with summit X chosen so that $FX \simeq Y$. As the local bijections Corollary 13.3.2(ii) and (iii) can also be defined relative to specified equivalences of objects, the same style of argument goes through. \square

In the next chapter, we approach this model-independence question more systematically by proving that a cosmological biequivalence induces a biequivalence of virtual equipments.

Proof of model independence

Recall from Chapter 11, that the **virtual double category of modules** $\mathcal{Mod}(\mathfrak{h}\mathcal{K})$ in an ∞ -cosmos \mathcal{K} consists of

- a category of **objects** and **vertical arrows**, here the ∞ -categories and ∞ -functors
- for any pair of objects A, B , a class of **horizontal arrows** $A \xrightarrow{E} B$, here the modules $(q, p): E \twoheadrightarrow A \times B$ from A to B
- **cells**, with boundary depicted as follows

$$\begin{array}{ccccccc} A_0 & \xrightarrow{E_1} & A_1 & \xrightarrow{E_2} & \cdots & \xrightarrow{E_n} & A_n \\ f \downarrow & & & \Downarrow & & & \downarrow g \\ B_0 & \xrightarrow{\quad\quad\quad} & & \xrightarrow{F} & & & B_n \end{array}$$

including those whose horizontal source has length zero, in the case $A_0 = A_n$. Here, a cell with the displayed boundary is an isomorphism class of objects in the functor space

$$\begin{array}{ccc} \mathrm{Fun}_{f,g}(E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n, F) & \longrightarrow & \mathrm{Fun}(E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n, F) \\ \downarrow & \lrcorner & \downarrow \\ \mathbb{1} & \longrightarrow & \mathrm{Fun}(E_1 \times_{A_1} \cdots \times_{A_{n-1}} E_n, B_0 \times B_n) \end{array}$$

i.e., a fibered isomorphism class of maps of spans over $f \times g$

- a **composite cell**, for any configuration

$$\begin{array}{ccccccc} A_0 & \xrightarrow{E_{11}, \dots, E_{1k_1}} & A_1 & \xrightarrow{E_{21}, \dots, E_{2k_2}} & \cdots & \xrightarrow{E_{n1}, \dots, E_{nk_n}} & A_n \\ f_0 \downarrow & & \downarrow f_1 & & \downarrow \cdots & & \downarrow f_n \\ B_0 & \xrightarrow{F_1} & B_1 & \xrightarrow{F_2} & \cdots & \xrightarrow{F_n} & B_n \\ g \downarrow & & & \Downarrow & & & \downarrow h \\ C_0 & \xrightarrow{\quad\quad\quad} & & \xrightarrow{G} & & & C_n \end{array}$$

- an **identity cell** for every horizontal arrow

$$\begin{array}{ccc} A & \xrightarrow{E} & B \\ \parallel & \Downarrow \mathrm{id}_E & \parallel \\ A & \xrightarrow{E} & B \end{array}$$

so that composition of cells is strictly associative and unital in the usual multi-categorical sense.

The virtual double category of modules is a **virtual equipment** in the sense introduced by Cruttwell and Shulman [15, §7], which means that it satisfies the two further properties:

- (i) For any module and pair of functors as displayed on the left, there exists a module and cartesian cell as displayed on the right

$$\begin{array}{ccc} A' & & B' \\ a \downarrow & & \downarrow b \\ A & \xrightarrow{E} & B \end{array} \rightsquigarrow \begin{array}{ccc} A' & \xrightarrow{E(b,a)} & B' \\ a \downarrow & \Downarrow \rho & \downarrow b \\ A & \xrightarrow{E} & B \end{array}$$

characterized by the universal property that any cell as displayed below-left factors uniquely through ρ as below-right:

$$\begin{array}{ccc} X_0 & \xrightarrow{E_1} & X_1 & \xrightarrow{E_2} & \cdots & \xrightarrow{E_n} & X_n \\ af \downarrow & & & \Downarrow & & & \downarrow bg \\ A & \xrightarrow{E} & B \end{array} = \begin{array}{ccc} X_0 & \xrightarrow{E_1} & X_1 & \xrightarrow{E_2} & \cdots & \xrightarrow{E_n} & X_n \\ f \downarrow & & & \Downarrow \exists! \Downarrow & & & \downarrow g \\ A' & \xrightarrow{E(b,a)} & B' \\ a \downarrow & \Downarrow \rho & \downarrow b \\ A & \xrightarrow{E} & B \end{array}$$

- (ii) Every object A admits a *unit* module equipped with a nullary cocartesian cell

$$\begin{array}{ccc} A & \xrightarrow{\quad} & A \\ \parallel & \Downarrow \iota & \parallel \\ A & \xrightarrow{\text{Hom}_A} & A \end{array}$$

satisfying the universal property that any cell in the virtual double category of modules whose horizontal source includes the object A , as displayed on the left

$$\begin{array}{ccc} X & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & A & \xrightarrow{F_1} & \cdots & \xrightarrow{F_m} & Y \\ f \downarrow & & & \Downarrow & & & & & \downarrow g \\ B & \xrightarrow{G} & C \end{array} = \begin{array}{ccc} X & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & A & \xrightarrow{\quad} & A & \xrightarrow{F_1} & \cdots & \xrightarrow{F_m} & Y \\ \parallel & \Downarrow \text{id}_{E_1} & \parallel & \cdots & \parallel & \Downarrow \text{id}_{E_n} & \parallel & \Downarrow \iota & \parallel & \Downarrow \text{id}_{F_1} & \parallel & \cdots & \parallel & \Downarrow \text{id}_{F_m} & \parallel \\ X & \xrightarrow{E_1} & \cdots & \xrightarrow{E_n} & A & \xrightarrow{\text{Hom}_A} & A & \xrightarrow{F_1} & \cdots & \xrightarrow{F_m} & Y \\ f \downarrow & & & \Downarrow \exists! & & & & & & & \downarrow g \\ B & \xrightarrow{G} & C \end{array}$$

factors uniquely through ι as displayed on the right.

The module in (i) is defined by pulling back a module $A \xrightarrow{E} B$ along functors $a: A' \rightarrow A$ and $b: B' \rightarrow B$. The simplicial pullback defining $E(b, a)$ induces an equivalence of functor spaces

$$\text{Fun}_{af, bg}(E_1 \times \cdots \times E_n, E) \simeq \text{Fun}_{f, g}(E_1 \times \cdots \times E_n, E(b, a)),$$

which gives rise to the universal property. See Proposition 11.2.1.

The unit module is the arrow ∞ -category, given the notation $A \xrightarrow{\text{Hom}_A} A$ when considered as a module from A to A . The universal property of (ii) follows from the Yoneda lemma; see Proposition 11.2.4.

The virtual equipment of modules in \mathcal{K} has a lot of pleasant properties, which follow formally from the axiomatization of a virtual equipment. For instance, certain sequences of composable modules can be said to *have composites*, witnessed by cocartesian cells as in (ii) (see 11.3.5, 11.3.11, 11.4.7, and 11.4.8 and the non-formal composite given in 11.3.7). Also, for any functor $f: A \rightarrow B$, the modules $A \xrightarrow{\text{Hom}_B(B,f)} B$ and $B \xrightarrow{\text{Hom}_B(f,B)} A$ behave like adjoints in a sense suitable to a virtual double category; more precisely, the module $A \xrightarrow{\text{Hom}_B(B,f)} B$ defines a *companion* and the module $B \xrightarrow{\text{Hom}_B(f,B)} A$ defines a *conjoint* to $f: A \rightarrow B$ (see 11.4.1, 11.4.4, and 11.4.6). Another consequence of Theorem 11.2.6 is the following: for any parallel pair of functors there are natural bijections between 2-cells in the homotopy 2-category

$$\begin{array}{ccc} & f & \\ A & \xrightarrow{\quad} & B \\ & \Downarrow & \\ & g & \end{array}$$

and cells in the virtual equipment of modules:

$$\begin{array}{ccccc} A & \xrightarrow{\text{Hom}_B(B,f)} & B & & A & \xrightarrow{\text{Hom}_A} & A & & B & \xrightarrow{\text{Hom}_B(g,B)} & A \\ \parallel & & \Downarrow & & \parallel & & \Downarrow & & \parallel & & \Downarrow & & \parallel \\ A & \xrightarrow{\text{Hom}_B(B,g)} & B & \xleftrightarrow{\quad} & B & \xrightarrow{\text{Hom}_B} & B & \xleftrightarrow{\quad} & B & \xrightarrow{\text{Hom}_B(f,B)} & A \end{array}$$

See Proposition 11.4.10.

As remarked upon in Definition 11.4.11, as a consequence of these results, there are two locally-fully-faithful homomorphisms $\mathfrak{h}\mathcal{K} \hookrightarrow \mathcal{M}od(\mathfrak{h}\mathcal{K})$ and $\mathfrak{h}\mathcal{K}^{\text{coop}} \hookrightarrow \mathcal{M}od(\mathfrak{h}\mathcal{K})$ — referred to as the *covariant* and *contravariant embeddings*, respectively — embedding the homotopy 2-category into the substructure¹ of $\mathcal{M}od(\mathfrak{h}\mathcal{K})$ comprised only of unary cells whose vertical boundaries are identities. The modules in the image of the covariant embedding are the right representables and the modules in the image of the contravariant embedding are the left representables.

The theme of Chapter 12 could be summarized by saying that the virtual equipment of modules in an ∞ -cosmos is a robust setting to develop the category theory of ∞ -categories. On the one hand, it contains the homotopy 2-category of the ∞ -cosmos, which was the setting for the results of Part I. It is also a very natural home to study ∞ -categorical properties that are somewhat awkward to express in the homotopy 2-category. For instance, the weak 2-universal property of comma ∞ -categories is now encoded by a bijection in Lemma 11.1.16: cells in the virtual equipment whose codomain is a comma module correspond bijectively to natural transformations of a particular form in the homotopy 2-category. Fibered equivalences of modules, as used to express the universal properties of adjunctions, limits, and colimits in Chapter 4, are now vertical isomorphisms in the virtual equipment between parallel modules. The virtual equipment also cleanly encodes the universal property of pointwise left and right Kan extensions.

In this chapter, we show that a cosmological biequivalence $F: \mathcal{K} \rightleftarrows \mathcal{L}$ induces a *biequivalence of virtual equipments* $F: \mathcal{M}od(\mathfrak{h}\mathcal{K}) \rightleftarrows \mathcal{M}od(\mathfrak{h}\mathcal{L})$ in a suitable sense that we introduce to describe what

¹This substructure is very nearly a bicategory, with horizontal composites of unary cells constructed as in Definition 11.3.12, except that compatible sequences of modules do not always admit a horizontal composite.

is true in our setting. We then explain the interpretation of this result: that the category theory of ∞ -categories is preserved, reflected, and created by any “change-of-model” functor of this form.

14.1. A biequivalence of virtual equipments

We first elaborate on Proposition 13.3.1(ix).

14.1.1. PROPOSITION. *A cosmological biequivalence $F: \mathcal{K} \rightleftarrows \mathcal{L}$ preserves, reflects, and creates modules:*

- (i) *An isofibration $E \twoheadrightarrow A \times B$ is a module in \mathcal{K} if and only if $FE \twoheadrightarrow FA \times FB$ is a module in \mathcal{L} .*
- (ii) *For every module $G \twoheadrightarrow A' \times B'$ in \mathcal{L} and every pair of ∞ -categories A, B in \mathcal{K} with specified equivalences $FA \simeq A'$ and $FB \simeq B'$ there is a module $E \twoheadrightarrow A \times B$ in \mathcal{K} so that FE is equivalent to G over the pair of equivalences.*

PROOF. For (i) consider an isofibration $E \twoheadrightarrow A \times B$ in $\mathcal{K}_{/A \times B}$ and the induced biequivalence $F: \mathcal{K}_{/A \times B} \rightleftarrows \mathcal{L}_{/FA \times FB}$ of Proposition 13.2.4. By Proposition 13.3.5(iii), E defines a discrete object in $\mathcal{K}_{/A \times B}$ if and only if FE defines a discrete object in $\mathcal{L}_{/FA \times FB}$. By Theorem 13.4.1(i), $E \rightarrow \mathrm{Hom}_B(B, p)$ admits a right adjoint and $E \rightarrow \mathrm{Hom}_A(q, A)$ admits a left adjoint in $\mathcal{K}_{/A \times B}$ if and only if $FE \rightarrow F\mathrm{Hom}_B(B, p) \cong \mathrm{Hom}_{FB}(FB, Fp)$ admits a right adjoint and $FE \rightarrow F\mathrm{Hom}_A(q, A) \cong \mathrm{Hom}_{FA}(Fq, FA)$ admits a left adjoint in $\mathcal{L}_{/FA \times FB}$. By Lemma 10.4.2 these properties characterize modules.

For (ii), fix a pair of equivalences $FA \simeq A'$ and $FB \simeq B'$, defining an equivalence $e: A' \times B' \rightleftarrows FA \times FB$, and consider the composite biequivalence

$$\mathcal{K}_{/A \times B} \xrightarrow[\sim]{F} \mathcal{L}_{/FA \times FB} \xrightarrow[\sim]{e^*} \mathcal{L}_{/A' \times B'}$$

given by Propositions 13.2.4 and 13.2.7. Consider a module $G \twoheadrightarrow A' \times B'$. By essential surjectivity, there is an isofibration $E \twoheadrightarrow A \times B$ whose image under this cosmological functor—the pullback of $FE \twoheadrightarrow FA \times FB$ along $e: A' \times B' \rightleftarrows FA \times FB$ —defines an isofibration $(q, p): E' \twoheadrightarrow A' \times B'$ that is equivalent to G in $\mathcal{L}_{/A' \times B'}$. It remains only to argue that E defines a module from A to B , which will follow, essentially as in the proof of (i), from the fact that $E' \simeq G$ defines a module from A' to B' .

As the image E' of E is equivalent to a discrete object, Proposition 13.3.5(iii) tells us E is discrete in $\mathcal{K}_{/A \times B}$. The final step is to argue that the desired right adjoint to $E \rightarrow \mathrm{Hom}_B(B, p)$ is present in the image of the biequivalence $\mathcal{K}_{/A \times B} \rightleftarrows \mathcal{L}_{/A' \times B'}$, and apply Theorem 13.4.1(i) to deduce its presence in $\mathcal{K}_{/A \times B}$; a similar argument of course applies to the functor $E \rightarrow \mathrm{Hom}_A(q, A)$. To see this note that $F: \mathcal{K}_{/A \times B} \rightleftarrows \mathcal{L}_{/FA \times FB}$ carries $\mathrm{Hom}_B(B, p) \twoheadrightarrow A \times B$ to $\mathrm{Hom}_{FB}(FB, Fp) \twoheadrightarrow FA \times FB$. By (i), it suffices to argue that this functor has a right adjoint over $FA \times FB$. Applying Theorem 13.4.1(i) to the biequivalence $e^*: \mathcal{L}_{/FA \times FB} \rightleftarrows \mathcal{L}_{/A' \times B'}$, this follows from the fact that $E' \rightarrow \mathrm{Hom}_{B'}(B', p')$ has a right adjoint over $A' \times B'$. \square

14.1.2. PROPOSITION. *Let $F: \mathcal{K} \rightleftarrows \mathcal{L}$ be a cosmological biequivalence. Then a module $A \xrightarrow{E} B$ in \mathcal{K} is right representable if and only if the module $FA \xrightarrow{FE} FB$ is right representable in \mathcal{L} , in which case, F carries the representing functor $f: A \rightarrow B$ in \mathcal{K} to a representing functor $Ff: FA \rightarrow FB$ in \mathcal{L} .*

PROOF. To say that $A \xrightarrow{E} B$ is right representable in \mathcal{K} is to say that there exists a functor $f: A \rightarrow B$ together with an equivalence $E \simeq_{A \times B} \mathrm{Hom}_B(B, f)$ of modules over B . If this is the case then any cosmological functor $F: \mathcal{K} \rightarrow \mathcal{L}$ carries this to a fibered equivalence $FE \simeq_{FA \times FB} \mathrm{Hom}_{FB}(FB, Ff)$, and hence the module $FA \xrightarrow{FE} FB$ is right-represented by $Ff: FA \rightarrow FB$ in \mathcal{L} .

Conversely, if $FA \xrightarrow{FE} FB$ is right-represented by some functor $g: FA \rightarrow FB$, then by Corollary 13.3.2(ii), there exists a functor $f: A \rightarrow B$ in \mathcal{K} so that $Ff \cong g$ in \mathcal{L} . By Proposition 11.4.10, naturally isomorphic functors represent equivalent modules; that is, $\text{Hom}_{FB}(FB, g) \simeq_{FA \times FB} \text{Hom}_{FB}(FB, Ff)$. Thus $FE \simeq_{FA \times FB} \text{Hom}_{FB}(FB, Ff)$. By Corollary 13.3.2(i), this fibered equivalence lifts along the cosmological functor $F: \mathcal{K}_{/A \times B} \rightarrow \mathcal{L}_{/FA \times FB}$ to a fibered equivalence $E \simeq_{A \times B} \text{Hom}_B(B, f)$, which proves that E is right represented by $f: A \rightarrow B$ in \mathcal{K} . \square

Because cosmological functors preserve modules, simplicial pullbacks, and the arrow construction, we see that a functor $F: \mathcal{K} \rightarrow \mathcal{L}$ induces a functor of virtual equipments $F: \text{Mod}(\mathfrak{h}\mathcal{K}) \rightarrow \text{Mod}(\mathfrak{h}\mathcal{L})$ preserving all of the structures described in Theorem 11.2.6.

14.1.3. THEOREM (model independence of ∞ -category theory). *If $F: \mathcal{K} \rightarrow \mathcal{L}$ is a cosmological biequivalence, then the induced functor of virtual equipments*

$$F: \text{Mod}(\mathfrak{h}\mathcal{K}) \rightarrow \text{Mod}(\mathfrak{h}\mathcal{L})$$

defines a biequivalence of virtual equipments: i.e., it is

- (i) *bijective on equivalence classes of objects;*
- (ii) *locally bijective on isomorphism classes of parallel vertical functors extending the bijection of (i);*
- (iii) *locally bijective on equivalence classes of parallel modules extending the bijection of (ii);*
- (iv) *locally bijective on cells extending the bijections of (i), (ii), and (iii).*

Consequently, any ∞ -categorical notion that can be encoded as an equivalence-invariant proposition in the virtual equipment of modules is model invariant: preserved, reflected, and created by cosmological biequivalences.

Note further that if two ∞ -cosmoi are connected by a finite zig-zag of biequivalences, then the bijections described in Theorem 14.1.3 compose.

PROOF. Properties (i) and (ii) are restatements of Corollary 13.3.2(i) and (ii).

The local bijection (iii) follows immediately from Proposition 14.1.1 and the fact that for any pair of equivalences $e: A' \times B' \simeq FA \times FB$, the composite biequivalence

$$\mathcal{K}_{/A \times B} \xrightarrow[\sim]{F} \mathcal{L}_{/FA \times FB} \xrightarrow[\sim]{e^*} \mathcal{L}_{/A' \times B'}$$

preserves, reflects, and creates equivalences between objects (Corollary 13.3.2(i)). Finally (iv) is an application of Corollary 13.3.2(ii) to this cosmological biequivalence. \square

For instance, the presence of an adjunctions between ∞ -categories and the existence of limits and colimits inside an ∞ -category can both be encoded as an equivalence-invariant proposition in the virtual equipment of modules. Using Theorem 14.1.3, we can reprove Theorem 13.4.1.

MODULE-THEORETIC PROOF OF THEOREM 13.4.1. By Proposition 4.1.1, $u: A \rightarrow B$ admits a left adjoint if and only if the module $A \xrightarrow{\text{Hom}_B(B, u)} B$ is contravariantly represented. Any representing functor in \mathcal{L} lifts up to isomorphism to define a functor $f: B \rightarrow A$ in \mathcal{K} and now by Theorem 14.1.3(iii) there is an equivalence $\text{Hom}_A(f, A) \simeq \text{Hom}_B(B, u)$ of modules from A to B in \mathcal{K} if and only if there is an equivalence $\text{Hom}_{FA}(Ff, FA) \simeq \text{Hom}_{FB}(FB, fu)$ of modules from FA to FB in \mathcal{L} .

Similarly, a diagram $d: 1 \rightarrow A^I$ admits a limit if and only if the module $1 \xrightarrow{\text{Hom}_{A^I}(\Delta, d)} A$ is covariantly represented, and Proposition 14.1.2 or the argument just given completes the proof in this case as well. \square

A biequivalence of virtual equipments preserves, reflects, and creates composites of modules.

14.1.4. LEMMA. *Let $F: \mathcal{K} \rightleftarrows \mathcal{L}$ be a cosmological biequivalence.*

- (i) *Then a composable sequence of modules in \mathcal{K} admits a composite in $\mathbf{Mod}(\mathfrak{h}\mathcal{K})$ if and only if the image of this sequence admits a composite in $\mathbf{Mod}(\mathfrak{h}\mathcal{L})$.*
- (ii) *Hence, cosmological biequivalences preserve and reflect exact squares.*

PROOF. Via Definition 12.1.1, (ii) follows immediately from (i), so it remains only to show that a biequivalence of virtual equipments $F: \mathbf{Mod}(\mathfrak{h}\mathcal{K}) \rightleftarrows \mathbf{Mod}(\mathfrak{h}\mathcal{L})$ preserves, reflects, and creates composites of modules. To see that an n -ary composite cell $\mu: E_1 \times \cdots \times E_n \Rightarrow E$ in $\mathfrak{h}\mathcal{K}$ is preserved, note that by Theorem 14.1.3(iv), any cell in $\mathbf{Mod}(\mathfrak{h}\mathcal{L})$ is isomorphic to a cell in the image of F : first replace the objects by equivalent ones in the image, then replace the vertical functors by naturally isomorphic ones in the image, then replace the modules by equivalent ones in the image over the specified equivalences between their ∞ -categorical sources and targets, and then finally apply the local bijection (iv) to replace the cell in $\mathbf{Mod}(\mathfrak{h}\mathcal{L})$ by a unique cell in the image of $\mathbf{Mod}(\mathfrak{h}\mathcal{K})$ by composing with this data. Now, by local full and faithfulness and essential surjectivity, the universal property of the cocartesian cell $\mu: E_1 \times \cdots \times E_n \Rightarrow E$ implies that its image $F\mu: FE_1 \times \cdots \times FE_n \Rightarrow FE$ is again a cocartesian cell. Thus composites $E_1 \otimes \cdots \otimes E_n \simeq E$ are preserved by cosmological biequivalences.

Now if $F\mu: FE_1 \times \cdots \times FE_n \Rightarrow FE$ is a composite, the fact that $F: \mathbf{Mod}(\mathfrak{h}\mathcal{K}) \rightarrow \mathbf{Mod}(\mathfrak{h}\mathcal{L})$ is locally fully faithful implies immediately that $\mu: E_1 \times \cdots \times E_n \Rightarrow E$ is a composite; thus composites $E_1 \otimes \cdots \otimes E_n \simeq E$ are reflected by cosmological biequivalences.

Finally, suppose the sequence $FE_1 \times \cdots \times FE_n$ of modules in $\mathbf{Mod}(\mathfrak{h}\mathcal{L})$ admits a composite $FA_0 \xrightarrow{G} FA_n$; since the composable sequence of modules is in the image of F the source and target ∞ -categories of the composite module G are as well. By Theorem 14.1.3(iii) there exists a module $A_0 \xrightarrow{E} A_n$ in $\mathfrak{h}\mathcal{K}$ so that $FE \simeq G$ as modules from FA_0 to FA_n . The cocartesian cell $FE_1 \times \cdots \times FE_n \Rightarrow G$ composes with the unary cell of this equivalence to define a cocartesian cell $FE_1 \times \cdots \times FE_n \Rightarrow FE$. By Theorem 14.1.3(iv), this lifts to an n -ary cell $E_1 \times \cdots \times E_n \Rightarrow E$ in $\mathbf{Mod}(\mathfrak{h}\mathcal{K})$. As we've just seen that cocartesianness of cells is reflected by biequivalences $F: \mathbf{Mod}(\mathfrak{h}\mathcal{K}) \rightarrow \mathbf{Mod}(\mathfrak{h}\mathcal{L})$, this completes the proof that composites are created by cosmological biequivalences. \square

Exercises.

14.1.i. EXERCISE. Prove that cosmological biequivalences between cartesian closed ∞ -cosmoi preserve and reflect initial and final functors.

Appendix of Abstract Nonsense

APPENDIX A

Basic concepts of enriched category theory

Enriched category theory exists because enriched categories exist in nature. To explain, consider the data of a (small) 1-category \mathcal{C} , given by:

- a set of objects
- for each pair of objects $x, y \in \mathcal{C}$, a set $\mathcal{C}(x, y)$ of arrows in \mathcal{C} from x to y
- for each $x \in \mathcal{C}$, a specified identity element $\text{id}_x: 1 \rightarrow \mathcal{C}(x, x)$, and for each $x, y, z \in \mathcal{C}$, a specified composition map $\circ: \mathcal{C}(y, z) \times \mathcal{C}(x, y) \rightarrow \mathcal{C}(x, z)$ satisfying the associativity and unit conditions:

$$\begin{array}{ccc}
 \mathcal{C}(y, z) \times \mathcal{C}(x, y) \times \mathcal{C}(w, x) & \xrightarrow{\circ \times \text{id}} & \mathcal{C}(x, z) \times \mathcal{C}(w, x) & \quad & \mathcal{C}(x, y) & \xrightarrow{\text{id} \times \text{id}_x} & \mathcal{C}(x, y) \times \mathcal{C}(x, x) \\
 \text{id} \times \circ \downarrow & & \downarrow \circ & & \text{id}_y \times \text{id} \downarrow & \searrow & \downarrow \circ \\
 \mathcal{C}(y, z) \times \mathcal{C}(w, y) & \xrightarrow{\circ} & \mathcal{C}(w, z) & & \mathcal{C}(y, y) \times \mathcal{C}(x, y) & \xrightarrow{\circ} & \mathcal{C}(x, y)
 \end{array} \tag{A.0.1}$$

In many mathematical examples of interest, the set $\mathcal{C}(x, y)$ can be given additional structure, in which case it would be strange not to take it account when performing further categorical constructions.

Perhaps there exists a specified zero arrow $0_{x,y} \in \mathcal{C}(x, y)$, the set of which defines a two-sided ideal for composition: $g \circ 0 \circ f = 0$. Or extending this, perhaps $\mathcal{C}(x, y)$ admits an abelian group structure, for which composition is \mathbb{Z} -bilinear. Or in another direction, perhaps the set of arrows from x to y in \mathcal{C} form the objects of a 1-category. In this setting, we regard the objects of $\mathcal{C}(x, y)$ as “1-dimensional” morphisms from x to y and the arrows of $\mathcal{C}(x, y)$ as “2-dimensional” morphisms from x to y in \mathcal{C} ; now, it’s natural natural to require the composition map to define a functor. Or perhaps the set of arrows from x to y in \mathcal{C} form the vertices of a simplicial set, whose higher simplices now provides arrows in each positive dimension; in this setting, it is natural to ask composition to define a simplicial map. In such settings, one says that the 1-category \mathcal{C} can be enriched over the category \mathcal{V} in which the objects $\mathcal{C}(x, y)$ and diagrams (A.0.1) live¹ — with \mathcal{V} equal to the category of pointed sets, abelian groups, categories, or simplicial sets in the examples just described.

An alternate point of view of enriched category theory is often emphasized — adopted for instance in the classic textbook [31] from which we stole the title of this chapter. To borrow a distinction used by Peter May, the term “enriched” can be used as a compound noun — *enriched categories* — or as an adjective — *enriched* categories. In the noun form, an enriched category \mathcal{C} has no pre-existing underlying ordinary category, although we shall see below that the underlying unenriched 1-category can always be identified a posteriori. When used as an adjective, an enriched category \mathcal{C} is perhaps

¹To interpret the diagrams (A.0.1) in \mathcal{V} one needs to specify an interpretation for the monoidal product “ \times ” and its unit object 1 (which is not displayed in the diagram). In the examples we will consider, this product is the cartesian product and this unit is the terminal object.

most naturally an ordinary category, whose hom-sets can be given additional structure.² While the noun perspective is arguably more elegant when discussing the general theory of enriched categories, the adjective perspective dominates when discussing examples, so we choose to emphasize the adjective form and focus on enriching unenriched categories here.

Before giving a precise definition of enriched category and the enriched functors between them in §A.2, in §A.1 we study that category \mathcal{V} that defines the base for enrichment in which the hom-objects will ultimately live. Here we are interested primarily in two examples $\mathcal{V} = \mathbf{Cat}$ and $\mathcal{V} = \mathbf{SSet}$, as well as the unenriched case $\mathcal{V} = \mathbf{Set}$, each of which has the special property of being cartesian closed categories. Since there are some simplifications in enriching over a cartesian closed category, we grant ourselves the luxury of working explicitly with this notion; see [31] or [47, Chapter 3] for an introduction to categories enriched over a more general symmetric monoidal category.

We continue in §A.3 with an introduction to enriched natural transformations and the enriched Yoneda lemma. These notions allow us to correctly state the universal properties that characterize *tensors* and *cotensors* in §A.4 and *conical limits* and *colimits* in §A.5, both of which are characterized by universal properties involving an enriched natural isomorphism. We conclude in §A.6 with a general theory of change of base — the one part of the theory of enriched categories that is not covered in encyclopedic detail in [31], the original reference instead being [20] — which allows us to be more precise about the procedure by which a 2-category may be regarded as a simplicial category (as used to great effect in Chapters 8 and 9) or by which a simplicial category may be quotiented to define a 2-category (see e.g., Definition 1.4.1) as alluded to in Digression 1.4.2.

A.1. Cartesian closed categories

Throughout this text, the base category for enrichment will always be taken to be a cartesian closed category:

A.1.1. DEFINITION. A category \mathcal{V} is **cartesian closed** when it

- admits finite products, or equivalently, a terminal object $1 \in \mathcal{V}$ and binary products and
- for each $A \in \mathcal{V}$, the functor $A \times -: \mathcal{V} \rightarrow \mathcal{V}$ admits a right adjoint $(-)^A: \mathcal{V} \rightarrow \mathcal{V}$.

A.1.2. LEMMA. In a cartesian closed category \mathcal{V} , the product bifunctor is the left adjoint of a two-variable adjunction, this being captured by a commutative triangle of natural isomorphisms

$$\begin{array}{ccc} & \mathcal{V}(A \times B, C) & \\ \cong \nearrow & & \nwarrow \cong \\ \mathcal{V}(A, C^B) & \cong & \mathcal{V}(B, C^A) \end{array} \quad (\text{A.1.3})$$

PROOF. The family of functors $(-)^A: \mathcal{V} \rightarrow \mathcal{V}$ extend to bifunctors

$$(-)^{-}: \mathcal{V}^{\text{op}} \times \mathcal{V} \rightarrow \mathcal{V}$$

in a unique way so that the isomorphism defining each adjunction $A \times - \dashv (-)^A$

$$\mathcal{V}(A \times B, C) \cong \mathcal{V}(B, C^A)$$

becomes natural in A (as well as B and C). The details are left as Exercise A.1.i or to [48, 4.3.6]. This defines the natural isomorphism on the right-hand side of (A.1.3). The natural isomorphism on the

²To quote [41] “Thinking from the two points of view simultaneously, it is essential that the constructed ordinary category be isomorphic to the ordinary category that one started out with. Either way, there is a conflict of notation between that preferred by category theorists and that in common use by ‘working mathematicians’ (to whom [39] is addressed).”

left-hand is defined by composing with the symmetry isomorphism $A \times B \cong B \times A$. The third natural isomorphism is taken to be the composite of these two. \square

A.1.4. EXAMPLE (cartesian closed categories).

- (i) The category of sets is cartesian closed, with B^A defined to be the set of functions from A to B . Transposition across the natural isomorphism (A.1.3) is referred to as “currying.”
- (ii) The category \mathbf{Cat} of small categories is cartesian closed, with B^A defined to be the category of functors and natural transformations from A to B .³ The natural isomorphism

$$\mathbf{Cat}(A, C^B) \cong \mathbf{Cat}(A \times B, C) \cong \mathbf{Cat}(B, C^A)$$

identifies natural transformations, which are arrows $\mathbf{2} \rightarrow C^A$ in the category of functors, with “homotopies” $A \times \mathbf{2} \rightarrow C$.

- (iii) For any small category \mathbf{C} , the category $\mathbf{Set}^{\mathbf{C}^{\text{op}}}$ is cartesian closed. By the Yoneda lemma for $F, G \in \mathbf{Set}^{\mathbf{C}^{\text{op}}}$, the value of G^F at $c \in \mathbf{C}$ must be defined by

$$G^F(c) \cong \mathbf{Set}^{\mathbf{C}^{\text{op}}}(\mathbf{C}(-, c), G^F) \cong \mathbf{Set}^{\mathbf{C}^{\text{op}}}(F \times \mathbf{C}(-, c), G).$$

By the proof of Lemma A.1.2, the action of G^F on a morphism $f: c \rightarrow c' \in \mathbf{C}$ is defined by precomposition with the corresponding natural transformation $f_*: \mathbf{C}(-, c) \rightarrow \mathbf{C}(-, c')$. This defines the functor G^F . Since any functor $H \in \mathbf{Set}^{\mathbf{C}^{\text{op}}}$ is canonically a colimit of representables, this definition extends to the required natural isomorphism $\mathbf{Set}^{\mathbf{C}^{\text{op}}}(H, G^F) \cong \mathbf{Set}^{\mathbf{C}^{\text{op}}}(F \times H, G)$.

- (iv) In particular taking $\mathbf{C} = \Delta^{\text{op}}$, the category of simplicial sets $\mathbf{SSet} := \mathbf{Set}^{\Delta^{\text{op}}}$ is cartesian closed.

The exponential B^A is frequently referred to as an *internal hom*. As this name suggests, the internal hom B^A can be viewed as a lifting of the hom-set $\mathcal{V}(A, B)$ along a functor that we now introduce.

A.1.5. DEFINITION. For any cartesian closed category \mathcal{V} the **underlying set functor** is the functor

$$\mathcal{V} \xrightarrow{(-)_0 := \mathcal{V}(1, -)} \mathbf{Set}$$

represented by the terminal object $1 \in \mathcal{V}$.

A.1.6. LEMMA. For any pair of objects $A, B \in \mathcal{V}$ in a cartesian closed category, the underlying set of the internal hom B^A is $\mathcal{V}(A, B)$, i.e.:

$$(B^A)_0 \cong \mathcal{V}(A, B).$$

PROOF. Combining Definition A.1.5 with (A.1.3):

$$(B^A)_0 := \mathcal{V}(1, B^A) \cong \mathcal{V}(1 \times A, B) \cong \mathcal{V}(A, B)$$

since there is a natural isomorphism $1 \times A \cong A$. \square

It makes sense to ask whether an isomorphism of underlying sets can be “enriched” to lie in \mathcal{V} , that is, lifted along the underlying set functor $(-)_0: \mathcal{V} \rightarrow \mathbf{Set}$.

³Size matters here: the category of large but locally small categories is not cartesian closed, though it is still possible to define B^A in the case where A is a small category.

A.1.7. LEMMA. The natural isomorphisms (A.1.3) characterizing the defining two-variable adjunction of a cartesian closed category lift to \mathcal{V} : for any $A, B, C \in \mathcal{V}$

$$(C^B)^A \cong C^{A \times B} \cong (C^A)^B \quad (\text{A.1.8})$$

PROOF. This follows from the associativity of finite products and the Yoneda lemma. To prove (A.1.8), it suffices to show that $C^{A \times B}$, $(C^B)^A$, and $(C^A)^B$ represent the same functor. We have a sequence of natural isomorphisms:

$$\begin{aligned} \mathcal{V}(X, (C^B)^A) &\cong \mathcal{V}(X \times A, C^B) \\ &\cong \mathcal{V}((X \times A) \times B, C) \cong \mathcal{V}(X \times (A \times B), C) \\ &\cong \mathcal{V}(X, C^{A \times B}) \\ &\cong \mathcal{V}((A \times B) \times X, C) \cong \mathcal{V}(A \times (B \times X), C) \\ &\cong \mathcal{V}(B \times X, C^A) \\ &\cong \mathcal{V}(X, (C^A)^B), \end{aligned}$$

and hence

$$\mathcal{V}(X, (C^B)^A) \cong \mathcal{V}(X, C^{A \times B}) \cong \mathcal{V}(X, (C^A)^B). \quad \square$$

A.1.9. REMARK. Note $(-)^1: \mathcal{V} \rightarrow \mathcal{V}$ is naturally isomorphic to the identity functor — i.e., $B^1 \cong B$, — since it is right adjoint to a functor $- \times 1: \mathcal{V} \rightarrow \mathcal{V}$ that is naturally isomorphic to the identity.

A bicomplete cartesian closed category is a special case of a complete and cocomplete closed symmetric monoidal category, this being deemed a **cosmos** by Bénabou, to signify that such bases are an ideal setting for enriched category theory. For obvious reasons, we won't use this term here. There is a competing 2-categorical notion of (fibrational) “cosmos” due to Street [57] that is more similar to the notion we consider here, which was the direct inspiration for the terminology we introduce in Definition 1.2.1.

Exercises.

A.1.i. EXERCISE. Prove that in a cartesian closed category \mathcal{V} , the family of functors $(-)^A: \mathcal{V} \rightarrow \mathcal{V}$ extend to bifunctors

$$(-)^-: \mathcal{V}^{\text{op}} \times \mathcal{V} \rightarrow \mathcal{V}$$

in a unique way so that the isomorphism defining each adjunction $A \times - \dashv (-)^A$

$$\mathcal{V}(A \times B, C) \cong \mathcal{V}(B, C^A)$$

becomes natural in A (as well as B and C).

A.1.ii. EXERCISE. The data of a **closed symmetric monoidal category** generalizes Definition A.1.1 by replacing finite products by an arbitrary bifunctor $- \otimes -: \mathcal{V} \times \mathcal{V} \rightarrow \mathcal{V}$, replacing the terminal object by an object $I \in \mathcal{V}$, and requiring the additional specification of natural isomorphisms

$$A \otimes (B \otimes C) \cong (A \otimes B) \otimes C \quad I \otimes A \cong A \cong A \otimes I \quad A \otimes B \cong B \otimes A$$

satisfying various coherence axioms [20, 27]; see also [28]. Explain why these isomorphisms do not need to be specified in the special case of a cartesian closed category and why the coherence conditions are automatic.

A.2. Enriched categories

We now briefly switch perspectives and explain the meaning of the noun phrase “enriched category” because discussion what is required to “enrich” an ordinary 1-category. Throughout we fix a cartesian closed category $(\mathcal{V}, \times, 1)$ to serve as the base for enrichment.

A.2.1. DEFINITION. A \mathcal{V} -enriched category \mathcal{C} is given by:

- a set of objects
- for each pair of objects $x, y \in \mathcal{C}$, an **object of arrows** $\mathcal{C}(x, y) \in \mathcal{V}$
- for each $x \in \mathcal{C}$, a specified identity element encoded by a map $\text{id}_x: 1 \rightarrow \mathcal{C}(x, x) \in \mathcal{V}$, and for each $x, y, z \in \mathcal{C}$, a specified composition map $\circ: \mathcal{C}(y, z) \times \mathcal{C}(x, y) \rightarrow \mathcal{C}(x, z) \in \mathcal{V}$ satisfying the associativity and unit conditions, both commutative diagrams lying in \mathcal{V} :⁴

$$\begin{array}{ccc}
 \mathcal{C}(y, z) \times \mathcal{C}(x, y) \times \mathcal{C}(w, x) & \xrightarrow{\circ \times \text{id}} & \mathcal{C}(x, z) \times \mathcal{C}(w, x) \\
 \text{id} \times \circ \downarrow & & \downarrow \circ \\
 \mathcal{C}(y, z) \times \mathcal{C}(w, y) & \xrightarrow{\circ} & \mathcal{C}(w, z)
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathcal{C}(x, y) & \xrightarrow{\text{id} \times \text{id}_x} & \mathcal{C}(x, y) \times \mathcal{C}(x, x) \\
 \text{id}_y \times \text{id} \downarrow & \searrow & \downarrow \circ \\
 \mathcal{C}(y, y) \times \mathcal{C}(x, y) & \xrightarrow{\circ} & \mathcal{C}(x, y)
 \end{array}$$

Evidently from the diagrams of (A.0.1), a locally-small 1-category defines a category enriched in \mathbf{Set} . The underlying set functor of Definition A.1.5 can be used to define the “underlying category” of an enriched category.

A.2.2. DEFINITION. If \mathcal{C} is a \mathcal{V} -category, its **underlying category** is the 1-category with the same set of objects and with hom-sets $\mathcal{C}(x, y)_0$ defined by applying the underlying set functor $(-)_0: \mathcal{V} \rightarrow \mathbf{Set}$ to the hom-objects $\mathcal{C}(x, y) \in \mathcal{V}$.

Note the identity arrow $\text{id}_x: 1 \rightarrow \mathcal{C}(x, x)$ of the \mathcal{V} -category is by definition an element of the hom-set $\mathcal{C}(x, x)_0 := \mathcal{V}(1, \mathcal{C}(x, x))$. The composite of two arrows $f: 1 \rightarrow \mathcal{C}(x, y)$ and $g: 1 \rightarrow \mathcal{C}(y, z)$ in the underlying category is defined to be the arrow constructed as the composite

$$1 \xrightarrow{g \times f} \mathcal{C}(y, z) \times \mathcal{C}(x, y) \xrightarrow{\circ} \mathcal{C}(x, z)$$

In analogy with the discussion around Definition A.1.5, when one speaks of “enriching” an a priori unenriched category \mathcal{C} over \mathcal{V} , the task is to define a \mathcal{V} -enriched category as in Definition A.2.1 whose underlying category recovers \mathcal{C} . When $\mathcal{V} = \mathbf{Cat}$, the task is to define a 2-category whose underlying 1-category is the one given. When $\mathcal{V} = \mathbf{sSet}$, the task is define simplicial hom-sets of n -arrows so that the 0-arrows are the ones given. When a simplicially enriched category \mathcal{C} is encoded as a simplicial object \mathcal{C}_\bullet in \mathbf{Cat} as explained in Digression 1.2.2, its underlying category is the category \mathcal{C}_0 , further justifying the notion introduced in Definition A.2.2.

For example, a cartesian closed category \mathcal{V} as in Definition A.1.1 can be enriched to define a \mathcal{V} -category.

A.2.3. LEMMA. A cartesian closed category \mathcal{V} defines a \mathcal{V} -category whose:

- objects are the objects of \mathcal{V} ,
- hom-object in \mathcal{V} from A to B is given by the internal hom B^A , and

⁴These diagrams suppose the associativity and unit natural isomorphisms involving the product bifunctors \times and its unit object 1. In a cartesian closed category these are *canonical* — rather than given by extra data, as is the case in the more general *closed symmetric monoidal category*; see Exercise A.1.ii.

- the identity map $\text{id}_A: 1 \rightarrow A^A$ and composition map $\circ: C^B \times B^A \rightarrow C^A$ are defined to be the transposes of

$$1 \times A \xrightarrow{\cong} A \quad \text{and} \quad C^B \times B^A \times A \xrightarrow{\text{id} \times \epsilon} C^B \times B \xrightarrow{\epsilon} C$$

the latter defined using the counit of the cartesian closure adjunction.

PROOF. The task is to verify the commutative diagrams of (A.2.1) in \mathcal{V} and then observe that Lemma A.1.6 reveals that the underlying category of the \mathcal{V} -category defined by the statement is the 1-category \mathcal{V} . We leave the identity conditions to the reader and verify associativity.

The definition of the composition map as an adjoint transpose implies that its adjoint transpose, the top-right composite below, is given by the left-bottom composite:

$$\begin{array}{ccc} C^B \times B^A \times A & \xrightarrow{\circ \times \text{id}} & C^A \times A \\ \text{id} \times \epsilon \downarrow & & \downarrow \epsilon \\ C^B \times B & \xrightarrow{\epsilon} & C \end{array}$$

The associativity diagram below-left commutes if and only if the transposed diagram appearing as the outer boundary composite below-right commutes:

$$\begin{array}{ccccc} D^C \times C^B \times B^A & \xrightarrow{\circ \times \text{id}} & D^B \times B^A & & \\ \text{id} \times \circ \downarrow & & \downarrow \circ & \Leftrightarrow & \\ D^C \times C^A & \xrightarrow{\circ} & D^A & & \\ & & & & \\ & & D^C \times C^B \times B^A \times A & \xrightarrow{\circ \times \text{id} \times \text{id}} & D^B \times B^A \times A \\ & & \downarrow \text{id} \times \text{id} \times \epsilon & & \downarrow \text{id} \times \epsilon \\ & & D^C \times C^B \times B & \xrightarrow{\circ \times \text{id}} & D^B \times B \\ & & \downarrow \text{id} \times \epsilon & & \downarrow \epsilon \\ & & D^C \times C^A \times A & \xrightarrow{\text{id} \times \epsilon} & D^C \times C \xrightarrow{\epsilon} D \end{array}$$

which follows from bifactoriality of \times and two instances of the commutative square above. \square

A.2.4. DEFINITION. The free \mathcal{V} -category on a 1-category \mathcal{C} has

- the same objects as \mathcal{C}
- the hom-objects defined to be coproducts $\coprod_{C(x,y)} 1$ of the terminal object 1 indexed by the hom-set $\mathcal{C}(x,y)$
- the identity map $\text{id}_x: 1 \rightarrow \coprod_{C(x,x)} 1$ given by the inclusion of the component indexed by the identity arrow
- the composition map given by acting by the composition function on the indexing sets:

$$\coprod_{C(y,z)} 1 \times \coprod_{C(x,y)} 1 \cong \coprod_{C(y,z) \times C(x,y)} 1 \xrightarrow{\coprod \circ} \coprod_{C(x,z)} 1$$

For example, free \mathbf{Cat} -enriched categories are those with no non-identity 2-cells and free \mathbf{SSet} -enriched categories are those with no non-degenerate arrows in positive dimensions. When context allows, we use the same name for the 1-category \mathcal{C} and the free \mathcal{V} -category it generates, using language to disambiguate.

A.2.5. DEFINITION. A \mathcal{V} -enriched functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is given by

- a mapping on objects that carries each $x \in \mathcal{C}$ to some $Fx \in \mathcal{D}$

- for each pair of objects $x, y \in \mathcal{C}$, an internal action on the \mathcal{V} -objects of arrows given by a morphism $F_{x,y}: \mathcal{C}(x, y) \rightarrow \mathcal{D}(Fx, Fy) \in \mathcal{V}$ so that the \mathcal{V} -functoriality diagrams commute:

$$\begin{array}{ccc}
 \mathcal{C}(y, z) \times \mathcal{C}(x, y) & \xrightarrow{\circ} & \mathcal{C}(x, z) \\
 F_{y,z} \times F_{x,y} \downarrow & & \downarrow F_{x,z} \\
 \mathcal{D}(Fy, Fz) \times \mathcal{D}(Fx, Fy) & \xrightarrow{\circ} & \mathcal{D}(Fx, Fz)
 \end{array}
 \qquad
 \begin{array}{ccc}
 1 & \xrightarrow{\text{id}_x} & \mathcal{C}(x, x) \\
 \text{id}_{Fx} \searrow & & \downarrow F_{x,x} \\
 & & \mathcal{D}(Fx, Fx)
 \end{array}$$

A prototypical example is given by the representable functors:

A.2.6. EXAMPLE. For any \mathcal{V} -category \mathcal{C} and object $c \in \mathcal{C}$, the **enriched representable \mathcal{V} -functor** $\mathcal{C}(c, -): \mathcal{C} \rightarrow \mathcal{V}$ is defined on objects by the assignment $x \in \mathcal{C} \mapsto \mathcal{C}(c, x) \in \mathcal{V}$ and whose internal action on arrows

$$\mathcal{C}(x, y) \xrightarrow{\mathcal{C}(c, -)_{x,y}} \mathcal{C}(c, y)^{\mathcal{C}(c, x)} \quad \rightsquigarrow \quad \mathcal{C}(x, y) \times \mathcal{C}(c, x) \xrightarrow{\circ} \mathcal{C}(c, y)$$

is given by the adjoint transpose of the internal composition map for \mathcal{C} . The \mathcal{V} -functoriality diagrams are transposes of associativity and identity diagrams in \mathcal{C} .

The contravariant enriched representable functors are defined similarly; see Exercise A.2.ii.

As the next result explains, an enriched representable functor can be thought of as a “two-step” enrichment of the corresponding unenriched representable functor: the first step enriches the hom-sets to hom-objects in \mathcal{V} and the second step enriches the composition function to an internal composition map in \mathcal{V} .

A.2.7. PROPOSITION. *To enrich a 1-category \mathcal{C} over \mathcal{V} one must:*

- First lift each of the unenriched representable functors through the underlying set functor to define an unenriched functor that encodes the data of the objects of arrows in \mathcal{V} :*

$$\begin{array}{ccc}
 \mathcal{C} & \xrightarrow{\mathcal{C}(c, -)} & \mathcal{V} \\
 \mathcal{C}(c, -) \searrow & & \swarrow (-)_0 \\
 & \text{Set} &
 \end{array}
 \qquad
 \begin{array}{ccc}
 \mathcal{C} & \xrightarrow{\mathcal{C}(c, -)} & \mathcal{V} \\
 x \longmapsto & \mathcal{C}(c, x) &
 \end{array}$$

- Then enrich each of the unenriched \mathcal{V} -valued representable functors defined in (i) to a \mathcal{V} -functor $\mathcal{C}(c, -): \mathcal{C} \rightarrow \mathcal{V}$ whose internal action on arrows encodes the data of the internal composition map for \mathcal{C} .*

PROOF. The correspondence between the data in (i) and (ii) and the data of a \mathcal{V} -enriched category whose underlying category is \mathcal{C} is clear. As discussed in Definition A.2.2, there is no additional data required by the identity arrows in an enriched category. Now the \mathcal{V} -functoriality of the enriched representable functor $\mathcal{C}(c, -): \mathcal{C} \rightarrow \mathcal{V}$ is expressed by commutative diagrams

$$\begin{array}{ccc}
 \mathcal{C}(y, z) \times \mathcal{C}(x, y) & \xrightarrow{\circ} & \mathcal{C}(x, z) \\
 \mathcal{C}(c, -)_{y,z} \times \mathcal{C}(c, -)_{x,y} \downarrow & & \downarrow \mathcal{C}(c, -)_{x,z} \\
 \mathcal{C}(c, z)^{\mathcal{C}(c, y)} \times \mathcal{C}(c, y)^{\mathcal{C}(c, x)} & \xrightarrow{\circ} & \mathcal{C}(c, z)^{\mathcal{C}(c, x)}
 \end{array}
 \qquad
 \begin{array}{ccc}
 1 & \xrightarrow{\text{id}_x} & \mathcal{C}(x, x) \\
 \text{id}_{\mathcal{C}(c, x)} \searrow & & \downarrow \mathcal{C}(c, -)_{x,x} \\
 & & \mathcal{C}(c, x)^{\mathcal{C}(c, x)}
 \end{array}$$

— where the composition map in \mathcal{C} is the one that has just been defined — and these transpose to the required associativity and identity axioms for the \mathcal{V} -category \mathcal{C} . \square

Both of the constructions of underlying unenriched categories and free categories extend functorially to functors; see Exercise A.2.iii. The relationship between these constructions is summarized by the following proposition, which we also decline to prove, because it will be generalized by a result that we do provide a proof for in §A.6.

A.2.8. PROPOSITION. *The free \mathcal{V} -category functor defines a fully faithful left adjoint to the underlying category functor. Consequently, a \mathcal{V} -category is free just when it is isomorphic to the free category on its underlying category via the counit of this adjunction.*

PROOF. Exercise A.2.iv or see §A.6. □

Exercises.

A.2.i. EXERCISE. Verify the unit condition left to the reader in the proof of Lemma A.2.3.

A.2.ii. EXERCISE. Define the **opposite** of a \mathcal{V} -category and dualize Example A.2.6 to define contravariant enriched representable functors.

A.2.iii. EXERCISE.

- (i) Define the underlying functor of an enriched functor.
- (ii) Prove that the passage from enriched functors to underlying unenriched functors is functorial.
- (iii) Define the free enriched functor on an unenriched functor.
- (iv) Prove the passage from unenriched functors to free enriched functors is functorial.

A.2.iv. EXERCISE. Prove A.2.8.

A.3. Enriched natural transformations and the enriched Yoneda lemma

Recall an (unenriched) natural transformation $\alpha: F \Rightarrow G$ between parallel functors $F, G: \mathcal{C} \Rightarrow \mathcal{D}$ is given by:

- the data of an arrow $\alpha_x \in \mathcal{D}(Fx, Gx)$ for each $x \in \mathcal{C}$
- subject to the condition that for each morphism $f \in \mathcal{C}(x, y)$, the diagram

$$\begin{array}{ccc} Fx & \xrightarrow{\alpha_x} & Gx \\ Ff \downarrow & & \downarrow Gf \\ Fy & \xrightarrow{\alpha_y} & Gy \end{array} \quad (\text{A.3.1})$$

commutes in \mathcal{D} .

This enriches to the notion of a \mathcal{V} -natural transformation whose data is exactly the same — a family of arrows in the underlying category of \mathcal{D} indexed by the objects of \mathcal{C} — but with a stronger \mathcal{V} -naturality condition expressed by internalizing the naturality condition (A.3.1) given above.

A.3.2. DEFINITION. A \mathcal{V} -enriched natural transformation $\alpha: F \Rightarrow G$ between \mathcal{V} -enriched functors $F, G: \mathcal{C} \Rightarrow \mathcal{D}$ is given by:

- an arrow $\alpha_x: 1 \rightarrow \mathcal{D}(Fx, Gx)$ for each $x \in \mathcal{C}$

- so that for each pair of objects $x, y \in \mathcal{C}$, the follow \mathcal{V} -naturality square commutes in \mathcal{V} :

$$\begin{array}{ccc}
\mathcal{C}(x, y) & \xrightarrow{\alpha_y \times F_{x,y}} & \mathcal{D}(Fy, Gy) \times \mathcal{D}(Fx, Fy) \\
G_{x,y} \times \alpha_x \downarrow & & \downarrow \circ \\
\mathcal{D}(Gx, Gy) \times \mathcal{D}(Fx, Gx) & \xrightarrow{\circ} & \mathcal{D}(Fx, Gy)
\end{array} \tag{A.3.3}$$

A.3.4. EXAMPLE. An arrow $f: 1 \rightarrow \mathcal{C}(x, y)$ in the underlying category of a \mathcal{V} -category \mathcal{C} defines a \mathcal{V} -natural transformation $f^*: \mathcal{C}(y, -) \Rightarrow \mathcal{C}(x, -)$ between the enriched representable functors whose component at $z \in \mathcal{C}$ is defined by evaluating the adjoint transpose of the composition map at f :

$$1 \xrightarrow{f} \mathcal{C}(x, y) \xrightarrow{\mathcal{C}(-, z)_{x,y}} \mathcal{C}(y, z)^{\mathcal{C}(x,y)}$$

Evaluating one component of the associative diagram for \mathcal{C} at f provides the required \mathcal{V} -naturality square.

A.3.5. LEMMA.

- (i) The **vertical composite** of \mathcal{V} -enriched natural transformations $\alpha: F \Rightarrow G$ and $\beta: G \Rightarrow H$, both from \mathcal{C} to \mathcal{D} has component $(\beta \cdot \alpha)_x$ at $x \in \mathcal{C}$ defined by the composite

$$1 \xrightarrow{\beta_x \times \alpha_x} \mathcal{D}(Gx, Hx) \times \mathcal{D}(Fx, Gx) \xrightarrow{\circ} \mathcal{D}(Fx, Hx)$$

- (ii) The **horizontal composite** of $\alpha: F \Rightarrow G$ from \mathcal{C} to \mathcal{D} and $\gamma: H \Rightarrow K$ from \mathcal{D} to \mathcal{E} has component $(\gamma * \alpha)_x$ at $x \in \mathcal{C}$ defined by the composite

$$\begin{array}{ccc}
1 & \xrightarrow{\alpha_x} & \mathcal{D}(Fx, Gx) \xrightarrow{\gamma_{Gx} \times H_{Fx, Gx}} \mathcal{E}(KGx, HGx) \times \mathcal{E}(HFX, HGx) \\
& & \downarrow \circ \\
& & \mathcal{E}(KFX, KGx) \times \mathcal{E}(HFX, KFX) \xrightarrow{\circ} \mathcal{D}(HFX, KGx)
\end{array}$$

which is well-defined by \mathcal{V} -naturality of γ .

PROOF. Exercise A.3.i. □

The data of the **underlying natural transformation** of a \mathcal{V} -naturality transformation is given by the same family of arrows. The unenriched naturality condition (A.3.1) is proven by evaluating the enriched naturality condition (A.3.3) at an underlying arrow $f: 1 \rightarrow \mathcal{C}(x, y)$. In particular, the middle four interchange rule for horizontal and vertical composition of \mathcal{V} -natural transformations follows from the middle four interchange rule for horizontal and vertical composition of unenriched natural transformations for the data of the latter determines the data of the former. Consequently, Lemma A.3.5 implies that:

A.3.6. COROLLARY. For any cartesian closed category \mathcal{V} , there is a 2-category $\mathcal{V}\text{-Cat}$ of \mathcal{V} -enriched categories, \mathcal{V} -enriched functors, and \mathcal{V} -enriched natural transformations. Moreover, the underlying category functor $\mathcal{V}\text{-Cat} \rightarrow \text{Cat}$ and the free \mathcal{V} -category functor $\text{Cat} \rightarrow \mathcal{V}\text{-Cat}$ are both 2-functors. □

We now turn our attention to the \mathcal{V} -enriched Yoneda lemma, which we present in several forms. One role of the Yoneda lemma is to give a representable characterization of isomorphic objects in \mathcal{C} . When \mathcal{C} is a \mathcal{V} -category, this has several forms involving each of the three notions of “representable”

functor appearing in Proposition A.2.7. The notion of **\mathcal{V} -natural isomorphism** referred to in the following result is defined to be a \mathcal{V} -natural transformation with an inverse for vertical composition.

A.3.7. LEMMA. *For objects x, y in a \mathcal{V} -category \mathcal{C} the following are equivalent:*

- (i) *x and y are isomorphic as objects of the underlying category of \mathcal{C} .*
- (ii) *The \mathbf{Set} -valued unenriched representable functors $\mathcal{C}(x, -)_0, \mathcal{C}(y, -)_0: \mathcal{C} \rightrightarrows \mathbf{Set}$ are naturally isomorphic.*
- (iii) *The \mathcal{V} -valued unenriched representable functors $\mathcal{C}(x, -), \mathcal{C}(y, -): \mathcal{C} \rightrightarrows \mathcal{V}$ are naturally isomorphic.*
- (iv) *The \mathcal{V} -valued \mathcal{V} -functors $\mathcal{C}(x, -), \mathcal{C}(y, -): \mathcal{C} \rightrightarrows \mathcal{V}$ are naturally \mathcal{V} -isomorphic.*

PROOF. Applying the underlying category functor $(-)_0: \mathcal{V}\text{-Cat} \rightarrow \mathbf{Cat}$, the fourth statement implies the third. The third statement implies the second by composing the underlying set functor $(-)_0: \mathcal{V} \rightarrow \mathbf{Set}$. The second statement implies the first by the unenriched Yoneda lemma; this is still the main point. Finally, the first statement implies the last by a direct construction: if $f: 1 \rightarrow \mathcal{C}(x, y)$ and $g: 1 \rightarrow \mathcal{C}(y, x)$ define an isomorphism in the underlying category of \mathcal{C} , the corresponding representable \mathcal{V} -natural transformations of Example A.3.4 define a \mathcal{V} -natural isomorphism. \square

Lemma A.3.7 defines a common notion of **isomorphism** between two objects of an enriched category, which turns out to be no different the usual unenriched notion of isomorphism. This can be thought of as defining a “cheap” form of the enriched Yoneda lemma. The full form of the \mathcal{V} -Yoneda lemma enriches the usual statement — a natural isomorphism between the set of natural transformations whose domain is a representable functor to the set defined by evaluating the codomain at the representing object — to an isomorphism in \mathcal{V} . The first step to make this precise is to enrich the set of \mathcal{V} -enriched natural transformations between a parallel pair of \mathcal{V} -functors can to define an object of \mathcal{V} .

A.3.8. DEFINITION. Let \mathcal{V} be a complete cartesian closed category and consider a parallel pair of \mathcal{V} -functors $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$, with \mathcal{C} a small \mathcal{V} -category. Then the **\mathcal{V} -object of \mathcal{V} -natural transformations** is defined by the equalizer diagram

$$\mathcal{V}^{\mathcal{C}}(F, G) \rightrightarrows \prod_{z \in \mathcal{C}} \mathcal{D}(Fz, Gz) \rightrightarrows \prod_{x, y \in \mathcal{C}} \mathcal{D}(Fx, Gy)^{\mathcal{C}(x, y)}$$

where one map in the equalizer diagram is defined by projecting to $\mathcal{D}(Fx, Gx)$, applying the internal action of G on arrows, and then composing, while the other is defined by projection to $\mathcal{D}(Fy, Gy)$, applying the internal action of F on arrows, and then composing.

A.3.9. LEMMA. *The underlying set of the \mathcal{V} -object of \mathcal{V} -natural transformations $\mathcal{V}^{\mathcal{C}}(F, G)$ is the set of \mathcal{V} -natural transformations from F to G .*

PROOF. By its defining universal property, elements of the underlying set of $\mathcal{V}^{\mathcal{C}}(F, G)$ correspond to maps $\alpha: 1 \rightarrow \prod_{z \in \mathcal{C}} \mathcal{D}(Fz, Gz)$ that equalize the parallel pair of maps described in Definition A.3.8. The map α defines the components of a \mathcal{V} -natural transformation $\alpha: F \Rightarrow G$ and the commutativity condition transposes to (A.3.3). \square

The Yoneda lemma is usually expressed by the slogan “evaluation at the identity is an isomorphism,” but since in the enriched context the enriched object of natural transformations is defined via a limit, it is easier to define the map that induces a natural transformation instead. Given an object $a \in \mathcal{A}$

in a small \mathcal{V} -category and a \mathcal{V} -functor $F: \mathcal{A} \rightarrow \mathcal{V}$, the internal action of F on arrows transposes to define a map that equalizes the parallel pair

$$Fa \xrightarrow{F_{a,-}} \prod_{z \in \mathcal{A}} Fz^{\mathcal{A}(a,z)} \rightrightarrows \prod_{x,y \in \mathcal{A}} Fy^{Fx \times \mathcal{A}(x,y)} \quad (\text{A.3.10})$$

and thus induces a map $Fa \rightarrow \mathcal{V}^{\mathcal{A}}(\mathcal{A}(a, -), F)$ in \mathcal{V} .

A.3.11. THEOREM (enriched Yoneda lemma). *For any small \mathcal{V} -category \mathcal{A} , object $a \in \mathcal{A}$, and \mathcal{V} -functor $F: \mathcal{A} \rightarrow \mathcal{V}$, the canonical map defines an isomorphism in \mathcal{V}*

$$Fa \xrightarrow{\cong} \mathcal{V}^{\mathcal{A}}(\mathcal{A}(a, -), F),$$

that is \mathcal{V} -natural in both a and F .

PROOF. To prove the isomorphism, it suffices to verify that (A.3.10) is a limit cone. To that end consider another cone over the parallel pair

$$V \xrightarrow{\lambda} \prod_{z \in \mathcal{A}} Fz^{\mathcal{A}(a,z)} \rightrightarrows \prod_{x,y \in \mathcal{A}} Fy^{Fx \times \mathcal{A}(x,y)}$$

and define a candidate factorization by evaluating the component λ_a at id_a :

$$\lambda_a(\text{id}_a) := V \xrightarrow{\text{id}_a \times \text{id}} \mathcal{A}(a, a) \times V \xrightarrow{\lambda_a} Fa$$

To see that $\lambda_a(\text{id}_a): V \rightarrow Fa$ indeed defines a factorization of λ through the limit cone, it suffices to show commutativity at each component $Fz^{\mathcal{A}(a,z)}$ of the product, which we verify in transposed form:

$$\begin{array}{ccc} \mathcal{A}(a, z) \times V & & \\ \text{id} \times \text{id}_a \times \text{id} \downarrow & \searrow & \\ \mathcal{A}(a, z) \times \mathcal{A}(a, a) \times V & \xrightarrow{\circ \times \text{id}} & \mathcal{A}(a, z) \times V \\ \text{id} \times \lambda_a \downarrow & & \downarrow \lambda_z \\ \mathcal{A}(a, z) \times Fa & \xrightarrow{F_{a,z}} & Fz \end{array}$$

The upper triangle commutes by the identity law for \mathcal{A} while the bottom square commutes because λ defines a cone over the parallel pair. Uniqueness of the factorization $\lambda_a(\text{id}_a)$ follows from the same diagram by taking $z = a$ and evaluating at id_a .

We leave the verification of \mathcal{V} -naturality to the reader or to [31, §2.4]. \square

Passing to underlying sets:

A.3.12. COROLLARY. *For any small \mathcal{V} -category \mathcal{A} , object $a \in \mathcal{A}$, and \mathcal{V} -functor $F: \mathcal{A} \rightarrow \mathcal{V}$, there is a bijection between \mathcal{V} -natural transformations $\alpha: \mathcal{A}(a, -) \Rightarrow F$ and elements $1 \rightarrow Fa$ in the underlying set of Fa implemented by evaluating the component at $a \in \mathcal{A}$ at the identity id_a .* \square

Since we have assumed our bases for enrichment to be cartesian closed, the 2-category $\mathcal{V}\text{-Cat}$ admits finite products, allowing us to define multivariable \mathcal{V} -functors. The following result will imply that the structures characterized by \mathcal{V} -natural isomorphisms in §A.4 and §A.5 assemble into \mathcal{V} -functors.

A.3.13. PROPOSITION. Let $M: \mathcal{B}^{\text{op}} \times \mathcal{A} \rightarrow \mathcal{V}$ be a \mathcal{V} -functor so that for each $a \in \mathcal{A}$, the \mathcal{V} -functor $M(-, a): \mathcal{B}^{\text{op}} \rightarrow \mathcal{V}$ is represented by some $Fa \in \mathcal{B}$, meaning there exists a \mathcal{V} -natural isomorphism

$$\mathcal{B}(b, Fa) \cong M(b, a).$$

Then there is a unique way of extending the mapping $a \in \mathcal{A} \mapsto Fa \in \mathcal{B}$ to a \mathcal{V} -functor $F: \mathcal{A} \rightarrow \mathcal{B}$ so that the isomorphisms are \mathcal{V} -natural in $a \in \mathcal{A}$ as well as $b \in \mathcal{B}$.

PROOF. By the Yoneda lemma in the form of Corollary A.3.12, to define a family of isomorphisms $\alpha_{b,a}: \mathcal{B}(b, Fa) \cong M(b, a)$ for each $a \in \mathcal{A}$ that are \mathcal{V} -natural in $b \in \mathcal{B}$ is to define a family of elements $\eta_a: 1 \rightarrow M(Fa, a)$ for each $a \in \mathcal{A}$. By the \mathcal{V} -naturality statement in the Yoneda lemma, for the former isomorphism to be \mathcal{V} -natural in a is equivalent to the family of elements $\eta_a: 1 \rightarrow M(Fa, a)$ being “extraordinarily” \mathcal{V} -natural in a . What this means is that for any pair of objects $a, a' \in \mathcal{A}$, the outer square commutes:

$$\begin{array}{ccc}
\mathcal{A}(a', a) & \xrightarrow{M(F-, a)_{a, a'}} & M(Fa', a)^{M(Fa, a)} \\
\downarrow M(Fa', -)_{a', a} & \dashrightarrow^F & \nearrow M(-, a) \\
& & \mathcal{B}(Fa', Fa) \\
& & \searrow \alpha_{Fa', a} \\
M(Fa', a)^{M(Fa', a')} & \xrightarrow{M(Fa', a)^{\eta_{a'}}} & M(Fa', a) \\
& & \downarrow M(Fa', a)^{\eta_a}
\end{array}$$

The definition of the top-horizontal map $M(F-, a)_{a', a}$ depends on the internal action of F on arrows, which we seek to define, but note that the composite of the other factor with the right vertical map is the natural isomorphism $\alpha_{Fa', a}$. Thus, there is a unique way to define $F_{a', a}$ making the extraordinary \mathcal{V} -naturality square commute, which is exactly the claim. \mathcal{V} -functoriality of these internal action maps for F follows from \mathcal{V} -functoriality of M in the \mathcal{A} variable. \square

We close this section with some applications. The correct notions of \mathcal{V} -enriched equivalence or \mathcal{V} -enriched adjunction are given by interpreting the standard 2-categorical notions of equivalence and adjunction in the 2-category \mathcal{V} . For sake of contrast, we present both notions in an alternate form here and leave it to the reader to apply Theorem A.3.11 to relate these to the 2-categorical notions.

A.3.14. DEFINITION. A pair of \mathcal{V} -categories \mathcal{C} and \mathcal{D} are **\mathcal{V} -equivalent** if there exists a \mathcal{V} -functor $F: \mathcal{C} \rightarrow \mathcal{D}$ that is

- **\mathcal{V} -fully faithful:** i.e., each $F_{x,y}: \mathcal{C}(x,y) \rightarrow \mathcal{D}(Fx,Fy)$ is an isomorphism in \mathcal{V} and
- **essentially surjective on objects:** i.e., each $d \in \mathcal{D}$ is isomorphic to Fc for some $c \in \mathcal{C}$.

A.3.15. DEFINITION. A **\mathcal{V} -enriched adjunction** is given by a pair of \mathcal{V} -functors $F: \mathcal{B} \rightarrow \mathcal{A}$ and $U: \mathcal{A} \rightarrow \mathcal{B}$ together with isomorphisms

$$\mathcal{A}(Fb, a) \cong \mathcal{B}(b, Ua)$$

that are \mathcal{V} -natural in both $a \in \mathcal{A}$ and $b \in \mathcal{B}$.

A.3.16. REMARK. By Proposition A.3.13, a \mathcal{V} -functor $U: \mathcal{A} \rightarrow \mathcal{B}$ admits a \mathcal{V} -left adjoint if and only if each $\mathcal{B}(b, U-): \mathcal{A} \rightarrow \mathcal{V}$ is represented by some object $Fb \in \mathcal{A}$, in which case the data of the \mathcal{V} -natural isomorphism $\mathcal{A}(Fb, -) \cong \mathcal{B}(b, U-)$ equips $b \in \mathcal{B} \mapsto Fb \in \mathcal{A}$ with the structure of a \mathcal{V} -functor. Dual remarks construct enriched right adjoints.

Exercises.

A.3.i. EXERCISE. Prove Lemma A.3.5.

A.3.ii. EXERCISE. Use Corollary A.3.12 to show that the notions of \mathcal{V} -equivalence and \mathcal{V} -adjunction given in Definitions A.3.14 and A.3.15 are equivalent to the 2-categorical notions in $\mathcal{V}\text{-Cat}$.

A.4. Tensors and cotensors

A \mathcal{V} -category \mathcal{C} admits *tensors* just when for all $C \in \mathcal{C}$, the covariant representable functor $\mathcal{C}(C, -): \mathcal{C} \rightarrow \mathcal{V}$ admits a left \mathcal{V} -adjoint $- \otimes C: \mathcal{V} \rightarrow \mathcal{C}$. Dually, a \mathcal{V} -category \mathcal{C} admits *cotensors* just when the contravariant representable functor $\mathcal{C}(-, C): \mathcal{C}^{\text{op}} \rightarrow \mathcal{V}$ admits a mutual right adjoint $C^-: \mathcal{V}^{\text{op}} \rightarrow \mathcal{C}$. The aim in this section is to introduce both constructions formally. In the next section, we establish some useful formal properties of enriched categories that are either *tensored* or *cotensored*.

A.4.1. DEFINITION. A \mathcal{V} -category \mathcal{C} is **cotensored**, if for all $V \in \mathcal{V}$ and $C \in \mathcal{C}$, the \mathcal{V} -functor $\mathcal{C}(-, C)^V: \mathcal{C}^{\text{op}} \rightarrow \mathcal{V}$ is represented by an object $C^V \in \mathcal{C}$, i.e., there exists an isomorphism

$$\mathcal{C}(X, C^V) \cong \mathcal{C}(X, C)^V$$

in \mathcal{V} that is \mathcal{V} -natural in X . By Proposition A.3.13, the cotensor product defines a unique \mathcal{V} -functor

$$\mathcal{C} \times \mathcal{V}^{\text{op}} \xrightarrow{(-)^-} \mathcal{C}$$

making the defining isomorphism \mathcal{V} -natural in all three variables.

A.4.2. DEFINITION. Dually, a \mathcal{V} -category \mathcal{C} is **cotensored** if for all $V \in \mathcal{V}$ and C the \mathcal{V} -functor $\mathcal{C}(C, -)^V: \mathcal{C} \rightarrow \mathcal{V}$ is represented by an object $V \otimes C \in \mathcal{C}$, i.e., there exists an isomorphism

$$\mathcal{C}(V \otimes C, X) \cong \mathcal{C}(C, X)^V$$

in \mathcal{V} that is \mathcal{V} -natural in X . By Proposition A.3.13, the tensor product defines a unique \mathcal{V} -functor

$$\mathcal{V} \times \mathcal{C} \xrightarrow{- \otimes -} \mathcal{C}$$

making the defining isomorphism \mathcal{V} -natural in all three variables.

Immediately from these definitions

A.4.3. LEMMA. A \mathcal{V} -category \mathcal{C} is tensored and cotensored if and only if the \mathcal{V} -functor $\mathcal{C}(-, -): \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \mathcal{V}$ is part of a two-variable \mathcal{V} -adjunction

$$\begin{array}{ccc} & \mathcal{C}(V \times A, B) & \\ \nearrow & \cong & \nwarrow \\ \mathcal{C}(A, B^V) & \cong & \mathcal{C}(A, B)^V \end{array}$$

as expressed by the commutative triangle of \mathcal{V} -natural isomorphisms. □

A.4.4. LEMMA. In any category \mathcal{C} that is enriched and cotensored over \mathcal{V} , there are \mathcal{V} -natural isomorphisms

$$C^1 \cong C \quad \text{and} \quad (C^V)^U \cong C^{U \times V} \cong (C^U)^V$$

for $U, V \in \mathcal{V}$ and $C \in \mathcal{C}$.

PROOF. By Lemma A.3.7, to define the displayed \mathcal{V} -natural isomorphisms, it suffices to prove that these objects represent the same \mathcal{V} -functors $\mathcal{C}^{\text{op}} \rightarrow \mathcal{V}$. By the defining universal property of the cotensor, for any $X \in \mathcal{C}$,

$$\mathcal{C}(X, C^1) \cong \mathcal{C}(X, C)^1 \cong \mathcal{C}(X, C)$$

by Remark A.1.9. Similarly, by the defining universal property of the cotensor, we have \mathcal{V} -natural isomorphisms in each of the three vertices of the triangle below

$$\begin{array}{ccc} & \mathcal{C}(X, C^{U \times V}) \cong \mathcal{C}(X, C)^{U \times V} & \\ & \cong & \\ \mathcal{C}(X, (C^V)^U) \cong (\mathcal{C}(X, C)^V)^U & & \cong & \mathcal{C}(X, (C^U)^V) \cong (\mathcal{C}(X, C)^U)^V \end{array}$$

whence the connecting \mathcal{V} -natural isomorphisms are given by Lemma A.1.7. \square

Extending Lemma A.2.3:

A.4.5. LEMMA. *A cartesian closed category $(\mathcal{V}, \times, 1)$ is enriched, tensored, and cotensored over itself, with tensors defined by the cartesian product and cotensors defined by the internal hom⁵:*

$$V \otimes W := V \times W \quad \text{and} \quad W^V := W^V.$$

PROOF. Lemma A.1.7 establishes the required isomorphisms (A.1.8) in \mathcal{V} . The proof of their \mathcal{V} -naturality is left to the reader or [31, §1.8]. \square

The presence of tensors and cotensors provides a convenient mechanism for testing whether an a priori unenriched adjunction may be enriched to a \mathcal{V} -adjunction.

A.4.6. PROPOSITION. *Let $U: \mathcal{A} \rightarrow \mathcal{B}$ and $F: \mathcal{B} \rightarrow \mathcal{A}$ be unenriched adjoint functors between categories \mathcal{A} and \mathcal{B} that are both enriched over \mathcal{V} .*

- (i) *If \mathcal{A} and \mathcal{B} are cotensored over \mathcal{V} and $U: \mathcal{A} \rightarrow \mathcal{B}$ is a cotensor-preserving \mathcal{V} -functor, then $F \dashv U$ may be enriched to a \mathcal{V} -adjunction.*
- (ii) *If \mathcal{A} and \mathcal{B} are tensored over \mathcal{V} and $F: \mathcal{B} \rightarrow \mathcal{A}$ is a tensor-preserving \mathcal{V} -functor, then $F \dashv U$ may be enriched to a \mathcal{V} -adjunction.*

PROOF. Exercise A.4.i. \square

There is a convenient device for turning an a priori unenriched category \mathcal{C} into a category that is both enriched and cotensored over simplicial sets that is of utility in constructing ∞ -cosmoi. This is a specialization of the notion of *closed \mathcal{V} -module* of [54, 14.3] to the case $\mathcal{V} = \mathbf{SSet}$, in which case less data is required to prove Proposition A.4.8.

A.4.7. DEFINITION. An unenriched category \mathcal{C} is a **right \mathbf{SSet} -module** if there exists a bifunctor

$$\mathcal{C} \times \mathbf{SSet}^{\text{op}} \xrightarrow{(-)^-} \mathcal{C}$$

equipped with natural isomorphisms

$$\begin{array}{ccc} \mathcal{C} \times \mathbf{SSet}^{\text{op}} \times \mathbf{SSet}^{\text{op}} & \xrightarrow{(-)^- \times \text{id}} & \mathcal{C} \times \mathbf{SSet}^{\text{op}} \\ \text{id} \times (- \times -) \downarrow & \cong & \downarrow (-)^- \\ \mathcal{C} \times \mathbf{SSet}^{\text{op}} & \xrightarrow{(-)^-} & \mathcal{C} \end{array} \quad \begin{array}{ccc} \mathcal{C} & \xrightarrow{(-, 1)} & \mathcal{C} \times \mathbf{SSet}^{\text{op}} \\ & \searrow \text{id} & \downarrow (-)^- \\ & & \mathcal{C} \end{array}$$

⁵This justifies the abuse of exponential notation for both internal homs and cotensors.

asserting that for $U, V \in \mathcal{S}\mathcal{S}et$ and $A \in \mathcal{C}$

$$A^{U \times V} \cong (A^U)^V \quad \text{and} \quad A \cong A^1$$

with these natural isomorphisms satisfying the manifest pseudo-algebra laws. A right $\mathcal{S}\mathcal{S}et$ -module is **continuous** if the bifunctor $\mathcal{C} \times \mathcal{S}\mathcal{S}et^{op} \rightarrow \mathcal{C}$ carries limits in its first variable to limits in \mathcal{C} and carries colimits in its second variable to limits in \mathcal{C} .

A.4.8. PROPOSITION. *A continuous right $\mathcal{S}\mathcal{S}et$ -module \mathcal{C} can be enriched to a $\mathcal{S}\mathcal{S}et$ -category in a unique way so that there exist isomorphisms in $\mathcal{S}\mathcal{S}et$*

$$C(A, B^V) \cong C(A, B)^V$$

for all $A, B \in \mathcal{C}$ and $V \in \mathcal{S}\mathcal{S}et$ natural⁶ in all three variables.

PROOF. We must construct an enrichment from the supplied right pseudo-action. This is done straightforwardly by defining the n -arrow in $\mathcal{C}(A, B)$ to be arrows $A \rightarrow B^{\Delta[n]}$ in \mathcal{C} and using the pseudo-action laws and the canonical diagonal co-algebra structure on $\Delta[n]$ to define an associative and unital composition of such. Note that the identity axiom of the right pseudo-action ensures that arrows $A \rightarrow B^{\Delta[0]}$ are in bijective correspondence with arrows $A \rightarrow B$ and thus that this construction really does give an enrichment of \mathcal{C} .

Furthermore, we must show that the pseudo-action supplies cotensors for this derived enrichment: that is that

$$C(A, B^V) \cong C(A, B)^V$$

for all $A, B \in \mathcal{C}$ and $V \in \mathcal{S}\mathcal{S}et$ natural in all three-variables, which fact follows from one of the assumed continuity properties of $(-)^- : \mathcal{C} \times \mathcal{S}\mathcal{S}et^{op} \rightarrow \mathcal{C}$ using the fact that every simplicial set can be expressed as a colimit of representables. \square

We have not yet made use of continuity in of the right action bifunctor in its first variable. The reason for this hypothesis will explained in §A.5.

Exercises.

A.4.i. EXERCISE. Prove Proposition A.4.6.

A.4.ii. EXERCISE. Let \mathcal{J} be a small unenriched category and let \mathcal{C} be a \mathcal{V} -category. Prove that if \mathcal{C} is tensored or cotensored then so is $\mathcal{C}^{\mathcal{J}}$.

A.5. Conical limits

Let \mathcal{V} be a cartesian closed category. The **conical limit** of a \mathcal{V} -enriched functor is the limit weighted by the terminal weight, the \mathcal{V} -functor that is constant at $1 \in \mathcal{V}$. In what follows, we focus on the slightly less general case of conical limits of unenriched diagrams — those indexed by 1-categories instead of \mathcal{V} -categories — as they will be of greatest interest here. Conical limits necessarily define 1-categorical limits, so we pay particular attention to what is required to enriched a 1-categorical limit to a conical limit.

⁶In fact these isomorphisms are $\mathcal{S}\mathcal{S}et$ -natural.

To motivate the universal property that characterizes conical limits, consider a diagram $F: \mathcal{J} \rightarrow \mathcal{V}$ indexed by a 1-category \mathcal{J} and valued in \mathcal{V} itself. A cone λ over the diagram F with summit suggestively denoted $\lim F \in \mathcal{V}$ is a limit cone if it satisfies the universal property

$$\mathcal{V}(A, \lim F) \cong \lim_{j \in \mathcal{J}} \mathcal{V}(A, Fj),$$

an isomorphism of hom-sets. The next lemma reveals that this isomorphism can always be enriched to lie in \mathcal{V} , i.e., lifted along the underlying set functor of Definition A.1.5.

A.5.1. LEMMA. *If \mathcal{V} is a cartesian closed category, then any 1-categorical limit cone $\lambda: \Delta \lim F \Rightarrow F$ over a diagram $F: \mathcal{J} \rightarrow \mathcal{V}$ gives rise to an isomorphism in \mathcal{V}*

$$(\lim F)^A \cong \lim_{j \in \mathcal{J}} (Fj^A)$$

that is \mathcal{V} -natural in $A \in \mathcal{V}$.

PROOF. For any $A \in \mathcal{V}$, the exponential $(-)^A: \mathcal{V} \rightarrow \mathcal{V}$ is right adjoint to the product functor $- \times A: \mathcal{V} \rightarrow \mathcal{V}$; as such it preserves limits, giving rise to the isomorphism of the statement. \square

In terminology we now introduce, Lemma A.5.1 asserts that all 1-categorical limits in a cartesian closed category \mathcal{V} automatically enriched to define *conical limits*.

A.5.2. DEFINITION. Let \mathcal{C} be a \mathcal{V} -category and let \mathcal{J} be a 1-category. The **conical limit** of an unenriched diagram $F: \mathcal{J} \rightarrow \mathcal{C}$ is given by an object $L \in \mathcal{C}$ and a cone $\lambda: \Delta L \Rightarrow F$ inducing a \mathcal{V} -natural isomorphism of hom-objects in \mathcal{V}

$$\mathcal{C}(X, L) \xrightarrow[\cong]{\lambda_*} \lim_{j \in \mathcal{J}} \mathcal{C}(X, Fj) \in \mathcal{V} \quad (\text{A.5.3})$$

for all $X \in \mathcal{C}$.

The isomorphism (A.5.3) looks identical to the usual isomorphism that characterizes 1-categorical limits except for one very important difference: it postulates an isomorphism in \mathcal{V} rather than an isomorphism in *Set*. In the case where $\mathcal{V} = \mathbf{SSet}$, the isomorphism of vertices that underlies this isomorphism of simplicial sets describes the usual 1-categorical universal property. To say that the limit is *conical* and not merely *1-categorical* is to assert that this universal property extends to all positive dimensions.

Inspecting Definition A.5.2, we see immediately that:

A.5.4. PROPOSITION. *A 1-categorical limit cone is conical just when it is preserved by all \mathcal{V} -valued representable functors $\mathcal{C}(X, -): \mathcal{C} \rightarrow \mathcal{V}$.* \square

The proof of Lemma A.5.1 generalizes to show:

A.5.5. PROPOSITION. *If \mathcal{C} has tensors, then all 1-categorical limits in \mathcal{C} are conical.*

PROOF. By Proposition A.5.4, to show that a 1-categorical limit is conical, it suffices to show that it is preserved by the \mathcal{V} -valued representable functors $\mathcal{C}(X, -): \mathcal{C} \rightarrow \mathcal{V}$ for all $X \in \mathcal{V}$. If \mathcal{C} admits tensors, then each of these functors admits a left adjoint; as right adjoints, they necessarily preserve the 1-categorical limits of the statement. \square

A.5.6. PROPOSITION. *Let \mathcal{C} be enriched and cotensored over \mathcal{V} . A limit of an unenriched diagram $F: \mathcal{J} \rightarrow \mathcal{C}$ is a conical limit if and only if it is preserved by cotensors with all objects $V \in \mathcal{V}$.*

PROOF. Cotensors are \mathcal{V} -enriched right adjoints, which preserve conical limits. The content is that preservation by cotensors suffices to enriched a 1-categorical limit to a \mathcal{V} -categorical one.

Recall that a 1-categorical limit cone $(\lambda_j: L \rightarrow Fj)_{j \in \mathcal{J}}$ is conical just when it is preserved by all \mathcal{V} -valued representable functors $C(X, -): \mathcal{C} \rightarrow \mathcal{V}$. To see that the natural map

$$C(X, L) \rightarrow \lim_{j \in \mathcal{J}} C(X, Fj)$$

is an isomorphism in \mathcal{V} we appeal to the (unenriched) Yoneda lemma and prove that for all $V \in \mathcal{V}$, the map of hom-sets

$$\mathcal{V}(V, C(X, L))_0 \rightarrow \mathcal{V}(V, \lim_{j \in \mathcal{J}} C(X, Fj))_0 \quad (\text{A.5.7})$$

is an isomorphism. Since unenriched representables preserve 1-categorical limits,

$$\mathcal{V}(V, \lim_{j \in \mathcal{J}} C(X, Fj))_0 \cong \lim_{j \in \mathcal{J}} \mathcal{V}(V, C(X, Fj))_0.$$

By the unenriched universal property of cotensors, maps $V \rightarrow C(X, L)$ in \mathcal{V} correspond bijectively to maps $X \rightarrow L^V$ in \mathcal{C} . So the map (A.5.7) is isomorphic to the map of hom-sets

$$C(X, L^V)_0 \rightarrow \lim_{j \in \mathcal{J}} C(X, Fj^V)_0 \cong C(X, \lim_{j \in \mathcal{J}} (Fj^V))_0,$$

where again the unenriched representable commutes with the 1-categorical limit. To say that cotensors preserve the limit $L \cong \lim_{j \in \mathcal{J}} Fj$ means that $\lim_{j \in \mathcal{J}} (Fj^V) \cong (\lim_{j \in \mathcal{J}} Fj)^V \cong L^V$, so by the Yoneda lemma, the map of hom-sets

$$C(X, L^V)_0 \rightarrow C(X, \lim_{j \in \mathcal{J}} (Fj^V))_0,$$

is an isomorphism, and thus (A.5.7) and hence $C(X, L) \cong \lim_{j \in \mathcal{J}} C(X, Fj)$ is an isomorphism as desired. \square

A.5.8. PROPOSITION. *Suppose \mathcal{C} is a \mathcal{V} -category that admits conical limits indexed by a small category \mathcal{J} . Then the limit functor $\lim: \mathcal{C}^{\mathcal{J}} \rightarrow \mathcal{C}$ is a \mathcal{V} -functor.*

PROOF. We first prove that the conical limit functor $\lim: \mathcal{V}^{\mathcal{J}} \rightarrow \mathcal{V}$ is a \mathcal{V} -functor. The result for a general \mathcal{V} -category \mathcal{C} then follows from the defining \mathcal{V} -natural isomorphism (A.5.3) via Proposition A.3.13.

The advantage of this reduction is that we can make use of the fact that \mathcal{V} and $\mathcal{V}^{\mathcal{J}}$ are tensored, the latter following from the former by Exercise A.4.ii. Now by Proposition A.4.6, to show that the conical limit is a \mathcal{V} -functor it suffices to show that its unenriched left adjoint $\Delta: \mathcal{V} \rightarrow \mathcal{V}^{\mathcal{J}}$ is a \mathcal{V} -functor that preserves tensors, and this is straightforward. \square

Exercises.

A.5.i. EXERCISE. Specialize the result of Proposition A.5.5 to prove the following: in any 2-category \mathcal{C} that admits tensors with the walking-arrow category $\mathbf{2}$, any 1-categorical limits that \mathcal{C} admits are automatically conical.⁷

⁷The statement asserts that the presence of tensors with $\mathbf{2}$ implies that the universal property of 1-dimensional limits automatically has an additional 2-dimensional aspect. See the discussion around Proposition 1.4.5 for an illustration of this and see [30, pp. 306] for a proof.

A.6. Change of base

Change of base for enriched categories was first considered in [20]. Their main result, appearing as Proposition A.6.4 below, is that a *lax monoidal functor* $T: \mathcal{V} \rightarrow \mathcal{W}$ induces a change-of-base 2-functor $T_*: \mathcal{V}\text{-Cat} \rightarrow \mathcal{W}\text{-Cat}$.

A.6.1. DEFINITION. A **(lax) monoidal functor** between cartesian closed categories \mathcal{V} and \mathcal{W} is a functor $T: \mathcal{V} \rightarrow \mathcal{W}$ equipped with natural transformations

$$\begin{array}{ccc} \mathcal{V} \times \mathcal{V} & \xrightarrow{T \times T} & \mathcal{W} \times \mathcal{W} \\ \times \downarrow & \Downarrow \phi & \downarrow \times \\ \mathcal{V} & \xrightarrow{T} & \mathcal{W} \end{array} \quad \begin{array}{ccc} \mathbb{1} & \xrightarrow{1} & \mathcal{V} \\ & \nearrow \uparrow \phi_0 & \downarrow T \\ & 1 & \mathcal{W} \end{array}$$

so that the evident associativity and unit diagrams commute.

A.6.2. DEFINITION. A **(lax) monoidal natural transformation** between monoidal functors between cartesian closed categories $T, U: \mathcal{V} \Rightarrow \mathcal{W}$ is given by a natural transformation $\theta: T \Rightarrow U$ so that the pasting diagrams commute

$$\begin{array}{ccc} \mathcal{V} \times \mathcal{V} & \xrightarrow{T \times T} & \mathcal{W} \times \mathcal{W} \\ \times \downarrow & \Downarrow \theta \times \theta & \downarrow \times \\ \mathcal{V} & \xrightarrow{U} & \mathcal{W} \end{array} \quad \begin{array}{ccc} \mathcal{V} \times \mathcal{V} & \xrightarrow{T \times T} & \mathcal{W} \times \mathcal{W} \\ \times \downarrow & \Downarrow \phi & \downarrow \times \\ \mathcal{V} & \xrightarrow{T} & \mathcal{W} \end{array} \quad \begin{array}{ccc} \mathbb{1} & \xrightarrow{1} & \mathcal{V} \\ & \nearrow \uparrow \phi_0 & \downarrow T \\ & 1 & \mathcal{W} \end{array} \quad \begin{array}{ccc} \mathbb{1} & \xrightarrow{1} & \mathcal{V} \\ & \nearrow \uparrow \phi_0 & \downarrow U \\ & 1 & \mathcal{W} \end{array}$$

A.6.3. EXAMPLE. A functor $T: \mathcal{V} \rightarrow \mathcal{W}$ between cartesian closed categories **preserves finite products** just when the natural maps defined for any $A, B \in \mathcal{V}$

$$T(A \times B) \xrightarrow{\cong} TA \times TB \quad \text{and} \quad T1 \xrightarrow{\cong} 1$$

are isomorphisms. The inverse isomorphisms then make T into a **strong monoidal functor** between the cartesian closed categories \mathcal{V} and \mathcal{W} , with the structure maps of Definition A.6.1 given by natural isomorphisms. Moreover, any natural transformation between product-preserving functors is automatically a monoidal natural transformation.

The following result was first stated as [20, II.6.3], with the proof left to the reader. We adopt the same tactic and leave the diagram chases to the reader or to [14, 4.2.4] and instead just give the definition.

A.6.4. PROPOSITION. A monoidal functor $T: \mathcal{V} \rightarrow \mathcal{W}$ induces a change-of-base 2-functor

$$T_*: \mathcal{V}\text{-Cat} \rightarrow \mathcal{W}\text{-Cat}.$$

PROOF. The construction of the change-of-base 2-functor is the important thing. Let \mathcal{C} be a \mathcal{V} -category and define a \mathcal{W} -category $T_*\mathcal{C}$ to have the same objects and to have mapping objects $T_*\mathcal{C}(x, y) := TC(x, y)$. The composition and identity maps are given by the composites

$$TC(y, z) \times TC(x, y) \xrightarrow{\phi} T(\mathcal{C}(y, z) \times \mathcal{C}(x, y)) \xrightarrow{T \circ} TC(x, z) \quad 1 \xrightarrow{\phi_0} T1 \xrightarrow{T \text{id}_x} TC(x, x)$$

which make use of the structure maps of the monoidal functor. A straightforward diagram chase verifies that $T_*\mathcal{C}$ is a \mathcal{W} -category.

If $F: \mathcal{C} \rightarrow \mathcal{D}$ is a \mathcal{V} -functor, then we define a \mathcal{W} -functor $T_*F: T_*\mathcal{C} \rightarrow T_*\mathcal{D}$ to act on objects by $c \in \mathcal{C} \mapsto Fc \in \mathcal{D}$ and with internal action on arrows defined by

$$TC(x, y) \xrightarrow{TF} \mathcal{D}(Tx, Ty)$$

Again, a straightforward diagram chase verifies that T_*F is \mathcal{V} -functorial. It is evident from this definition that $T_*(GF) = T_*G \cdot T_*F$.

Finally, let $\alpha: F \Rightarrow G$ be a \mathcal{V} -natural transformation between \mathcal{V} -functors $F, G: \mathcal{C} \Rightarrow \mathcal{D}$ and define a \mathcal{W} -natural transformation $T_*\alpha: T_*F \Rightarrow T_*G$ to have components

$$1 \xrightarrow{\phi_0} T1 \xrightarrow{T\alpha_c} T\mathcal{D}(Fc, Gc)$$

Another straightforward diagram chase verifies that $T_*\alpha$ is \mathcal{W} -natural.

It remains to verify this assignment is functorial for both horizontal and vertical composition of enriched natural transformations. Consulting Lemma A.3.5, we see that the component of $T_*(\beta \cdot \alpha)$ is defined by the top-horizontal composite while the component of the vertical composite of $T_*\alpha$ with $T_*\beta: T_*G \Rightarrow T_*H$ is defined by the bottom composite:

$$\begin{array}{ccccc} 1 & \xrightarrow{\phi_0} & T1 & \xrightarrow{T(\beta_c \times \alpha_c)} & T(\mathcal{D}(Gc, Hc) \times \mathcal{D}(Fc, Gc)) \xrightarrow{T\circ} T\mathcal{D}(Fc, Hc) \\ & \searrow \phi_0 \times \phi_0 & \uparrow \phi & & \uparrow \phi \\ & & T1 \times T1 & \xrightarrow{T\beta_c \times T\alpha_c} & T\mathcal{D}(Gc, Hc) \times T\mathcal{D}(Fc, Gc) \end{array}$$

By the unit axiom for the monoidal functor and naturality of ϕ , these composites agree. The argument for functoriality of horizontal composites is similar. \square

For any cartesian closed category \mathcal{V} , the underlying set functor $(-)_0: \mathcal{V} \rightarrow \mathbf{Set}$ is monoidal (Exercise A.6.i). Consequently:

A.6.5. COROLLARY. *For any cartesian closed category \mathcal{V} , the the underlying category construction defines a 2-functor*

$$(-)_0: \mathcal{V}\text{-Cat} \rightarrow \mathbf{Cat}. \quad \square$$

A.6.6. REMARK. In fact, the change of base procedure is *itself* a 2-functor from the 2-category of monoidal categories, monoidal functors, and monoidal natural transformations to the 2-category of 2-categories, 2-functors, and 2-natural transformations. See [14, §4.3] for a discussion and proof.

If the lax monoidal functor $T: \mathcal{V} \rightarrow \mathcal{W}$ does not commute with the underlying set functors for \mathcal{V} and \mathcal{W} up to natural isomorphism, the change-of-base 2-functor $T_*: \mathcal{V}\text{-Cat} \rightarrow \mathcal{W}\text{-Cat}$ will not preserve underlying categories, even up to natural isomorphism. Consulting Definition A.2.2, the following condition on T is required to ensure that underlying categories are preserved.

A.6.7. LEMMA. *The change-of-base 2-functor induced by a monoidal functor $(T, \phi, \phi_0): \mathcal{V} \rightarrow \mathcal{W}$ preserves underlying categories, if and only if, for each $V \in \mathcal{V}$ the composite function on hom-sets*

$$\mathcal{V}(1, V)_0 \xrightarrow{T} \mathcal{W}(T1, TV)_0 \xrightarrow{- \circ \phi_0} \mathcal{W}(1, TV)_0$$

is a bijection.

PROOF. The displayed function defines the component at $V \in \mathcal{V}$ of the unique monoidal natural transformation from the underlying set-functor for \mathcal{V} with the composite of T with the underlying set functor for \mathcal{W} . By Remark A.6.6, if it defines a monoidal natural isomorphism, then it induces a 2-natural isomorphism between the underlying category 2-functor $(-)_0: \mathcal{V}\text{-Cat} \rightarrow \text{Cat}$ and the composite of the change of base 2-functor $T_*: \mathcal{V}\text{-Cat} \rightarrow \mathcal{W}\text{-Cat}$ with the underlying category 2-functor $(-)_0: \mathcal{W}\text{-Cat} \rightarrow \text{Cat}$.

Conversely, this condition is necessary for the underlying category of the \mathcal{W} -category $T_*\mathcal{V}$ to coincide with the underlying category of the cartesian closed category \mathcal{V} . \square

One situation in which the condition of Lemma A.6.7 is automatic is when the lax monoidal functor is the right adjoint of a monoidal adjunction, which in this context might be thought of as a *change-of-base adjunction*. The proof, originally given in [29], is by a short diagram chase left to Exercise A.6.ii.

Another immediate consequence of Remark A.6.6 is that the monoidal adjunctions of Exercise ?? induce an adjunction between the corresponding change-of-base 2-functors. Between cartesian closed categories \mathcal{V} and \mathcal{W} , the statement of this more general result simplifies by applying the ideas of Example A.6.3. The right adjoint functor preserves finite products and so is automatically strong monoidal, and by Exercise ??(i) the left adjoint is as well. Any natural transformation between product-preserving functors automatically defines a monoidal natural transformation. Consequently:

A.6.8. PROPOSITION. *Any adjunction comprised of finite-product preserving functors between cartesian closed categories induces a change-of-base 2-adjunction*

$$\mathcal{V} \begin{array}{c} \xrightarrow{F} \\ \perp \\ \xleftarrow{U} \end{array} \mathcal{W} \quad \rightsquigarrow \quad \mathcal{V}\text{-Cat} \begin{array}{c} \xrightarrow{F_*} \\ \perp \\ \xleftarrow{U_*} \end{array} \mathcal{W}\text{-Cat} \quad \square$$

A.6.9. EXAMPLE. Both adjoints of the adjunction

$$\text{Cat} \begin{array}{c} \xleftarrow{h} \\ \perp \\ \xrightarrow{\quad} \end{array} \mathcal{S}\text{Set}$$

of Proposition 1.1.11 preserve finite products. Hence, by Proposition A.6.8 induces a change-of-base adjunction defined by the 2-functors

$$2\text{-Cat} \begin{array}{c} \xleftarrow{h_*} \\ \perp \\ \xrightarrow{\quad} \end{array} \mathcal{S}\text{Set}\text{-Cat}$$

that act identically on objects and act by applying the homotopy category functor or nerve functor, respectively, on homs. Note h also satisfies the condition of Lemma A.6.7 so both adjoints preserve underlying categories, as is evident from direct computation.

Exercises.

A.6.i. EXERCISE. For any cartesian closed category \mathcal{V} , prove that the underlying set functor $(-)_0: \mathcal{V} \rightarrow \text{Set}$ is lax monoidal

A.6.ii. EXERCISE. Consider an adjunction in the 2-category of monoidal categories, monoidal functors, and monoidal natural transformations.

- (i) Prove that the left adjoint is strong monoidal.⁸
- (ii) Prove that the right adjoint is “pro-normal,” satisfying the condition of Lemma A.6.7.

⁸Hint: take the mates of the structure maps of the monoidal right adjoint.

Introduction to 2-category theory

2-categories and double categories were first introduced by Charles Ehresmann. A notable early expository account appeared in [32].

B.1. 2-categories and the calculus of pasting diagrams

The category *Cat* of small categories is cartesian closed with exponentials B^A defined to be the category of functors and natural transformations from A to B and terminal object $\mathbf{1}$. Exploiting the work in Appendix A, we can concisely define a 2-category to be a category enriched over this cartesian closed category. Unpacking this definition, we see it contains a considerable amount of structure:

B.1.1. DEFINITION (2-category). A **2-category** \mathcal{C} is a category enriched in *Cat*. Explicitly it has:

- a collection of objects A, B ;
- a collection of arrows $f: A \rightarrow B$, frequently called **1-cells**, these being the objects of the hom-categories $\mathcal{C}(A, B)$; and
- a collection of arrows between arrows $A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B$, called **2-cells**,¹ these being the morphisms of the hom-categories $\mathcal{C}(A, B)$ from f to g

so that:

- (i) For each fixed pair of objects $A, B \in \mathcal{C}$, the 1-cells and 2-cells form a category. In particular:
 - A pair of 2-cells as below-left admits a **vertical composite** as below-right:

$$\begin{array}{c} f \\ \curvearrowright \\ A \xrightarrow{\quad} B \\ \curvearrowleft \\ h \end{array} \quad \Downarrow \alpha \quad \begin{array}{c} f \\ \curvearrowright \\ A \xrightarrow{\quad} B \\ \curvearrowleft \\ h \end{array} \quad =: \quad \begin{array}{c} f \\ \curvearrowright \\ A \xrightarrow{\quad} B \\ \Downarrow \beta \cdot \alpha \\ \curvearrowleft \\ h \end{array}$$

- Each 1-cell $f: A \rightarrow B$ has an identity 2-cell $A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \text{id}_f \\ \xrightarrow{f} \end{array} B$.

- (ii) The objects and 1-cells define a category in the ordinary sense; in particular, each object has an identity arrow $\text{id}_A: A \rightarrow A$.
- (iii) The objects and 2-cells form a category. In particular:

¹Implicitly in this graphical representation, is the requirement that a 2-cell α has a domain 1-cell f and a codomain 1-cell g , and these 1-cells have a common domain object A and codomain object B . The objects A and B may be referred to as the 0-cell source and 0-cell target of α .

- A pair of 2-cells as below-left admits a **horizontal composite** as below-right:

$$A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{j} \\ \Downarrow \gamma \\ \xrightarrow{k} \end{array} C \quad =: \quad A \begin{array}{c} \xrightarrow{jf} \\ \Downarrow \gamma * \alpha \\ \xrightarrow{kg} \end{array} C$$

- The identity 2-cells on identity 1-cells

$$A \begin{array}{c} \xrightarrow{\text{id}_A} \\ \Downarrow \text{id}_{\text{id}_A} \\ \xrightarrow{\text{id}_A} \end{array} A$$

define identities for horizontal composition.

(iv) Finally, the horizontal composition is functorial with respect to the vertical composition:

- The horizontal composite of the identity 2-cells is an identity 2-cell:

$$A \begin{array}{c} \xrightarrow{g} \\ \Downarrow \text{id}_g \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{k} \\ \Downarrow \text{id}_k \\ \xrightarrow{k} \end{array} C \quad = \quad A \begin{array}{c} \xrightarrow{kg} \\ \Downarrow \text{id}_{kg} \\ \xrightarrow{kg} \end{array} C$$

- In the situation below, the horizontal composite of the vertical composites coincides with the vertical composite of the horizontal composites, a property referred to as **middle-four interchange**

$$\begin{array}{ccccc} & f & & j & \\ & \curvearrowright & & \curvearrowright & \\ A & \Downarrow \alpha & B & \Downarrow \gamma & C \\ & \curvearrowleft & & \curvearrowleft & \\ & g & & k & \\ & \Downarrow \beta & & \Downarrow \delta & \\ & \curvearrowright & & \curvearrowright & \\ & h & & \ell & \end{array}$$

A degenerate special case of horizontal composition, in which all but one of the 2-cells is an identity id_f on its boundary 1-cell f , is called “whiskering.”

B.1.2. DEFINITION (whiskering). The **whiskered composite** of a 2-cell $A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B$ with a pair of 1-cells $a: X \rightarrow A$ and $b: B \rightarrow Y$ is defined by the horizontal composite:

$$X \begin{array}{c} \xrightarrow{bfa} \\ \Downarrow b \cdot \alpha \cdot a \\ \xrightarrow{bga} \end{array} Y \quad := \quad X \xrightarrow{a} A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B \xrightarrow{b} Y \quad := \quad X \begin{array}{c} \xrightarrow{a} \\ \Downarrow \text{id}_a \\ \xrightarrow{a} \end{array} A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{b} \\ \Downarrow \text{id}_b \\ \xrightarrow{b} \end{array} Y$$

As the following lemma reveals, horizontal composition can be recovered from vertical composition and whiskering. Our primary interest in this result, however, has to do with a rather prosaic consequence appearing as the final part of the statement, which will be applied shockingly often.

B.1.3. LEMMA (naturality of whiskering). *Any horizontally-composable pair of 2-cells in a 2-category gives rise to a commutative square in the hom-category from the domain object to the codomain object whose diagonal*

defines the horizontal composite:

$$C \ni A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{h} \\ \Downarrow \beta \\ \xrightarrow{k} \end{array} C \rightsquigarrow \begin{array}{ccc} hf & \xrightarrow{\beta f} & kf \\ h\alpha \Downarrow & \Downarrow \beta * \alpha & \Downarrow k\alpha \\ hg & \xrightarrow{\beta g} & kg \end{array} \in C(A, C)$$

In particular, if any three of the four whiskered 2-cells $h\alpha$, $k\alpha$, βf , and βg are invertible, so is the fourth.

PROOF. By middle-four interchange:

$$\beta g \cdot h\alpha = (\beta * \text{id}_g) \cdot (\text{id}_h * \alpha) = (\beta \cdot \text{id}_h) * (\text{id}_g \cdot \alpha) = \beta * \alpha = (\text{id}_k \cdot \beta) * (\alpha \cdot \text{id}_f) = (\text{id}_k * \alpha) \cdot (\beta * \text{id}_f) = k\alpha \cdot \beta f. \quad \square$$

The operations of horizontal and vertical composition are special cases of composition by *pasting*, an operation first introduced by Bénabou [2]. The main result, proven in the 2-categorical context by Power [44] is that a well-formed pasting diagram such as

$$\begin{array}{ccccc} & B & \xrightarrow{b} & F & \xrightarrow{c} \\ & \searrow d & \Downarrow \alpha & \searrow g & \searrow \beta \\ A & \xrightarrow{a} & C & \xrightarrow{e} & E & \xrightarrow{f} & F & \xrightarrow{g} & H & \xrightarrow{h} & Z \\ & \searrow i & \Downarrow \gamma & \searrow k & \Downarrow \delta & \searrow \epsilon & \searrow m & \searrow \zeta & \searrow n \\ & D & \xrightarrow{j} & G & \xrightarrow{\ell} & G & \xrightarrow{m} & H & \xrightarrow{h} & Z \end{array} \quad (\text{B.1.4})$$

has a unique 2-cell composite.² We leave the formal statement and proof of this result to the literature and instead describe informally how such pasting composites should be interpreted.

B.1.5. DIGRESSION (how to read a pasting diagram). A pasting diagram in a 2-category \mathcal{C} represents a unique composite 2-cell, defining a morphism in one of the hom-categories between a pair of objects. To identify these objects, look at the underlying directed graph of objects and 1-cells in the pasting diagram. If the pasting diagram is well-formed, that graph should have a unique source object A and a unique target object Z . This indicates that the pasting diagram defines a 2-cell in the hom-category $C(A, Z)$. The object A is its **source 0-cell** and the object Z is its **target 0-cell**.

The next step is to identify the source 1-cell and the target 1-cell of the pasting diagram. These should both be objects of $C(A, Z)$, i.e., 1-cells in the 2-category from A to Z . Again if the pasting diagram is well-formed, the **source 1-cell** should be the unique composable path of 1-cells none of which occur as codomains of any 2-cells in the pasting diagram. In the diagram (B.1.4), these are the 1-cells whose labels appear above the arrow, and their composite is cba . Dually, the **target 1-cell** should be the unique composable path of 1-cells, none of which occur as domains of any 2-cells in the pasting diagram. In (B.1.4), these are the 1-cells whose labels appear below the diagram, and their composite is $n\ell j$.

The final step is to represent the pasting diagram as a vertical composite of 2-cells, each of which is a map between a pair of composite 1-cells from A to Z that trace a composable path through the directed graph of the pasting diagram. Each 2-cell in the pasting diagram will label precisely one of

²This result was generalized to the bicategorical context by Verity [62], in which case the composite 2-cell is well-defined once its source and target 1-cells are specified.

the 2-cells of this composite. The expressions of these vertical 2-cell composites are not necessarily unique and may not necessarily pass through every possible composable path of 1-cells (though there will be some vertical composite of 2-cells that does pass through each path of 1-cells).

To start, pick any 2-cell in the pasting diagram whose 1-cell source can be found as a subsequence of the source 1-cell; in the (B.1.4), either α or β can be chosen first. Whisker it so that it defines a 2-cell from the source 1-cell cba to another path of composable 1-cells from A to Z through the pasting diagram. Then this whiskered composite forms the first step in the sequence of composable 2-cells. Remove this part of the pasting diagram and repeat until you arrive at the target 1-cell. In the example above, there are three possible ways to express the composite pasted cell (B.1.4) as vertical composites of whiskered 2-cell, represented by the three paths through the following commutative diagram in the category $\mathcal{C}(A, Z)$:

$$\begin{array}{ccccccccccc}
 cba & \xrightarrow{caa} & cfeda & \xrightarrow{cfey} & cf ei & & & & & & \\
 \beta ba \Downarrow & & \beta feda \Downarrow & & \Downarrow \beta fei & & & & & & \in \mathcal{C}(A, Z) \\
 hgba & \xrightarrow{hgaa} & hgfeda & \xrightarrow{hgfe\gamma} & hgfei & \xrightarrow{hgf\delta} & hgfkj & \xrightarrow{hej} & hmlj & \xrightarrow{\zeta\ell j} & hlj
 \end{array}$$

B.1.6. DIGRESSION (notions of sameness inside a 2-category). From the point of view of 2-category theory, the most natural notion of “sameness” for two objects of a 2-category is *equivalence*: A and B are to be regarded as the same, if there exist 1-cells $f: A \rightarrow B$ and $g: B \rightarrow A$ together with invertible 2-cells $\alpha: \text{id}_A \cong gf$ and $\beta: fg \cong \text{id}_B$.

From the point of view of 2-category theory, the most natural notion of “sameness” for a parallel pair of morphisms in a 2-category is *isomorphism*: $h, k: A \rightrightarrows B$ are to be regarded as the same if there exists an invertible 2-cell $\gamma: h \cong k$.

From the point of view of 2-category theory, the most natural notion of “sameness” for a pair of 2-cells with common boundary is *equality*. Because a 2-category lacks any higher dimensional morphisms to mediate between 2-cells, there is no weaker notion of sameness available.

A 2-category has four duals, including itself, each of which have the same objects, 1-cells, and 2-cells, but with some domains and codomains swapped.

B.1.7. DEFINITION (op and co duals). Let \mathcal{C} be a 2-category.

- Its **op-dual** \mathcal{C}^{op} is the 2-category with $\mathcal{C}^{\text{op}}(A, B) := \mathcal{C}(B, A)$. This reverses the direction of the 1-cells but not the 2-cells.
- Its **co-dual** \mathcal{C}^{co} is the 2-category with $\mathcal{C}^{\text{co}}(A, B) := \mathcal{C}(A, B)^{\text{op}}$. This reverses the direction of the 2-cells but not the 1-cells.
- Its **coop-dual** $\mathcal{C}^{\text{coop}}$ is the 2-category with $\mathcal{C}^{\text{coop}}(A, B) := \mathcal{C}(B, A)^{\text{op}}$. This reverses the direction of both the 2-cells and the 1-cells.

Further details about the specification of \mathcal{C}^{op} , \mathcal{C}^{co} , and $\mathcal{C}^{\text{coop}}$ as *Cat*-enriched categories are left to Exercise B.1.iii.

The data of an equivalence in \mathcal{C} also defines an equivalence in each of its duals.

In Digression 1.2.2, we saw that the data of a simplicial category could be expressed as a diagram of a particular type valued in *Cat*. A small 2-category can be similarly encoded, in fact in two different ways, as a category defined *internally* to the category of categories.

B.1.8. DEFINITION (internal category). Let \mathcal{E} be any category with pullbacks. An **internal category** in \mathcal{E} is given by the data

$$\begin{array}{ccc}
 & C_1 \times_{C_0} C_1 & \\
 \pi_\ell \swarrow & \downarrow & \searrow \pi_r \\
 C_1 & & C_1 \\
 & d \searrow & \swarrow c \\
 & C_0 &
 \end{array}
 \quad
 C_1 \times_{C_0} C_1 \xrightarrow{\circ} C_1 \begin{array}{c} \xrightarrow{d} \\ \xleftarrow{i} \\ \xrightarrow{c} \end{array} C_0$$

subject to commutative diagrams that define the domains and codomains of composites and identities and encode the fact that composition is associative and unital. The details are left to Exercise B.1.i or the literature.

For example, a **double category** is a category internal to \mathbf{Cat} . A 2-category can be realized as a special case of this construction in the following two ways.

B.1.9. DIGRESSION (2-categories as category objects). A 2-category may be defined to be an internal category in \mathbf{Cat}

$$C_{1,2} \times_{C_0} C_{1,2} \xrightarrow{\circ} C_{1,2} \begin{array}{c} \xrightarrow{d} \\ \xleftarrow{i} \\ \xrightarrow{c} \end{array} C_0$$

in which the category C_0 is a set, namely the set of objects of the 2-category. The 1- and 2-cells occur as the objects and arrows of the category $C_{1,2}$. The functors $d, c: C_{1,2} \rightarrow C_0$ send 1- and 2-cells to their domain and codomain 0-cells. The functor $i: C_0 \rightarrow C_{1,2}$ sends each object to its identity 1-cell. The action of the functor $\circ: C_{1,2} \times_{C_0} C_{1,2} \rightarrow C_{1,2}$ on objects defines composition of 1-cells and the action on morphisms defines the horizontal composition on 2-cells. Vertical composition on 2-cells is the composition inside the category $C_{1,2}$. Functoriality of this map encodes middle-four interchange. This definition motivates the Segal category model of $(\infty, 1)$ -categories described in Appendix E.

Dually, a 2-category may be defined to be an internal category in \mathbf{Cat}

$$C_{0,2} \times_{C_{0,1}} C_{0,2} \xrightarrow{\circ} C_{0,2} \begin{array}{c} \xrightarrow{d} \\ \xleftarrow{i} \\ \xrightarrow{c} \end{array} C_{0,1}$$

in which the categories $C_{0,1}$ and $C_{0,2}$ have the same set of objects and all four functors are identity-on-objects. Here the common set of objects defines the objects of the 2-category and the arrows of $C_{0,1}$ and $C_{0,2}$ define the 1- and 2-cells, respectively. The functors $d, c: C_{1,2} \rightrightarrows C_{0,2}$ define the domain and codomain 1-cells for a 2-cell, which the functor $\circ: C_{0,2} \times_{C_{0,1}} C_{0,2} \rightarrow C_{0,2}$ encodes vertical composition of 2-cells. The composition inside the category $C_{0,2}$ defines horizontal composition of 2-cells. Functoriality of this map encodes middle-four interchange.

Exercises.

B.1.i. EXERCISE. Complete the definition of an internal category sketched in Definition B.1.8.

B.1.ii. EXERCISE. Define a duality involution on double categories that exchanges the two expressions of a 2-category as an internal category appearing in Digression B.1.9.

B.1.iii. EXERCISE. For any 2-category \mathcal{C} , define \mathbf{Cat} -enriched categories \mathcal{C}^{op} , \mathcal{C}^{co} , and $\mathcal{C}^{\text{coop}}$ along the lines specified by Definition B.1.7.

B.2. The 3-category of 2-categories

Ordinary 1-categories form the objects of a 2-category of categories, functors, and natural transformations. Similarly, 2-categories form the objects of a 3-category of 2-categories, 2-functors, 2-natural transformations, and modifications. In this section, we briefly introduce all of these notions.

Recall from Definition B.1.1, that a 2-category is a category enriched in \mathcal{Cat} . Similarly, 2-functors and 2-natural transformations are precisely the \mathcal{Cat} -enriched functors and \mathcal{Cat} -enriched natural transformations of Appendix A. By Corollary A.3.6, 2-categories, 2-functors, and 2-natural transformations assemble into a 2-category. The 3-dimensional cells between 2-categories — the modifications — are defined using the 2-cells of a 2-category, like the 2-dimensional cells between 1-categories — the natural transformations — are defined using the 1-cells in a 1-category.

B.2.1. DEFINITION. A **2-functor** $F: \mathcal{C} \rightarrow \mathcal{D}$ between 2-categories is given by:

- a mapping on objects $\mathcal{C} \ni x \mapsto Fx \in \mathcal{D}$;
- a functorial mapping on 1-cells $\mathcal{C} \ni f: x \rightarrow y \mapsto Ff: Fx \rightarrow Fy \in \mathcal{D}$ respecting domains and codomains; and
- a mapping on 2-cells

$$\mathcal{C} \ni \begin{array}{ccc} & f & \\ x & \xrightarrow{\Downarrow \alpha} & y \\ & g & \end{array} \mapsto \begin{array}{ccc} & Ff & \\ Fx & \xrightarrow{\Downarrow F\alpha} & Fy \\ & Fg & \end{array} \in \mathcal{D}$$

that respects 0- and 1-cell sources and targets that is functorial for both horizontal and vertical composition and horizontal and vertical identities.

B.2.2. DEFINITION. A **2-natural transformation** $\mathcal{C} \xrightarrow[\mathcal{G}]{\mathcal{F}} \mathcal{D}$ between a parallel pair of 2-functors

F and G is given by a family of 1-cells $(\phi_c: Fc \rightarrow Gc)_{c \in \mathcal{C}}$ in \mathcal{D} indexed by the objects of \mathcal{C} that are natural with respect to the 1-cells $f: x \rightarrow y$ in \mathcal{C} , in the sense that the square

$$\begin{array}{ccc} Fx & \xrightarrow{Ff} & Fy \\ \phi_x \downarrow & & \downarrow \phi_y \\ Gx & \xrightarrow{Gf} & Gy \end{array}$$

commutes in \mathcal{D} , and also natural with respect to the 2-cells $x \xrightarrow[\mathcal{G}]{\mathcal{F}} y$ in \mathcal{C} , in the sense that the top-right and bottom-left whiskered composites

$$\begin{array}{ccc} Fx & \xrightarrow{Ff} & Fy \\ \Downarrow F\alpha & & \Downarrow F\alpha \\ Fx & \xrightarrow{Fg} & Fy \\ \phi_x \downarrow & & \downarrow \phi_y \\ Gx & \xrightarrow{Gf} & Gy \\ \Downarrow G\alpha & & \Downarrow G\alpha \\ Gx & \xrightarrow{Gg} & Gy \end{array}$$

are equal: i.e., $\phi_y \cdot F\alpha = G\alpha \cdot \phi_x$.

B.2.3. DEFINITION. A **modification** $\Xi: \phi \Rightarrow \psi$

$$\begin{array}{ccc} & F & \\ \phi \swarrow & \circlearrowleft & \searrow \psi \\ \mathcal{C} & \Xi & \mathcal{D} \\ \swarrow G & \circlearrowright & \end{array}$$

between parallel 2-natural transformations is given by a family of 2-cells in \mathcal{D}

$$\begin{array}{ccc} & \phi_c & \\ Fc & \Downarrow \Xi_c & Gc \\ & \psi_c & \end{array}$$

indexed by the objects $c \in \mathcal{C}$ with the property that for any 1-cell $f: x \rightarrow y$ in \mathcal{C} , the whiskered composites $\Xi_y \cdot Ff = Gf \cdot \Xi_x$ are equal in \mathcal{D} and for any 2-cell $\alpha: f \Rightarrow g$ in \mathcal{D} , the horizontal composites in \mathcal{D}

$$Fx \begin{array}{c} \xrightarrow{Ff} \\ \Downarrow F\alpha \\ \xrightarrow{Fg} \end{array} Fy \begin{array}{c} \xrightarrow{\phi_y} \\ \Downarrow \Xi_y \\ \xrightarrow{\psi_y} \end{array} Gy = Fx \begin{array}{c} \xrightarrow{\phi_x} \\ \Downarrow \Xi_x \\ \xrightarrow{\psi_x} \end{array} Gx \begin{array}{c} \xrightarrow{Gf} \\ \Downarrow G\alpha \\ \xrightarrow{Gg} \end{array} Gy$$

are equal.

Finally, the category of 2-categories is cartesian closed, with internal hom $\mathcal{B}^{\mathcal{A}}$ defined to be the 2-category of 2-functors, 2-natural transformations, and modifications. So now we can define a **3-category** to be a category enriched in 2-categories.

Exercises.

B.2.i. EXERCISE. For the reader who has a lot of blank paper, unpack the definition of a 3-category just given.

B.3. Adjunctions and mates

B.3.1. PROPOSITION (equivalence invariance of adjointness). *Suppose given an essentially commutative square*

$$\begin{array}{ccc} B & \xrightarrow{b} & B' \\ u \downarrow \lceil f \cong \alpha \downarrow f' \rceil u' & & \\ A & \xrightarrow{a} & A' \end{array} \rightsquigarrow \begin{array}{ccc} B & \xrightarrow{b} & B' \\ u \downarrow \lceil u' a \epsilon \cdot u' \alpha u \cdot \eta' \rceil u' & & \\ A & \xrightarrow{a} & A' \end{array}$$

*Then f admits a right adjoint u if and only if f' admits a right adjoint u' , in which case the **mate** of the isomorphism α is an isomorphism.*

PROOF. [An exercise, for now.](#) □

B.3.2. LEMMA. *Suppose given a triple of adjoint functors $\ell \dashv i \dashv r$. Then the counit of $\ell \dashv i$ is invertible if and only if the unit of $i \dashv r$ is invertible.*

PROOF. [An exercise, for now.](#) □

B.4. Right adjoint right inverse adjunctions

B.4.1. LEMMA. Suppose we are given a pair of 1-cells $u: A \rightarrow B$ and $f: B \rightarrow A$ and a 2-isomorphism $fu \cong \text{id}_A$ in a 2-category. If there exists a 2-cell $\eta': \text{id}_B \Rightarrow uf$ with the property that $f\eta'$ and $\eta'u$ are 2-isomorphisms, then f is left adjoint to u . Furthermore, in the special case where u is a section of f , then f is left adjoint to u with the counit of the adjunction an identity.

PROOF. For now see [49, 4.1.2]. □

B.5. A bestiary of 2-categorical lemmas

B.5.1. LEMMA. Suppose $f \dashv u$ is an adjunction under B in the sense that

- the triangles involving both adjoints commute

$$\begin{array}{ccc} & B & \\ c \swarrow & & \searrow a \\ C & \xrightleftharpoons[u]{u} & A \end{array}$$

- and $\eta a = \text{id}_a$ and $\epsilon c = \text{id}_c$.

Then if c admits a right adjoint r with counit $v: cr \Rightarrow \text{id}_C$, then uv exhibits r as an absolute right lifting of u through a .

$$\begin{array}{ccc} & B & \\ r \curvearrowright & & \searrow a \\ C & \xrightarrow{u} & A \end{array}$$

PROOF. For now see [49, 5.3.2]. □

B.5.2. EXAMPLE. For example, consider the diagram of adjoint functors

$$\begin{array}{ccccc} \Delta & \xrightarrow{\quad} & \Delta_+ & \xrightarrow{\quad} & \Delta_\perp \\ \downarrow ! & \nearrow [-1] & \uparrow \perp & \searrow ! & \\ \mathbb{1} & & & & \end{array}$$

For now, see the proof of [49, 5.3.1].

APPENDIX C

Abstract homotopy theory

C.1. Lifting properties, weak factorization systems, and Leibniz closure

C.1.1. LEMMA. *Any class of maps characterized by a right lifting property is closed under composition, product, pullback, retract, and limits of towers; see Lemma C.1.1.*

PROOF. For now see [47, 11.1.4] and dualize. □

On account of the dual of Lemma C.1.1, any set of maps in a cocomplete category “cellularly generates” a larger class of maps with the same left lifting property.

C.1.2. DEFINITION. The class of maps **cellularly generated** by a set of maps is comprised of those maps obtained as sequential composites of pushouts of coproducts of those maps.

Appendix of Semantic Considerations

APPENDIX D

The combinatorics of simplicial sets

D.1. Simplicial sets and markings

D.1.1. DEFINITION. Write $\Delta_{\leq n} \subset \Delta$ for the full subcategory of the simplex category of 1.1.1 spanned by the ordinals $[0], \dots, [n]$. Restriction and left and right Kan extension define adjunctions

$$\begin{array}{ccc} & \xleftarrow{\text{lan}_n} & \\ \text{Set}^{\Delta^{\text{op}}} & \begin{array}{c} \perp \\ \text{-- res}_n \rightarrow \end{array} & \text{Set}^{\Delta_{\leq n}^{\text{op}}} \\ & \xleftarrow{\text{ran}_n} & \end{array}$$

inducing an idempotent comonad $\text{sk}_n := \text{lan}_n \circ \text{res}_n$ and an idempotent monad $\text{cosk}_n := \text{ran}_n \circ \text{res}_n$ on \mathcal{SSet} that are adjoint $\text{sk}_n \dashv \text{cosk}_n$. The counit and unit of this comonad and monad define canonical maps

$$\text{sk}_n X \xrightarrow{\epsilon} X \xrightarrow{\eta} \text{cosk}_n X$$

relating a simplicial set X with its n -**skeleton** and n -**coskeleton**. We say X is n -**skeletal** or n -**coskeletal** if the former or latter of these maps, respectively, is an isomorphism.

The next lemma proves that the monomorphisms are cellularly generated by the simplex boundary inclusions $\partial\Delta[n] \hookrightarrow \Delta[n]$ for $n \geq 0$.

D.1.2. LEMMA. *Any monomorphism of simplicial sets decomposes canonically as a sequential composite of pushouts of coproducts of the maps $\partial\Delta[n] \hookrightarrow \Delta[n]$ for $n \geq 0$.*

PROOF. [An exercise, for now.](#) □

D.1.3. DEFINITION ((left-/right-/inner-)anodyne extensions).

- The set of **horn inclusions** $\Lambda^k[n] \hookrightarrow \Delta[n]$ for $n \geq 1$ and $0 \leq k \leq n$ cellularly generates the **anodyne extensions**.
- The set of **left horn inclusions** $\Lambda^k[n] \hookrightarrow \Delta[n]$ for $n \geq 1$ and $0 \leq k < n$ cellularly generates the **left anodyne extensions**.
- The set of **right horn inclusions** $\Lambda^k[n] \hookrightarrow \Delta[n]$ for $n \geq 1$ and $0 < k \leq n$ cellularly generates the **right anodyne extensions**.
- The set of **inner horn inclusions** $\Lambda^k[n] \hookrightarrow \Delta[n]$ for $n \geq 2$ and $0 < k < n$ cellularly generates the **inner anodyne extensions**.

APPENDIX E

Examples of ∞ -cosmoi

For now see §IV.2 of [51].

APPENDIX F

Compatibility with the analytic theory of quasi-categories

The aim in this section is to prove that the synthetic theory of quasi-categories is compatible with the analytic theory pioneered by André Joyal, Jacob Lurie, and many others. We also discuss some special features of the ∞ -cosmos of quasi-categories, proving in particular that universal properties in this ∞ -cosmos are determined pointwise.

For now, see

- for limits: Proposition 4.3.2, I.5.2.6-8 of [49]
- for adjunctions: Proposition 5.2.6, IV.4.1.20-22 of [51], VIII.3.3.6 of [52]
- for cartesian fibrations: IV.4.1.24 of [51]

For one instantiation of the pointwise-detection of universal properties in $QCat$, see §6.1 of [49].

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