

# Synthetic perspectives on spaces and categories

Emily Riehl\*

## Abstract. TODO

**1 Introduction.** Over the past several decades, various formalisms have been developed for working with spaces or categories in a natively “derived” or equivalence-invariant manner [40, 81, 62, 33, 57, 44, 30, 54].

**1.1 On spaces.** In the case of topological spaces, the notion of equivalence we have in mind is *weak homotopy equivalence*, a map  $f: X \rightarrow Y$  that induces an isomorphism on path components and all homotopy groups. Constructions that respect this notion of equivalence are constructions on *homotopy types* — i.e., spaces up to weak homotopy equivalence — which are also known as  $\infty$ -*groupoids* (following Grothendieck [41]) or *anima* (following Česnavičius, Clausen, and Scholze [27, §11.1], [80, §1.2]). In this note, we use the more familiar term “spaces” to refer to these equivalent notions but caution that our spaces do not have a well-defined underlying set: instead, a point in a space refers to a homotopy class of maps out of a contractible space, i.e., an element of the set of path components.

Our aim in the first part of this note is to provide a prospective on spaces that captures the insights of *homotopy type theory* and *univalent foundations*, a “surprising synthesis of constructive intensional type theory and abstract homotopy theory” [71] discovered in the early 21st century. Homotopy type theory can be thought of as a synthetic theory of spaces, where spaces are primitive notions, usually called “types.” We will introduce notations, constructions, and proofs inspired by that formal framework in a concrete setting that can be described in traditional foundations.

To make sense of the constructions that follow we must work in a very convenient category of spaces. In [75], Steenrod explained how to construct a category that contained the familiar examples of spaces and had the property of being *cartesian closed*, meaning that the cartesian product with a fixed space  $X$  has a right adjoint, defining an internal hom: for spaces  $X$  and  $Y$ , this constructs the *mapping space*  $Y^X$  from  $X$  to  $Y$ . Here we require our category of spaces to be *locally cartesian closed*, a notion we review in §2. As our intention is to work “synthetically” rather than “analytically” — where our basic objects are presented as primitive notions with axioms describing their structure and properties rather than constructed in some other metatheory — our focus is on introducing notations and the ideas behind the basic constructions, leaving the technical details to the references which are well-known to experts and likely to be opaque to anyone else.

In fact our intended semantic setting is considerably more general than our language will suggest. Shulman has shown [72] that homotopy type theory, and in particular all of our constructions, can be interpreted in an arbitrary  $\infty$ -*topos* [64, 54], of which the base example is the  $\infty$ -topos of spaces. Thus our primitive “spaces” might be somewhat more elaborate.

**1.2 On categories.** Of the many interesting variants of the notion of a category, here we will focus on  $(\infty, 1)$ -*categories* — first introduced by Boardman and Vogt [15], further developed by Joyal [44], and nicknamed “ $\infty$ -categories” by Lurie [54] — which are the analogues of ordinary categories in which all the sets appearing in the definition are replaced by spaces, in the sense introduced above. This can be understood as *enriching* the ordinary notion of a category — adding morphisms between morphisms, and morphisms between morphisms, and morphisms between morphisms between morphisms ad infinitum thought of as paths, homotopies, and higher homotopies in the spaces of arrows. But on account of the fact that all of our constructions on spaces are required to be equivalence invariant, this must also be understood as *weakening* the only notion of a category. The central structure in an ordinary strict category is given by its composition function defined for any triple of objects  $x, y$ ,

---

\*This article is dedicated to Jack Morava, whose generous spirit and playful intellect are sorely missed (eriehl@jhu.edu, emilyriehl.github.io).

$z$ :

$$\mathrm{Hom}(y, z) \times \mathrm{Hom}(x, y) \xrightarrow{\circ} \mathrm{Hom}(x, z)$$

Here  $\mathrm{Hom}(x, y)$  denotes the space of arrows from  $x$  to  $y$  and maps of homotopy types are not well-defined functions in the usual sense. Instead, the composition of morphisms  $g: Y \rightarrow Z$  and  $f: X \rightarrow Y$  is only well-defined up to a contractible space of choices, which is the homotopical analog of the usual requirement that composition is defined uniquely. In this note, we use the term “categories” to refer to  $\infty$ -categories and use the term “(strict) 1-categories” to refer to the ordinary notion in the few settings it appears.

As categories, in our sense, are built out of spaces, it is attractive to develop the theory of categories in the synthetic setting for spaces described in §1.1. This avoids the notorious complexity inherent to the traditional “analytic” definitions of categories developed by [15, 31, 43, 63, 61, 9, 10, 47, 82, 47, 74, 8]; see [5, 11] for surveys of the analytic definitions and [24, 39, 42, 52, 54, 55, 45, 46] for developments of the analytic theory of categories. To the synthetic setting for spaces we add an axiomatic directed arrow satisfying strict interval axioms. In §5, we sketch the structures present in our setting for synthetic category theory, known in the literature as *simplicial type theory* [67]. Again, our intended semantic setting is more general than our language suggests. All of our constructions will make sense not just for categories—the  $\infty$ -categories described above—but to what are called *internal  $\infty$ -categories*, meaning  $\infty$ -categories defined in an arbitrary  $\infty$ -topos [58, 59].

**1.3 Outline.** We could easily fill this article with more precise descriptions of the formal frameworks for synthetic spaces and synthetic categories — homotopy type theory and simplicial type theory respectively. Instead, our plan is to highlight some of the fundamental constructions that can equally be defined in traditional foundations. In each parallel setting we will explore:

1. new induction principles, specifically *path induction* in §3 and *arrow induction* in §6 and
2. the use of universes that are respectively *univalent* in §4 and *directed univalent* in §7.

In §8, we conclude by highlighting ongoing work of our colleagues concerning synthetic spaces, synthetic categories, and synthetic mathematics more broadly.

There is a further benefit of synthetic mathematical frameworks, that will not feature here but also motivates this work, namely their amenity to computer formalization, as formal proofs in synthetic domains tend to more closely parallel their pen-and-paper counterparts. In particular, theorems in homotopy type theory, such as the applications of univalence mentioned in §4.3 have been formalized many times over, while the results on synthetic categories appearing in §5–6 have been formalized in the computer proof assistant RZK that implements the simplicial type theory [50, 51, 1], the first and to date essentially only formalization of results from higher category theory. This proof assistant did not exist while the paper [67] was being written, so the formalizations happened after the fact at which point they caught errors in the original paper, as noted in §6.

**2 A very convenient category of spaces.** Following Eilenberg and Zilber [32], Gabriel and Zisman [34], Kan [48], Quillen [62] and others, the classical homotopy theory of homotopy types can be modelled by a particular strict presheaf category, namely the strict 1-category  $\mathbf{sSet} := \mathbf{Set}^{\Delta^{\mathrm{op}}}$  of *simplicial sets*, indexed by the topologists’ strict 1-category  $\Delta$  of finite non-empty ordinals and order-preserving maps. The representables, the objects in the image of the Yoneda embedding  $\mathbf{y}: \Delta \hookrightarrow \mathbf{sSet}$  define the  $n$ -simplices  $\Delta^n$  for  $n \geq 0$ , thought of as combinatorial avatars of the topological  $n$ -simplices. By the density of the Yoneda embedding, all other simplicial sets may be canonically presented as colimits of the simplices. There is a canonically-defined adjunction between simplicial sets and the strict 1-category of point-set topological spaces whose left adjoint “geometrically realizes” a simplicial set as a topological space:

$$(2.1) \quad \begin{array}{ccc} & \Delta & \\ \mathbf{y} \swarrow & & \searrow \Delta^\bullet \\ \mathbf{sSet} & \xleftarrow{|\cdot| := \mathrm{colim}_{\Delta^\bullet}} & \mathcal{T}\mathrm{op} \\ & \xleftarrow[\mathrm{Sing} := \mathrm{Hom}(\Delta^\bullet, -)]{\perp} & \end{array}$$

There is something a bit strange about using simplicial sets as a combinatorial model for spaces, namely that the standard simplices are “directed”; for instance there is no “reversal” map  $\rho: \Delta^1 \rightarrow \Delta^1$  that exchanges the two vertices. While maps  $p: \Delta^1 \rightarrow X$  are thought of as “paths” in  $X$  they only behave like we would expect—meaning

paths can be reversed and composed—if  $X$  is a special sort of simplicial set called a *Kan complex*, which is characterized by a right lifting property:

$$\begin{array}{ccc} \Lambda_k^n & \xrightarrow{x} & X \\ \downarrow \wr & \nearrow \exists & \\ \Delta^n & & \end{array} \quad \begin{array}{ccc} \Lambda_k^n & \xrightarrow{x} & X \\ \downarrow \wr & \nearrow \exists & \downarrow f \\ \Delta^n & \xrightarrow{y} & Y \end{array} \quad n \geq 1, \quad 0 \leq k \leq n$$

More generally, a map of simplicial sets is called a *Kan fibration* and denoted  $f: X \twoheadrightarrow Y$  if it has the right lifting property against all inclusions of *horns*  $\Lambda_k^n \subset \Delta^n$ , these being the simplicial subset spanned by all of the codimension 1 simplices except the one opposite vertex  $k$ . The Kan complexes define the so-called *fibrant objects* and the Kan fibrations define the *fibrations* in a Quillen model structure, that is, a strict 1-categorical presentation of the  $\infty$ -category of spaces.

**THEOREM 2.2 (Quillen).** *There is a right proper simplicial model structure on simplicial sets whose cofibrations are the monomorphisms.*

**2.1 Families of spaces.** The category of simplicial sets is *locally cartesian closed*, meaning that for any  $f: \Delta \rightarrow \Gamma$  the composition functor has two right adjoints defined by pullback along  $f$  and pushforward along  $f$ :

$$(2.3) \quad \begin{array}{ccc} & \Sigma_f & \\ & \downarrow \perp & \\ \mathbf{sSet}_{/\Delta} & \xleftarrow{f^*} & \mathbf{sSet}_{/\Gamma} \\ & \uparrow \perp & \\ & \Pi_f & \end{array}$$

Since  $\mathbf{sSet}$  has a terminal object  $\Delta^0$ , this implies that  $\mathbf{sSet} \cong \mathbf{sSet}_{/\Delta^0}$  and indeed any slice  $\mathbf{sSet}_{/\Gamma}$  is cartesian closed and has all finite limits.

**LEMMA 2.4.** *When  $f: \Delta \rightarrow \Gamma$  is a fibration, all three adjoints  $\Sigma_f \dashv f^* \dashv \Pi_f$  preserve fibrations.*<sup>1</sup>

We introduce special notation for fibrations of simplicial sets  $\rho: A \twoheadrightarrow \Gamma$ , which we think of as families of spaces parametrized by a base space  $\Gamma$  referred to as the *context*; note that the fibers will be fibrant objects but this is not necessarily true nor is it necessary of the base  $\Gamma$ . Henceforth, we use “family of spaces” to refer to a fibration over a not necessarily fibrant base.

**Notation 2.5.** The following notation is intended to make the composition, pullback, and pushforward operations on families of spaces more legible.

- Fibrations will be depicted as an indexed family of spaces

$$\begin{array}{ccc} B & & B_a \longrightarrow B \\ \downarrow (B_a)_{a:A} & \lrcorner & \downarrow (B_a)_{a:A} \\ A & & \Gamma \xrightarrow{a} A \end{array}$$

particularly when the fibration is regarded as a fibrant object in the slice category  $\mathbf{sSet}_{/A}$ . Here  $B_a$  is also notation for the fiber over a generalized element  $a: \Gamma \rightarrow A$  abbreviated  $a: A$ . We refer to a fibration of this form as a “space  $B$  in context  $A$ .”

- With this notation, pullbacks are denoted as follows:

$$\begin{array}{ccc} B_f & \longrightarrow & B \\ (B_f c)_{c:C} \downarrow & \lrcorner & \downarrow (B_a)_{a:A} \\ C & \xrightarrow{f} & A \end{array}$$

In the identification of the fibers, the element  $fc$  is substituted for the element  $a$ , which is why pullbacks are also called *substitutions*.

<sup>1</sup>The fibration hypothesis is not needed for the pullback functor, but is needed for the other two adjoints.

- When  $A$  is a Kan complex, the functor  $\Sigma_A$  defined by composing with  $! : A \rightarrow \Delta^0$  sends a fibration  $(B_a)_{a:A}$  to a space  $\Sigma_{a:A} B_a$ , namely the domain  $B$  of the fibration.

$$\begin{array}{ccc} \Sigma_{a:A} B_a & & \Sigma_{a:A} B_a \\ (B_a)_{a:A} \downarrow & \mapsto & \downarrow ! \\ A & \xrightarrow{\quad ! \quad} & \Delta^0 \end{array}$$

More generally, when  $A$  is a space  $(A_\gamma)_{\gamma:\Gamma}$  in context  $\Gamma$ , the composition functor sends a fibration  $(B_a)_{a:A}$  to the fibration

$$\begin{array}{ccc} \Sigma_{a:A} B_a & & \Sigma_{\gamma:\Gamma} \Sigma_{a:A_\gamma} B_a \\ (B_a)_{a:A} \downarrow & \mapsto & \downarrow (\Sigma_{a:A_\gamma} B_a)_{\gamma:\Gamma} \\ A & \xrightarrow{(A_\gamma)_{\gamma:\Gamma}} & \Gamma \end{array}$$

Since the effect of composing a pair of fibrations is to “sum up the fibers” we also refer to the composition functor as *summation*.

- When  $A$  is a Kan complex, the functor  $\Pi_A$  defined by pushforward along  $! : A \rightarrow \Delta^0$  sends a fibration  $(B_a)_{a:A}$  to a space  $\Pi_{a:A} B_a$ , namely the space  $\text{Map}_A(A, B)$  of sections of the fibration.

$$\begin{array}{ccc} \Sigma_{a:A} B_a & & \Pi_{a:A} B_a \\ (B_a)_{a:A} \downarrow & \mapsto & \downarrow ! \\ A & \xrightarrow{\quad ! \quad} & \Delta^0 \end{array}$$

More generally, when  $A$  is a space  $(A_\gamma)_{\gamma:\Gamma}$  in context  $\Gamma$ , the pushforward functor sends a fibration  $(B_a)_{a:A}$  to the fibration

$$\begin{array}{ccc} \Sigma_{a:A} B_a & & \Sigma_{\gamma:\Gamma} \Pi_{a:A_\gamma} B_a \\ (B_a)_{a:A} \downarrow & \mapsto & \downarrow (\Pi_{a:A_\gamma} B_a)_{\gamma:\Gamma} \\ A & \xrightarrow{(A_\gamma)_{\gamma:\Gamma}} & \Gamma \end{array}$$

The notations just introduced are “stable under substitution,” commuting with pullbacks. For instance, the fibers over  $\gamma$  of the composition or pushforward along a fibration  $(A_\gamma)_{\gamma:\Gamma}$  agrees with the spaces obtained by composition or pushforward over the space  $A_\gamma$ , which we state in the case of a global element but the proof applies equally to a generalized element  $\gamma : \Delta \rightarrow \Gamma$ .

LEMMA 2.6. *For any element  $\gamma : \Delta^0 \rightarrow \Gamma$ ,*

$$\begin{array}{ccc} \Sigma_{a:A_\gamma} B_a & \longrightarrow & \Sigma_{\gamma:\Gamma} \Sigma_{a:A_\gamma} B_a \\ \downarrow & \lrcorner & \downarrow (\Sigma_{a:A_\gamma} B_a)_{\gamma:\Gamma} \\ \Delta^0 & \xrightarrow{\gamma} & \Gamma \end{array} \quad \text{and} \quad \begin{array}{ccc} \Pi_{a:A_\gamma} B_a & \longrightarrow & \Sigma_{\gamma:\Gamma} \Pi_{a:A_\gamma} B_a \\ \downarrow & \lrcorner & \downarrow (\Pi_{a:A_\gamma} B_a)_{\gamma:\Gamma} \\ \Delta^0 & \xrightarrow{\gamma} & \Gamma \end{array}$$

*Proof.* The space  $A_\gamma$  is defined by the pullback square

$$\begin{array}{ccc} A_\gamma & \longrightarrow & A \\ \downarrow & \lrcorner & \downarrow (A_\gamma)_{\gamma:\Gamma} \\ \Delta^0 & \xrightarrow{\gamma} & \Gamma \end{array}$$

By the composition and cancellation lemma for pullback squares, for any fibration over  $A$ , the result of composing along the inclusion  $(A_\gamma)_{\gamma:\Gamma}$  and then pulling back along  $\gamma$  is isomorphic to the result of pulling back along  $A_\gamma \rightarrow A$

and then summing over  $A_\gamma$ .<sup>2</sup> The corresponding operations in the case of the pushforward are right adjoints to these (though starting from the other corner of the square and traversing it in the other direction) and thus must also be isomorphic. This constructs the so-called *Beck-Chevalley isomorphisms*.  $\square$

**3 Path induction.** We work with the spaces and families of spaces introduced above, with technical details made precise in reference to the structures defined in Theorem 2.2 and elaborated further in [66].

For any space  $A$ , there is a natural *path space factorization* of the diagonal map defined by exponentiation with the simplicial interval

$$(3.1) \quad \Delta^0 + \Delta^0 \rightharpoonup \Delta^1 \xrightarrow{\sim} \Delta^0 \quad \rightsquigarrow \quad A \xrightarrow{\sim} A^{\Delta^1} \xrightarrow{(\text{ev}_0, \text{ev}_1)} A \times A$$

This constructs a family of spaces over  $A \times A$  whose total space is the path space  $A^{\Delta^1}$  and whose fiber over  $x, y : A$  we denote by  $x \sim y$  as we think of this family of spaces as defining a generalized binary relation on the base space  $A$ . An element  $p : x \sim y$  of the fiber is a *path* from  $x$  to  $y$  in  $A$

$$\begin{array}{ccc} x \sim y & \longrightarrow & A^{\Delta^1} \\ \downarrow & \lrcorner & \downarrow (x \sim y)_{x,y:A} \\ \Delta^0 & \xrightarrow{(x,y)} & A \times A \end{array}$$

As a consequence of Theorem 2.2, the left map of (3.1), the inclusion of constant paths, is a trivial cofibration in Quillen’s model structure, and as such has the right lifting property with respect to an family of spaces:

$$\begin{array}{ccc} \begin{array}{ccc} A & \xrightarrow{e} & E \\ \text{refl} \downarrow \wr & \nearrow & \downarrow \rho = (E_b)_{b:B} \\ A^{\Delta^1} & \xrightarrow{b} & B \end{array} & \rightsquigarrow & \begin{array}{ccc} \text{Map}(A^{\Delta^1}, E) & & \\ \wr \downarrow \wr \rho \circ - \circ \text{refl} & & \\ \text{Map}(A, E) \times_{\text{Map}(A, B)} \text{Map}(A^{\Delta^1}, B) & & \end{array} \end{array}$$

As a further consequence of Theorem 2.2, this lifting property can be *internalized*: the canonical map from the space  $\text{Map}(A^{\Delta^1}, E)$  of maps from the path space of  $A$  to  $E$  to the space  $\text{Map}(A, E) \times_{\text{Map}(A, B)} \text{Map}(A^{\Delta^1}, B)$  of commutative squares from  $\text{refl}$  to  $\rho$  is a *trivial fibration*, i.e., a “contractible family of spaces.” A section to this trivial fibration gives a continuous choice of solutions to lifting problems from  $\text{refl}$  to  $\rho$ . The fiber over a vertex  $(e, b)$  defines a contractible space; thus solutions to lifting problems from  $\text{refl}$  to  $\rho$  are “homotopically unique.”

By pulling back along the codomain  $b$ , to solve lifting problems of the form above it suffices to consider right lifting problems against families of spaces over the path space  $A^{\Delta^1}$  in which the codomain is the identity map:

(3.2)

$$\begin{array}{ccc} \begin{array}{ccccc} & & e & & \\ & \nearrow & & \searrow & \\ A & \xrightarrow{d} & P & \xrightarrow{\quad} & E \\ \text{refl} \downarrow \wr & \nearrow & \downarrow \chi \lrcorner & & \downarrow \rho \\ A^{\Delta^1} & \xrightarrow{\quad} & A^{\Delta^1} & \xrightarrow{b} & B \end{array} & \rightsquigarrow & \begin{array}{ccc} \text{Map}_{A^{\Delta^1}}(A^{\Delta^1}, P) & \longrightarrow & \text{Map}(A^{\Delta^1}, P) \\ \text{path-ind} \wr \downarrow \wr - \circ \text{refl} \lrcorner & & \wr \downarrow \wr \chi \circ - \circ \text{refl} \\ \text{Map}_A(A, P_{\text{refl}}) & \longrightarrow & \text{Map}(A, P) \times_{\text{Map}(A, A^{\Delta^1})} \text{Map}(A^{\Delta^1}, A^{\Delta^1}) \\ \downarrow & \lrcorner & \downarrow \pi \\ \Delta^0 & \xrightarrow{\text{id}} & \text{Map}(A^{\Delta^1}, A^{\Delta^1}) \end{array} \end{array}$$

Here the data of the lifting problem is given by a single map  $d : A \rightarrow P$  that is a partial section of the fibration  $\chi : P \rightarrow A^{\Delta^1}$  over the map  $\text{refl}$ .

$$\begin{array}{ccc} \begin{array}{ccc} & P & \\ d \nearrow & \downarrow (P_{x,y,p})_{x,y:A,p:x \sim y} & \\ A & \xrightarrow{\sim} & A^{\Delta^1} \end{array} & \rightsquigarrow & \begin{array}{ccc} P_{\text{refl}} & \longrightarrow & P \\ d \wr \downarrow \wr (P_{a,a,\text{refl}_a})_{a:A} \lrcorner & & \downarrow (P_{x,y,p})_{x,y:A,p:x \sim y} \\ A & \xrightarrow{\sim} & A^{\Delta^1} \end{array} \rightsquigarrow \begin{array}{ccc} & A \dashrightarrow^d P & \\ \text{refl} \downarrow \wr & & \downarrow (P_{x,y,p})_{x,y:A,p:x \sim y} \\ A^{\Delta^1} & \xrightarrow{\sim} & A^{\Delta^1} \end{array} \end{array}$$

<sup>2</sup>Importantly for the second part of this proof, if we don’t care whether the resulting map is a fibration, it doesn’t matter whether any maps in the pullback square are fibrations.

As before there exists a continuous choice of solutions to this lifting problem given by a section to the trivial fibration displayed above-center in (3.2). We call this map *path induction*, using an analogy first observed by Awodey and Warren [7] and Gambino and Garner [35]. The existence of this map proves the following proposition:

**PROPOSITION 3.3** (path induction, preliminary form). *To define a section of a fibration over a path space  $A^{\Delta^1}$ , it suffices to define a partial section over the subspace  $\text{refl} : A \rightarrowtail A^{\Delta^1}$  of constant paths.*

$$\begin{array}{ccc} A & \xrightarrow{d} & P \\ \text{refl} \downarrow \wr & \nearrow \text{path-ind} & \downarrow (P_{x,y,p})_{x,y:A, p:x \sim y} \\ A^{\Delta^1} & \xlongequal{\quad} & A^{\Delta^1} \end{array}$$

Path induction is a powerful proof technique, closely analogous to the principle of mathematical induction over the natural numbers. By analogy with that case, it also has constructive content, allowing the “recursive” definition of morphisms, though we follow convention and use the term “induction” for both induction and recursion.

**Construction 3.4** (inversion). Even though the simplicial interval  $\Delta^1$  has no symmetries, when  $A$  is a Kan complex, a path  $p : x \sim y$  can be inverted to define a path  $p^{-1} : y \sim x$ . In other words, the path relation on spaces is symmetric as well as reflexive. This symmetry can be defined as a continuous function on path spaces by path-induction, which says it suffices to specify the inverse of a constant path, which we take to be a constant path:

$$\begin{array}{ccc} A & \xrightarrow{\text{refl}} & A^{\Delta^1} \\ \text{refl} \downarrow \wr & \nearrow (-)^{-1} & \downarrow (y \sim x)_{x,y:A} \\ A^{\Delta^1} & \xrightarrow{(x \sim y)_{x,y:A}} & A \times A \end{array} \quad (-)^{-1} := \text{path-ind}(\text{refl} \mapsto \text{refl})$$

The full principle of path induction is more general than the version stated in Proposition 3.3 along two axes. The first extension uses the fact that Quillen’s model structure satisfies the *Frobenius condition* [36]: the trivial cofibrations are stable under pullback along fibrations. The operation of pullback along a fibration can be thought of as introducing a trivial dependency and is referred to as *weakening*. A more general version of path-induction states that given a fibration over a weakening of a path space, to define a section it suffices to define a section over the subspace of constant paths.

**PROPOSITION 3.5** (path induction, intermediate form). *Given a composable pair of fibrations  $\chi : Q \twoheadrightarrow P$  and  $\rho : P \twoheadrightarrow A^{\Delta^1}$  over a path space, to define a section of  $\chi$  it suffices to define a partial section over the pullback along  $\rho$  of the subspace  $\text{refl} : A \rightarrowtail A^{\Delta^1}$  of constant paths.*

$$\begin{array}{ccccc} A & \xleftarrow{\rho_{\text{refl}}} & P_{\text{refl}} & \xrightarrow{d} & Q \\ \text{refl} \downarrow \wr & & \downarrow \wr & \nearrow \text{path-ind} & \downarrow \chi = (Q_p)_{p:P} \\ A^{\Delta^1} & \xleftarrow{\rho} & P & \xlongequal{\quad} & P \end{array}$$

**Construction 3.6** (concatenation). In a space  $A$ , paths  $p : x \sim y$  and  $q : y \sim z$  can be composed to define a path  $p * q : x \sim z$ . The composition function, establishing the transitivity of the path space relation, can be defined by path induction using the weakening of the reflexivity map displayed below-left:

$$\begin{array}{ccccc} A & \xleftarrow{(\Sigma_{x:A} x \sim y)_{y:A}} & A^{\Delta^1} & \xlongequal{\quad} & A^{\Delta^1} \\ \text{refl} \downarrow \wr & & \downarrow \wr & \nearrow * & \downarrow (x \sim z)_{x,z:A} \\ A^{\Delta^1} & \xleftarrow{(\Sigma_{x:A} x \sim y)_{y,z:A, q:y \sim z}} & A^{\Delta^1} & \xrightarrow{(\Sigma_{y:A} x \sim y \sim z)_{x,z:A}} & A \times A \end{array} \quad * := \text{path-ind}(p, \text{refl} \mapsto p)$$

In summary, by path induction, the concatenation operation can be defined by specifying how to concatenate an arbitrary path  $p : x \sim y$  by a constant path  $\text{refl}_y : y \sim y$ , and we define concatenation with a constant path to be the identity function.

Note this construction of the concatenation function avoids the use of any higher simplices, though by homotopical uniqueness of solutions to lifting problems it is equivalent to the map defined by the more standard construction:

$$(3.7) \quad A^{\Delta^1} \xleftarrow[\sim]{\sim} A^{\Delta^2} \xrightarrow[-\delta^1]{-\delta^1} A^{\Delta^1}$$

*Construction 3.8* (transport). Families of spaces  $(B_a)_{a:A}$  are accompanied by path lifting or “transport” operations that lift a path  $p: x \sim y$  in the base space  $A$  to a continuous map  $\text{tr}_p: B_x \rightarrow B_y$  between the fibers.

As before, this operation can be expressed as a continuous function between spaces, where the domain is formed by pulling the domain projection  $e_0: A^{\Delta^1} \rightarrow A$  back along  $\rho: B \rightarrow A$ :

$$\begin{array}{ccc} A & \xleftarrow{(B_a)_{a:A}} B & \xrightarrow{\quad} B \\ \text{refl} \downarrow \wr & \downarrow \text{refl} \times 1 & \downarrow \rho = (B_y)_{y:A} \\ A^{\Delta^1} & \xleftarrow[(B_x)_{x,y:A,p:x \sim y}]{} A^{\Delta^1} \times_A B & \xrightarrow[(\Sigma_{x:A} (x \sim y) \times B_x)_{y:A}]{} A \end{array} \quad \text{tr} := \text{path-ind}(\text{refl}, u \mapsto u)$$

In summary, the transport operation is defined by path induction by declaring that transport along a constant path is the identity function.

We now describe the final extension of the homotopy type theoretic principle of path induction, which allows  $A$  to be a “space in an arbitrary context  $\Gamma$ .” We can perform an analogous construction starting from an arbitrary family of spaces  $(A_\gamma)_{\gamma:\Gamma}$ , whether or not the base  $\Gamma$  is a Kan complex. In context  $\Gamma$ , we replace the path space factorization (3.1) by the fibered path space factorization, a construction which is stable under substitution:

(3.9)

$$\begin{array}{ccc} A & \xrightarrow{\quad} A^{\Delta^1} & \rightarrow A \times A \\ \downarrow & \swarrow \Delta^1 \wr_{\Gamma} A & \downarrow \\ \Gamma & \xrightarrow{\quad} \Gamma^{\Delta^1} & \rightarrow \Gamma \times \Gamma \end{array} \quad \begin{array}{ccc} A_f & \xrightarrow{\quad} A & \xrightarrow{\quad} A \\ \downarrow & \swarrow \Delta^1 \wr_{\Delta} A_f & \downarrow \\ \Delta & \xrightarrow{\quad} \Gamma & \xrightarrow{\quad} \Gamma \end{array}$$

Once more the inclusion of constant paths is a trivial cofibration so we have a lifting property exactly as above. This proves the general form of the path induction principle.

**PROPOSITION 3.10** (path induction, final form). *Given a composable pair of fibrations  $\chi: Q \rightarrow P$  and  $\rho: P \rightarrow \Delta^1 \wr_{\Gamma} A$  over a path space in any context  $\Gamma$ , to define a section of  $\chi$  it suffices to define a partial section over the pullback along  $\rho$  of the subspace  $\text{refl}: A \rightarrow \Delta^1 \wr_{\Gamma} A$  of constant paths.*

$$\begin{array}{ccc} P_{\text{refl}} & \xrightarrow{\rho_{\text{refl}}} A & \\ \text{refl}_{\rho} \downarrow \wr & \lrcorner & \downarrow \text{refl} \\ P & \xrightarrow{\rho} \Delta^1 \wr_{\Gamma} A & \end{array} \quad \rightsquigarrow \quad \begin{array}{ccc} P_{\text{refl}} & \xrightarrow{d} Q & \\ \text{refl}_{\rho} \downarrow \wr & \text{path-ind} \nearrow & \downarrow \chi = (Q_p)_{p:P} \\ P & \xrightarrow{\quad} P & \end{array}$$

*Remark 3.11.* Proposition 3.10 is a precise analogue of Proposition 3.5 just interpreted in the slice category  $\mathbf{sSet}_{/\Gamma}$  instead of in  $\mathbf{sSet}$ . Crucially, all of the properties of Theorem 2.2 are stable under slicing, meaning inherited by all sliced categories  $\mathbf{sSet}_{/\Gamma}$ . In particular, this is why we described Quillen’s model structure as *simplicial* (enriched over Quillen’s model structure on simplicial sets) rather than *cartesian closed* (enriched over itself), because the former property is stable under slicing while the latter is not.

**4 Univalent universes.** In §4.1, we construct spaces whose points encode proofs of mathematical propositions, following [70, §4], where more details can be found. In §4.2, we introduced Voevodsky’s univalence axiom and sketch a modern approach to constructing univalent universes due to Shulman [72]. In §4.3, we tour a few standard applications, which are described in more detail in the textbooks [78, 69].

**4.1 Propositions as spaces.** The adjoint triples  $\Sigma_f \dashv f^* \dashv \Pi_f$  can be used to construct spaces in the empty context or fibrations in a general context  $\Gamma$  whose global elements — points in the former case and sections in the latter case — provide data witnessing the proof of some proposition. Thus, these spaces exhibit mathematical propositions as homotopy types. Since the inputs to our constructions are features that are equally present in slices  $\mathbf{sSet}/\Gamma$  we may leave the context  $\Gamma$  implicit in our notation, representing a family of spaces  $(A_\gamma)_{\gamma:\Gamma}$  as a space “ $A$ ” and reverting to the notation  $A^{\Delta^1}$  for the path space in context  $\Gamma$ .

*Construction 4.1* (contractibility). Fix a Kan complex  $A$ . Under the notations just introduced, the path space fibration  $(\text{ev}_0, \text{ev}_1): A^{\Delta^1} \rightarrow A \times A$  is also denoted by  $(x \sim y)_{x,y:A}$ . The pushforward along the projection away from the second coordinate defines the fibration  $(\Pi_{y:A} x \sim y)_{x:A}$ , and then the sum along the projection away from the first coordinate defines the space  $\Sigma_{x:A} \Pi_{y:A} x \sim y$ .

$$\begin{array}{ccccc} A^{\Delta^1} & & \Sigma_{x:A} \Pi_{y:A} x \sim y & & \Sigma_{x:A} \Pi_{y:A} x \sim y \\ \downarrow (x \sim y)_{x,y:A} & \mapsto & \downarrow (\Pi_{y:A} x \sim y)_{x:A} & \mapsto & \downarrow ! \\ A \times A & & A & & \Delta^0 \end{array}$$

A global element of  $\Sigma_{x:A} \Pi_{y:A} x \sim y$  defines firstly an element  $a : A$  together with an element of the fiber  $\Pi_{y:A} a \sim y$ , which is a section of the based path space fibration. Together this data proves the contractibility of  $A$ , and thus we define

$$\text{isContr}(A) := \Sigma_{x:A} \Pi_{y:A} x \sim y$$

An example of a contractible space is a based path space. Fix a point  $a : A$  and consider the space  $\Sigma_{y:A} a \sim y$  defined by

$$(4.2) \quad \begin{array}{ccc} \Sigma_{y:A} a \sim y & \longrightarrow & A^{\Delta^1} \\ \downarrow & \lrcorner & \downarrow (x \sim y)_{x,y:A} \\ \Delta^0 & \xrightarrow{a} & A \end{array}$$

A proof that  $\Sigma_{y:A} a \sim y$  is contractible defines a global element of  $\text{isContr}(\Sigma_{y:A} a \sim y)$ , but we can do better. When we “fix a point  $a : A$ ” or “let  $a$  be a point  $A$ ,” we are introducing the space  $A$  as the context. Thus, our based path spaces are more properly thought of as fibrations  $(\Sigma_{y:A} a \sim y)_{a:A} \in \mathbf{sSet}/A$ .

By Remark 3.11, the construction of Construction 4.1 can be interpreted in any context. When applied to a fibration  $(A_\gamma)_{\gamma:\Gamma}$  it defines a fibration  $\text{isContr}((A_\gamma)_{\gamma:\Gamma}) \cong (\text{isContr}(A_\gamma))_{\gamma:\Gamma} \in \mathbf{sSet}/\Gamma$  whose fiber over  $\gamma : \Gamma$  is the space  $\text{isContr}(A_\gamma)$  by Lemma 2.6. When applied to the fibration  $(\Sigma_{y:A} a \sim y)_{a:A}$ , we obtain a fibration  $(\text{isContr}(\Sigma_{y:A} a \sim y))_{a:A} \in \mathbf{sSet}/A$  admitting a section, which proves the contractibility of the based path spaces, simultaneously and continuously for all  $a : A$ . Indeed:

**LEMMA 4.3.** *A family of spaces  $(A_\gamma)_{\gamma:\Gamma}$  defines a contractible family of spaces if and only if and only if  $\text{isContr}((A_\gamma)_{\gamma:\Gamma}) \in \mathbf{sSet}/\Gamma$  has a section.*

*Construction 4.4* (equivalence). Consider a map  $f : A \rightarrow B$  between spaces. The familiar mapping path space construction defines a fibration:

$$(4.5) \quad \begin{array}{ccc} \Sigma_{a:A} \Sigma_{b:B} f a \sim b & \longrightarrow & B^{\Delta^1} \\ (f a \sim b)_{a:A, b:B} \downarrow & \lrcorner & \downarrow (x \sim y)_{x,y:B} \\ A \times B & \xrightarrow{f \times \text{id}} & B \times B \end{array} \rightsquigarrow \begin{array}{ccc} \Sigma_{b:B} \Sigma_{a:A} f a \sim b & & \\ \downarrow (\Sigma_{a:A} f a \sim b)_{b:B} & & \\ B & & \end{array}$$

whose fibers are the spaces

$$\text{fib}_f b := \Sigma_{a:A} f a \sim b.$$

These allow us to define the space

$$\text{isEquiv}(f) := \Pi_{b:B} \text{isContr}(\text{fib}_f b).$$



As the terminology suggests, a point in the space  $\text{isEquiv}(f)$  proves that  $f: A \rightarrow B$  is a homotopy equivalence between spaces. Such a term provides the data of a section to the fibration below-left:

$$\begin{array}{ccc} \Sigma_{b:B} \text{isContr}(\text{fib}_f b) & & \Sigma_{b:B} \text{fib}_f b \\ \downarrow (\text{isContr}(\text{fib}_f b))_{b:B} & \rightsquigarrow & \downarrow (\text{fib}_f b)_{b:B} \\ B & & B \end{array}$$

Passing to the center of contraction, this defines a section to the fibration above-right, which gives the data of a continuous function  $g: B \rightarrow A$  together with a homotopy  $\beta: \Pi_{b:B} f g b \sim b$ . The remaining data—which witnesses that the fibers are contractible, not just inhabited—can be used to construct a second homotopy  $\alpha: \Pi_{a:A} g f a \sim a$ .

Again, this construction can be interpreted in any context:

LEMMA 4.6. *A map  $f$  between families of spaces over  $\Gamma$  is a weak equivalence if and only if  $\text{isEquiv}(f) \in \mathbf{sSet}/\Gamma$  has a section.*

Construction 4.7 (equivalences). For spaces  $A$  and  $B$ , define a space

$$A \simeq B := \Sigma_{f:A \rightarrow B} \text{isEquiv}(f).$$

Here we’re using  $A \rightarrow B$  as alternate notation for the mapping space  $B^A$ . The space  $A \simeq B$  has a natural projection map to the mapping space  $A \rightarrow B$ , which is a homotopy monomorphism because the space  $\text{isEquiv}(f)$  is a *proposition*: if  $\text{isEquiv}(f)$  contains any points, then it is contractible.

**4.2 Constructing univalence universes.** The previous constructions were defined in the context of arbitrary spaces  $A$  and  $B$ . We can regard these as constructions in the slice where we use a *universe*  $\mathcal{U}$  of small<sup>3</sup> spaces to define our context. Our next task is to define this space  $\mathcal{U}$ .

What we seek is both a space  $\mathcal{U}$  of small spaces and a universal family  $(A)_{A:\mathcal{U}}$  of small spaces so that generalized elements  $A: \Gamma \rightarrow \mathcal{U}$  define families of small spaces in context  $\Gamma$ :

$$(4.8) \quad \begin{array}{ccc} A & \longrightarrow & \tilde{\mathcal{U}} \\ (A_\gamma)_{\gamma:\Gamma} \downarrow & \lrcorner & \downarrow (A)_{A:\mathcal{U}} \\ \Gamma & \xrightarrow{A} & \mathcal{U} \end{array}$$

The universal family of small spaces is known as an *object classifier*, in analogy with the *subobject classifier* that can be found in any elementary 1-topos.

Following Voevodsky [49], the universe is the fundamental ingredient used to solve the coherence problems inherent in interpreting the strict syntax of homotopy type theory (where in particular, the substitution operation is defined up to *equality*) in a 1-category, where constructions like the pullback (4.8) are only defined up to isomorphism, or even worse in an  $\infty$ -category, where constructions like (4.8) are only well-defined up to equivalence. Hence, we require a construction of the universe in a strict 1-categorical presentation of the  $\infty$ -category of spaces, such as given by Theorem 2.2, and require the classifying pullbacks to be 1-categorical rather than  $\infty$ -categorical.

Naïvely, it looks as if the 1-categorical universal property of the universal family  $(A)_{A:\mathcal{U}}$  is that it represents small families of spaces, but this isn’t quite right because small families of spaces and the action of morphisms into the base space by pullback, defines a 1-groupoid valued pseudofunctor, rather than a strict set-valued functor; see [66, §4.1] for discussion. Shulman introduces an axiomatic *notion of fibred structure* [72, §3], which in particular defines a 1-groupoid-valued pseudofunctor  $\mathbb{F}$ . Examples include pullback stable families of morphisms, like the fibrations in a Quillen model category, but also examples where the notion of “fibration” is encoded by additional structure borne by, rather than a mere property of, a map. In a Grothendieck 1-topos with a Cisinski model structure like in Theorem 2.2, any notion of fibred structure  $\mathbb{F}$  that satisfies a size condition—is *small groupoid*

<sup>3</sup>Here “small” means that the cardinality of the fibers is bounded by some infinite regular cardinal  $\kappa$ —an implicit parameter in everything that follows—which is often assumed to be inaccessible so that the universe is closed under all of the desired type theoretic operations.

valued—and a locality condition—is *locally representable*—admits a universe  $\mathcal{U}$  with a map  $\mathfrak{A}_{\mathcal{U}} \rightarrow \mathbb{F}$  that is a “surjective equivalence” in a suitable sense [72, 5.10]. By the Yoneda lemma, this data encodes a fibration (in the sense of the notion of fibred structure  $\mathbb{F}$ ) over  $\mathcal{U}$ , defining the desired universal family of spaces.

The univalence axiom characterizes the paths  $(A \sim B)_{A,B:\mathcal{U}}$  in terms of another universal family. Consider the family of spaces  $(A \simeq B)_{A,B:\mathcal{U}}$  encoded the universal equivalence, as defined by Construction 4.7. By construction, a generalized element

$$\begin{array}{ccc} A \simeq B & \longrightarrow & \text{Eq}(\tilde{\mathcal{U}}) \\ e \downarrow \lrcorner & & \downarrow (A \simeq B)_{A,B:\mathcal{U}} \\ \Gamma & \xrightarrow{(A,B)} & \mathcal{U} \times \mathcal{U} \end{array}$$

encodes an equivalence  $e: A \simeq B$  between the families of spaces over  $\Gamma$  classified by the maps  $A, B: \Gamma \rightarrow \mathcal{U}$ .

DEFINITION 4.9 (Voevodsky [49]). *The fibration  $v: \tilde{\mathcal{U}} \rightarrow \mathcal{U}$  is **univalent** if the comparison map from the path space to the space of equivalences defined by path induction is an equivalence:*

$$\begin{array}{ccc} \mathcal{U} & \xrightarrow{\text{id}} & \text{Eq}(\tilde{\mathcal{U}}) \\ \text{refl} \downarrow \wr & \nearrow \text{path-to-eq} & \downarrow (A \simeq B)_{A,B:\mathcal{U}} \\ \mathcal{U}^{\Delta^1} & \xrightarrow{(A \sim B)_{A,B:\mathcal{U}}} & \mathcal{U} \times \mathcal{U} \end{array} \quad \text{path-to-eq} := \text{path-ind}(\text{refl} \mapsto \text{id})$$

**4.3 Applications of Univalence.** Using univalence, we can prove that the synthetic language for spaces is natively “derived,” with all constructions respecting equivalence between spaces. A construction on spaces can be interpreted as defining a family of spaces  $(E_X)_{X:\mathcal{U}}$  over the universe  $\mathcal{U}$ . By Construction 3.8, one then has a transport function that carries a path  $p: X \sim Y$  between spaces  $X, Y: \mathcal{U}$  into a map  $\text{tr}_p: E_X \rightarrow E_Y$ . By another application of path induction, this transport function is an equivalence, since this is true in the case of transport along constant paths, which is given by the identity function. By univalence, if  $X \simeq Y$ , then the equivalence can be converted into such a path and consequently an equivalence  $E_X \simeq E_Y$ .

The universe  $\mathcal{U}$  can also be used to define other classifying spaces. Then univalence is used to characterize the path space in the classifying space by means of a family of theorems that are generally referred to as the *structure identity principle* [29, 2].

*Example 4.10.* For any natural number  $n$ , we can form the discrete space  $\mathbf{n}$  on  $n$  points and then define the subuniverse  $\text{Fin}_n := \Sigma_{X:\mathcal{U}} \|\mathbf{n} \simeq X\|$  of spaces that are equivalent to  $\mathbf{n}$ . Here, the “ $\|\cdot\|$ ” denotes the *propositional truncation*, meaning that the data of an explicit equivalence  $\mathbf{n} \simeq X$  is not recorded. It follows that the natural projection map from  $\text{Fin}_n$  to  $\mathcal{U}$  is a homotopy monomorphism. The space  $\text{Fin}_n$  is naturally regarded as a based space, with  $\mathbf{n}: \text{Fin}_n$  serving as the base point.

By the univalence axiom,  $\text{Fin}_n$  is a 1-type, with all homotopy groups vanishing above dimension 1. Paths in  $\text{Fin}_n$  are equivalent to paths  $p: X \sim Y$  in  $\mathcal{U}$  between the objects in  $\text{Fin}_n$ ; in particular, since all  $X, Y: \text{Fin}_n$  are equivalent to  $\mathbf{n}$  and thus to each other, the space  $\text{Fin}_n$  is 0-connected, i.e., has a single path component. By univalence, paths  $p: X \sim Y$  in  $\text{Fin}_n$  are equivalent to equivalences  $p: X \simeq Y$ . It follows that the based loop space  $\Omega(\text{Fin}_n) := \mathbf{n} \sim \mathbf{n}$  is equivalent to the space of equivalences  $\mathbf{n} \simeq \mathbf{n}$ , better known as the symmetric group  $\Sigma_n$  on  $n$  elements.

As noted in Example 4.10, the space  $\text{Fin}_n$  is a pointed, 0-connected, 1-type whose loop space is the discrete space  $\Sigma_n$ . Thus, we have the alternate notation  $B\Sigma_n := \text{Fin}_n$  that is more amenable to generalization.

*Example 4.11.* For a general discrete group  $G$ , there is a standard “analytic” construction of its classifying space as the geometric realization of the nerve of the strict 1-category with one object whose endomorphisms are elements of the group  $G$ . As this construction involves a left adjoint (2.1), it is somewhat delicate to establish the mapping in universal property of the space so-constructed. Using the language for synthetic spaces, we can instead construct  $BG$  as the space spanned by those  $X: \mathcal{U}$  that are  $G$ -torsors, those 0-types  $X$  equipped with a free and transitive  $G$ -action. To define a family of  $G$ -torsors over a base space  $\Gamma$  is then just to define a map  $X: \Gamma \rightarrow BG$ .

*Example 4.12.* Extending the perspective on groups introduced in Example 4.11, we may define the space of groups to be the space of pointed, 0-connected, 1-types. Alternatively, we can define the space of groups following the standard definition: “a group is a discrete space, with a binary multiplication, satisfying axioms” as we illustrate in the simpler case of  $H$ -spaces:

$$H\text{-}\mathbf{Spc} := \Sigma_X \mathcal{U} \Sigma_{e:X} \Sigma_{\mu:X \times X \rightarrow X} \Pi_{x:X} (\mu(x, e) \sim x) \times (\mu(e, x) \sim x).$$

By univalence, paths in  $H\text{-}\mathbf{Spc}$  are equivalences of  $H$ -spaces via  $H$ -space homomorphisms; this is an instance of the aforementioned structure identity principle. Similarly, paths in  $\mathbf{Group}$  are group isomorphisms [69].

Both spaces of groups just described, the “concrete” groups, as encoded by their classifying spaces  $BG$ , and the “abstract” groups, as captured by the usual set-theoretic definition are equivalent. For a development of group theory from the perspective of classifying spaces, see [12].

An advantage of the classifying space approach is that it allows many constructions of group theory to extend to *higher groups*. If  $a : A$  is a point in an arbitrary space  $A$ , one may form the space  $B\text{Aut}(a) := \Sigma_{x:A} \|a \sim x\|$  by generalizing the construction used in Example 4.10. This is again a pointed space, with basepoint  $a : B\text{Aut}(a)$ , and one recovers the higher automorphism group  $\text{Aut}(a)$  as  $\Omega(B\text{Aut}(a)) := a \sim a$ . If  $A$  is an  $(n+1)$ -type, then so is  $B\text{Aut}(a)$ , and the based loop space  $\text{Aut}(a)$  is  $n$ -truncated. This constructs an example of an  $(n+1)$ -group, where the notion of 1-group recovers the standard examples of automorphism groups of discrete spaces. In particular, we may form  $B\text{Aut}(A)$  associated to  $A : \mathcal{U}$  and immediately from its definition a map  $X \rightarrow B\text{Aut}(A)$  is a family of spaces over  $X$  whose fibers are equivalent to the space  $A$ .

In general, we define a *higher group* to be a pointed connected space  $BG$ , where  $G := \Omega BG$  is the carrier space for the higher group and  $BG$  is the classifying space. Groups with untruncated classifying spaces are  $\infty$ -groups, while groups with  $(n+1)$ -truncated classifying spaces are  $(n+1)$ -groups.

An *action* of a higher group  $BG$  on a space  $X$ , is just a map  $X : BG \rightarrow \mathcal{U}$  sending the basepoint of  $BG$  to  $X : \mathcal{U}$ . Thus an action provides a family of spaces  $(X_z)_{z:BG}$  over  $BG$ . The invariants and coinvariants of this action are given by the spaces  $X^{hG} := \Pi_{z:BG} X_z$  and  $X_{hG} := X // G := \Sigma_{z:BG} X_z$  respectively. See [17] for considerably more.

**5 A language for synthetic categories** In the language for synthetic categories—introduced in [67] and now commonly referred to as *simplicial type theory* or *simplicial homotopy type theory*—we extend the language for synthetic spaces with an axiomatic directed interval  $2$  satisfying strict interval axioms. That is  $2$  is equipped with distinct elements  $0, 1 : 2$  and a binary predicate  $(x \leq y)_{x,y:2}$  that is reflexive, antisymmetric, transitive, and total, with minimum  $0$ , maximum  $1$ . We think of the object  $2$  as the “walking arrow,” with source  $0$  and target  $1$ . From this structure, we can build a “walking composable pair of arrows”  $3$  — which we identify as the subspace of the square  $2 \times 2$  carved out by the predicate  $(y \leq x)_{x,y:2}$  — or more generally, the “walking composable sequence of  $n$  arrows”  $n+1$  for each  $n \geq 0$ .<sup>4</sup> Following the construction of Joyal’s proof that the classifying 1-topos of the theory of the strict interval is the 1-category of simplicial sets [56], we may construct face inclusions  $\delta^i : n \rightarrow n+1$  and degeneracy maps  $\sigma^j : n+1 \rightarrow n$  between these objects defining the cosimplicial object below-left

$$(5.1) \quad \begin{array}{ccccc} & & -\delta^2 \rightarrow & & \\ & -\delta^1 \rightarrow & \leftarrow \sigma^0 - & & \\ 1 \leftarrow \sigma^0 - 2 & -\delta^1 \rightarrow 3 & \cdots & =: & \Delta^0 \leftarrow \sigma^0 - \Delta^1 -\delta^1 \rightarrow \Delta^2 \cdots \\ & -\delta^0 \rightarrow & \leftarrow \sigma^1 - & & \\ & & -\delta^0 \rightarrow & & \end{array}$$

We may think of this simplicial structure as being freely added to the very convenient category of spaces introduced in §2, and thus our basic semantic setting is  $\mathbf{sSet}^{\Delta^{\text{op}}}$ —a strict 1-category whose objects we refer to as *simplicial spaces*. This is again an  $\infty$ -topos, and in particular a locally cartesian closed category, for which all of the constructions of §3 and §4 apply.

In  $\mathbf{sSet}^{\Delta^{\text{op}}}$  the walking arrow is interpreted by the discretely embedded representable  $\Delta^1$  and similarly for the other objects in the diagram (5.1). Indeed, it is conventional to reuse the simplicial notation for the walking arrows just constructed— $\Delta^0 := 1$ ,  $\Delta^1 := 2$ ,  $\Delta^2 := 3$ , etc—as indicated on the right-hand side. More generally, we’ll use simplicial notation such as  $\Delta_1^2 \subset \Delta^2$  for discretely embedded simplicial spaces, i.e., for simplicial objects valued in discrete spaces.

<sup>4</sup>See [67, 3.3] for a discussion of the convention to reverse the order of the coordinates

*Warning 5.2.* Beware that the object used to define the path space factorization in (3.1) is different from the simplicial space  $\Delta^1 := 2$  we use here: instant that object is a constant simplicial object valued in a non-discrete space. Because the map  $\text{refl}$  defining the inclusion of the subspace of constant paths is an equivalence, we may use  $A$  as an equivalent representation of the total space of the path space family on  $A$  on the occasions it appears here.

In an attempt to be as concrete as possible, we'll refer to "simplicial spaces" in what follows, but the semantics of the language of synthetic category theory is more general, interpretable in the category of simplicial objects in any  $\infty$ -topos [84].

*Construction 5.3.* For a simplicial space  $C$ , we define a family of simplicial spaces  $(\text{Hom}(x, y))_{x, y: C}$  by exponentiation with the walking arrow:

$$\Delta^0 + \Delta^0 \rightarrow \Delta^1 \rightarrow \Delta^0 \quad \rightsquigarrow \quad C \xrightarrow{\text{id}} C^{\Delta^1} \xrightarrow{(\text{ev}_0, \text{ev}_1)} C \times C$$

We refer to an element  $f : \text{Hom}(x, y)$  of the fiber as an *arrow* from  $x$  to  $y$  in  $C$

$$\begin{array}{ccc} \text{Hom}(x, y) & \longrightarrow & C^{\Delta^1} \\ \downarrow & \lrcorner & \downarrow (\text{Hom}(x, y))_{x, y: C} \\ \Delta^0 & \xrightarrow{(x, y)} & C \times C \end{array}$$

Thus, all simplicial spaces  $C$  have families of arrows  $(\text{Hom}(x, y))_{x, y: C}$  as well as identity arrows  $\text{id}_x : \text{Hom}(x, x)$  defined by the partial section  $\text{id} : C \rightarrow C^{\Delta^1}$ . But not all simplicial spaces should be thought of as categories. A *precategory* is a simplicial space  $C$  so that all pairs of composable arrows have a unique composite as is made precise by the following definition.

**DEFINITION 5.4.** A simplicial space  $C$  is a **precategory** if the map  $C^{\Delta^2} \rightarrow C^{\Lambda_1^2}$  defined by the inclusion  $\Lambda_1^2 \hookrightarrow \Delta^2$  is an equivalence.

A precategory  $C$  has a canonical composition function defined for any triple of elements  $x, y, z : C$

$$\text{Hom}(y, z) \times \text{Hom}(x, y) \xrightarrow{\circ} \text{Hom}(x, z)$$

This is defined by identifying a composable pair of arrows  $g, f$  with an element  $(g, f) : C^{\Lambda_1^2}$ , then using the inverse of the equivalence of Definition 5.4 to extend this data to a pair of composable arrows  $\text{comp}(g, f) : C^{\Delta^2}$ , and then precompose with the function  $\delta^1 : \Delta^1 \rightarrow \Delta^2$  to obtain an arrow  $g \circ f : C^{\Delta^1}$  from  $x$  to  $z$ , i.e., by the analogous construction of (3.7). But there are several advantages to giving the definition in the form that we did.

**LEMMA 5.5.** In a precategory  $C$ :

- For all  $f : \text{Hom}(x, y)$ ,  $f \circ \text{id}_x \sim f$  and  $f \sim f \circ \text{id}_y \circ f$ , and
- for all composable triples of arrows  $h, g, f$ ,  $(h \circ g) \circ f \simeq h \circ (g \circ f)$ .

These properties both follow from the higher structure inherent in the equivalence of simplicial spaces of Definition 5.4 and would not follow automatically from an axiomatized binary composition function. Another useful consequence is functoriality for free, essentially by commutativity of pre- and post-composition in the category of simplicial spaces:

**LEMMA 5.6.** Any function  $F : C \rightarrow D$  between precategories is automatically functorial, preserving both identities and composition.

The simplicial space of *isomorphisms* between elements  $x, y : C$  in a precategory is defined by

$$x \cong y := \Sigma_{f: \text{Hom}(x, y)} \Sigma_{g: \text{Hom}(y, x)} (g \circ f \sim \text{id}_x) \times (\Sigma_{h: \text{Hom}(y, x)} f \circ h \sim \text{id}_y).^5$$

<sup>5</sup>The unexpected complexity is because in the higher setting we must use a homotopy coherent model of the free living isomorphism  $\mathbb{I}$  in  $\mathbf{sSet}$ .

DEFINITION 5.7. A *precategory* is a **category** if for all  $x, y : C$ , the natural map is an equivalence:

$$\begin{array}{ccc} C & \xrightarrow{\text{path-ind}(\text{refl} \mapsto \text{id})} & C^{\mathbb{I}} \\ & \searrow (x \sim y)_{x,y:C} & \swarrow (x \cong y)_{x,y:C} \\ & C \times C & \end{array}$$

DEFINITION 5.8. A *simplicial space*  $C$  is a **groupoid** if for all  $x, y : C$ , the natural map is an equivalence:

$$\begin{array}{ccc} C & \xrightarrow{\text{path-ind}(\text{refl} \mapsto \text{id})} & C^{\Delta^1} \\ & \searrow (x \sim y)_{x,y:C} & \swarrow (\text{Hom}(x,y))_{x,y:C} \\ & C \times C & \end{array}$$

Remark 5.9. Using the commutative triangle

$$\begin{array}{ccc} & C & \\ \text{path-ind}(\text{refl} \mapsto \text{id}) \swarrow & & \searrow \text{path-ind}(\text{refl} \mapsto \text{id}) \\ C^{\mathbb{I}} & \xrightarrow{\quad} & C^{\Delta^1} \end{array}$$

one can show that a groupoid is a category in which all arrows are isomorphisms.

**6 Arrow induction.** Arrow induction extends the Yoneda lemma from traditional category theory, which describes the mapping out universal property of a representable functor. To use more familiar language, we refer to categories here but all the results about categories in this section actually apply in the more general setting of precategories, satisfying only Definition 5.4.

There are various formulations of the Yoneda lemma for families of categories first described by Street [77], then adapted to the higher categorical setting by [68], and to the setting of synthetic categories by [67, 18, 85]. Here we present the variant that is easiest to explain, rather than the most general, developing the Yoneda lemma for families of  $\infty$ -groupoids that vary covariantly functorially in arrows in the base  $\infty$ -category. Other variants consider families of  $\infty$ -categories which might mix covariant and contravariant dependencies.

**6.1 Arrow induction for covariant families.** Fixing a category  $C$  and element  $c : C$ , the covariant representable functor is encoded by the family of simplicial spaces  $(\text{Hom}(c, x))_{x:C}$ . This family has a special property of being *covariant*, meaning any arrow  $f : \text{Hom}(x, y)$  in the base simplicial space lifts uniquely to an arrow in the total space with specified source.

DEFINITION 6.1. A family of simplicial spaces  $(E_x)_{x:B}$  is **covariant** if for all arrows  $f : \text{Hom}(x, y)$  in  $B$  the function  $\text{ev}_0 : \Pi_{t:\Delta^1} E_{f(t)} \rightarrow E_x$  is an equivalence.

Here the simplicial space  $\Pi_{t:\Delta^1} E_{f(t)}$  is the space of arrows in the family living over the arrow  $f$  in the base. Definition 6.1 asserts that such arrows are uniquely determined by their source. Equivalently, Definition 6.1 asserts that the square is a pullback in the higher categorical sense:

$$\begin{array}{ccc} E^{\Delta^1} & \xrightarrow{\text{ev}_0} & E \\ (\Pi_{t:\Delta^1} E_{f(t)})_{f:B^{\Delta^1}} \downarrow \lrcorner & & \downarrow (E_x)_{x:B} \\ B^{\Delta^1} & \xrightarrow{\text{ev}_0} & B \end{array} \quad \rightsquigarrow \quad \Pi_{t:\Delta^1} E_{f(t)} \xrightarrow[\sim]{\text{ev}_0} E_x \text{ for all } f : \text{Hom}(x, y) \text{ in } B$$

which is equivalent to asserting that the induced map between fibers is an equivalence. By a contractibility argument, it follows:

LEMMA 6.2. If  $(E_x)_{x:B}$  is a covariant family of simplicial spaces, then the fibers  $E_x$  are groupoids.<sup>6</sup>

<sup>6</sup>The original reference [67, 8.18] asserts this result assuming that the base  $B$  is a precategory, but this hypothesis turns out to be unnecessary, as has been verified in an accompanying library where all of these results about synthetic categories have been verified in the computer proof assistant Rzk [1].

We now explain the terminology “covariant.” For each arrow  $f : \text{Hom}_B(x, y)$  in the base of a covariant family, there is a map between the fibers  $f_* : E_x \rightarrow E_y$  defined by composing the inverse of the equivalence of Definition 6.1 with the other projection  $\text{ev}_1 : \Pi_{t:2} E_{f(t)} \rightarrow E_y$ . As with the case of Definition 5.4, the advantage of formulating Definition 6.1 as we did is that it follows formally that these actions are covariantly functorial when the base is a category:

LEMMA 6.3. *When  $B$  is a category and  $(E_x)_{x:B}$  is a covariant family of simplicial spaces, the action of arrows in the base on the fibers is covariantly functorial: we have  $\text{id}_x(u) \sim u$  for  $u : E_x$  and  $(g \circ f)_* u \sim g_*(f_* u)$  for  $u : E_x$ ,  $f : \text{Hom}(x, y)$ , and  $g : \text{Hom}(y, z)$ .*

Just as functoriality comes for free for synthetic categories, similarly naturality comes for free for maps between covariant families:

LEMMA 6.4. *Given covariant families  $(E_x)_{x:B}$  and  $(F_x)_{x:B}$ , any fiberwise map  $\phi : \Pi_{x:B} (E_x \rightarrow F_x)$  as below-left is automatically natural: for any  $f : \text{Hom}(x, y)$ , the diagram below-right commutes up to homotopy.*

$$\begin{array}{ccc} E & \xrightarrow{\phi} & F \\ (E_x)_{x:B} \searrow & & \swarrow (F_x)_{x:B} \\ & B & \end{array} \qquad \begin{array}{ccc} E_x & \xrightarrow{\phi_x} & F_x \\ f_* \downarrow & & \downarrow f_* \\ E_y & \xrightarrow{\phi_y} & F_y \end{array}$$

LEMMA 6.5. *A simplicial space  $C$  is a precategory if and only if for each  $c : C$ , the family  $(\text{Hom}(c, x))_{x:C}$  is covariant, in which case the action on fibers  $f_* : \text{Hom}(c, x) \rightarrow \text{Hom}(c, y)$  coincides with composition  $f \circ - : \text{Hom}(c, x) \rightarrow \text{Hom}(c, y)$  with  $f : \text{Hom}(x, y)$ .<sup>7</sup>*

We can now state the arrow induction principle.

PROPOSITION 6.6 (arrow induction). *Fix  $c : C$ , with  $C$  a category, and consider the covariant family  $(\text{Hom}(c, x))_{x:C}$  whose total space is the coslice category  ${}^c/C$  of arrows under  $c$ . To define a section of a covariant family over the coslice category  ${}^c/C$ , it suffices to define the image of the identity arrow  $\text{id}_c$ .*

$$\begin{array}{ccc} \mathbb{1} & \xrightarrow{d} & F \\ \text{id}_c \downarrow & \text{arrow-ind} \nearrow & \downarrow (F_f)_{f: {}^c/C} \\ {}^c/C & \xlongequal{\quad} & {}^c/C \end{array}$$

The semantic justification for Proposition 6.6 is similar to the justification for Proposition 3.3. The functor  $\text{id}_c : \mathbb{1} \rightarrow {}^c/C$  is *initial*, which in this instance just means that  $\text{id}_c : {}^c/C$  is an initial element. Initial functors  $i : A \rightarrow X$  have a left lifting property against covariant families  $(E_b)_{b:B}$ , which may be internalized to the statement that the induced map on mapping spaces is a trivial fibration

$$\begin{array}{ccc} A & \xrightarrow{e} & E \\ i \downarrow & \nearrow & \downarrow \rho = (E_b)_{b:B} \\ X & \xrightarrow{b} & B \end{array} \quad \rightsquigarrow \quad \begin{array}{ccc} & & \text{Map}(X, E) \\ & & \downarrow \rho \circ - \circ \text{refl} \\ & & \text{Map}(A, E) \times_{\text{Map}(A, B)} \text{Map}(X, B) \end{array}$$

When expressed internally to the language of synthetic categories, arrow-induction provides a section to the map

$$\begin{array}{ccc} \text{Map}_{{}^c/C}({}^c/C, F) & \xrightarrow{\quad} & \text{Map}({}^c/C, F) \\ \text{arrow-ind} \nearrow \downarrow -\text{oid}_a & \lrcorner & \downarrow \rho \circ -\text{oid}_c \\ \mathbb{1} \xrightarrow{d} F & & \text{Map}(\mathbb{1}, F_{\text{id}_c}) \xrightarrow{\quad} \text{Map}(\mathbb{1}, F) \times_{\text{Map}(\mathbb{1}, {}^c/C)} \text{Map}({}^c/C, {}^c/C) \\ \text{id}_c \downarrow \text{arrow-ind} \downarrow \rho = (F_f)_{f: {}^c/C} & & \downarrow \pi \\ {}^c/C \xlongequal{\quad} {}^c/C & & \Delta^0 \xrightarrow{\text{id}} \text{Map}({}^c/C, {}^c/C) \end{array}$$

<sup>7</sup>The original published proof of this result [67, 8.13] had an error of circular reasoning that was uncovered in the process of formalizing the proof in Rzk [51].

Note that  $\text{Map}(\Delta^0, F_{\text{id}_c}) \cong F_{\text{id}_c}$  so top left-hand map in the right-hand diagram encodes the desired equivalence between sections of the family  $(F_f)_{f:c/C}$  and the fiber  $F_{\text{id}_c}$ .

**6.2 The Yoneda Lemma.** In [67], Proposition 6.6 is referred to as the *dependent Yoneda lemma*. We now see how the more familiar Yoneda lemma can be derived as a corollary. Consider a category  $C$ , two fixed elements  $a, b : C$ , and the respective covariant families  $(\text{Hom}(a, x))_{x:C}$  and  $(\text{Hom}(b, x))_{x:C}$ . By Lemma 6.4, the simplicial space  $\Pi_{x:C} \text{Hom}(a, x) \rightarrow \text{Hom}(b, x)$  defines the simplicial space of natural transformations from the first family to the second. There is a map from the space of natural transformations  $\Pi_{x:C} \text{Hom}(a, x) \rightarrow \text{Hom}(b, x)$  to  $\text{Hom}(b, a)$  that sends  $\phi$  to  $\phi_a(\text{id}_a)$  which we refer to as  $\text{ev}_{\text{id}}$ .

PROPOSITION 6.7 (Yoneda lemma). *For elements  $a, b : C$ , the map*

$$\text{ev}_{\text{id}} : (\prod_{x:C} \text{Hom}(a, x) \rightarrow \text{Hom}(b, x)) \rightarrow \text{Hom}(b, a)$$

is an equivalence.

If both the statement and the proof are fully expressed in the internal language for synthetic categories, it is arguably both simpler to state and prove than the Yoneda lemma for strict 1-categories [65]. When fully unraveled in our semantic setting, the argument is as follows:

*Proof.* We may form the same diagram as before:

$$\begin{array}{ccc}
\begin{array}{c} \mathbb{1} \xrightarrow{\quad d \quad} P \longrightarrow b/C \\ \text{id}_a \downarrow \wr \quad \swarrow \text{arrow-ind} \quad \downarrow \chi \lrcorner \\ a/C \rightrightarrows_{(\text{Hom}_C(a,x))_{x \in C}} a/C \longrightarrow_{(\text{Hom}_C(b,x))_{x \in C}} C \end{array} & \longleftrightarrow & \begin{array}{ccc} \text{Map}_{a/C}(^{a/C}P) & \longrightarrow & \text{Map}(^{a/C}P) \\ \text{arrow-ind} \left( \begin{array}{c} \uparrow \wr \\ \downarrow \end{array} \right) - \text{oid}_a \lrcorner & & \left( \begin{array}{c} \uparrow \wr \\ \downarrow \end{array} \right) \chi \circ - \text{oid}_a \\ \text{Map}(\mathbb{1}, P_{\text{id}_a}) & \longrightarrow & \text{Map}(\mathbb{1}, P) \times_{\text{Map}(\mathbb{1}, ^{a/C})} \text{Map}(^{a/C}, ^{a/C}) \\ \downarrow \wr & \lrcorner & \downarrow \pi \\ \mathbb{1} & \xrightarrow{\quad \text{id} \quad} & \text{Map}(^{a/C}, ^{a/C}) \end{array}
\end{array}$$

Note that by the universal property of the pullback  $\text{Map}_{a/C}(a/C, P) \cong \text{Map}_C(a/C, {}^b/C)$  and  $P_{\text{id}_a} \cong \text{Hom}(b, a)$ , so top left-hand map in the right-hand diagram encodes the desired equivalence:

$$\mathrm{Map}_C(a/C, b/C) \xrightarrow[\sim]{\mathrm{ev}_{id_a}} \mathrm{Hom}(b, a)$$

$\nwarrow$  arrow-ind

The same proofs works with an arbitrary covariant family  $(F_x)_{x:C}$  in place of the family  $(\mathrm{Hom}(b, x))_{x:C}$ , establishing an equivalence:

$$(\Pi_{x:C} \text{Hom}(a, x) \rightarrow F_x) \xrightarrow[\sim]{\text{ev}_{\text{id}}} F_a.$$

**7 Directed univalent universes.** The language for synthetic categories is an efficient formal system to state and prove theorems about them. But in the original form presented in [67], it does not provide any techniques for building examples of synthetic categories. As we saw in §4.3, interesting examples of synthetic spaces can be built from the universal family of spaces. In this section, we will sketch the construction of an analogous universal covariant family of simplicial spaces. After establishing a *directed* analog of Voevodsky’s univalence principle, we can show that the base of the universal covariant family is a category. By Lemma 6.2, its fibers are groupoids, aka “spaces” in the terminology introduced in the introduction. So this constructs the category of spaces internally to the theory, which can be used to construct other interesting examples.

In §7.1, we adapt the approach of [72] to construct a directed univalent universe of simplicial spaces—or more generally, in a strict 1-categorical presentation of the category of simplicial objects in any  $\infty$ -topos—previewing results from forthcoming joint work with Cavallo and Sattler [20]. There are various other approaches to constructing a directed univalent universe of categories [60, 54, 79, 24, 83, 26, 37] though it is not clear whether any of these could be adapted to the level of generality of internal  $\infty$ -categories. For applications beyond the construction of the category of spaces see particularly [26, 25, 37].

**7.1 Constructing directed univalent universes.** As discussed in §4.2, our objective is to define a universal covariant family of simplicial spaces so that  $\Gamma$ -indexed generalized elements define covariant families of small simplicial spaces in context  $\Gamma$ . We work in the strict 1-category of simplicial objects in a type theoretic model topos, for which the 1-category  $\mathbf{sSet}^{\Delta^{\text{op}}}$  introduced in §5 is the basic example; thus, we continue to refer to generic (fibrant) objects as simplicial spaces. In that setting, our covariant families are more commonly called *left fibrations*, these being maps  $\rho: E \rightarrowtail B$  that define fibrations in the ambient model structure with the property that the induced map

$$E^{\Delta^1} \xrightarrow[\sim]{(\rho^{\Delta^1}, \text{ev}_0)} B^{\Delta^1} \times_B E$$

is a trivial fibration. We show that this family of maps defines a notion of fibred structure that is small groupoid valued and locally representable, and thus admits a universe  $\varrho: \mathcal{S}_* \rightarrow \mathcal{S}$  that is univalent, satisfying the condition of Definition 4.9.

The directed univalence axiom characterizes the arrows  $(\text{Hom}(A, B))_{A, B: \mathcal{S}}$  in  $\mathcal{S}$  in terms of another universal family. There is a family of simplicial spaces  $(A \rightarrow B)_{A, B: \mathcal{S}}$  defined by using the internal hom in the category of simplicial spaces over  $\mathcal{S} \times \mathcal{S}$  [76, 6.2.2]. By construction a generalized element

$$\begin{array}{ccc} (A \rightarrow B) & \longrightarrow & \text{Fun}(\mathcal{S}_\bullet) \\ \downarrow e & \lrcorner & \downarrow (A \rightarrow B)_{A, B: \mathcal{S}} \\ \Gamma & \xrightarrow{(A, B)} & \mathcal{S} \times \mathcal{S} \end{array}$$

encodes a function  $f: A \rightarrow B$ , which we have also denoted by  $f: \Pi_{\gamma: \Gamma} A_\gamma \rightarrow B_\gamma$  between the covariant families over  $\Gamma$  classified by the maps  $A, B: \Gamma \rightarrow \mathcal{S}$ .

**DEFINITION 7.1.** *The fibration  $\varrho: \mathcal{S}_* \rightarrow \mathcal{S}$  is **directed univalent** if the comparison map from the space of arrows to the space of functions defined by arrow induction<sup>8</sup> is an equivalence:*

$$\begin{array}{ccc} \mathcal{S} & \xrightarrow{\text{id}} & \text{Fun}(\mathcal{S}_\bullet) \\ \text{id} \downarrow & \nearrow \text{arr-to-fun} & \downarrow (A \rightarrow B)_{A, B: \mathcal{S}} \\ \mathcal{S}^{\Delta^1} & \xrightarrow[\text{Hom}(A, B)]{} & \mathcal{S} \times \mathcal{S} \end{array} \quad \text{arr-to-fun} := \text{arrow-ind}(\text{id} \mapsto \text{id})$$

See [20] for more details and a proof that the universal covariant family  $\varrho: \mathcal{S}_\bullet \rightarrow \mathcal{S}$  is directed univalent. There we also establish a “higher” version of directed univalence:

- defining an equivalence between the simplicial space  $\mathcal{S}^{\Delta^n}$  of  $n$  composable arrows in  $\mathcal{S}$  and the simplicial space of  $n$  composable functions between covariant families over  $\mathcal{S}$ , and
- showing that transport in the universal covariant family is given by function composition.

**7.2 Applications of directed univalence.** Directed univalence can be used to provide the first example of a synthetic category.

**COROLLARY 7.2.** *The base of the universal covariant family defines a category.*

The higher version of directed univalence is used to verify the conditions Definition 5.4 and Definition 5.7.

*Remark 7.3.* As noted above, by Lemma 6.2, the points in  $\mathcal{S}$  are groupoids, aka spaces, so we refer to the base of the universal covariant family as the *category of spaces*. The total space  $\mathcal{S}_\bullet$  of the universal covariant family is a category as well, namely the category of pointed spaces  $(A, a)$ .

$$\begin{array}{ccc} A & \longrightarrow & \mathcal{S}_\bullet \\ \downarrow a & \lrcorner & \downarrow e \\ \Delta^0 & \xrightarrow{A} & \mathcal{S} \end{array}$$

<sup>8</sup>Here the arrow induction principle of Proposition 6.6 should be interpreted in context  $\mathcal{S}$ , holding the variable  $A: \mathcal{S}$  fixed.



This explains our notation for the universal covariant family.

A useful consequence of univalence, mentioned in §4.3 is the structure identity principle, characterizing path spaces of various classifying spaces built from the universe. Similarly, directed univalence implies a directed analog, which we might call the *structure homomorphism principle*, identifying the arrows in various classifying categories built from the universe as homomorphisms of the appropriate structures [83, 37]. As a first example, the arrows in the category  $\mathcal{S}_\bullet$  of pointed spaces can be identified with pointed functions.

For discussion of the categories of fully coherent monoids, groups, or spectra, see [37, §6].

**8 Vistas.** To conclude we highlight ongoing work involving related ideas.

**8.1 Higher Observational Type Theory.** While homotopy type theory is now almost two decades old, the precise rules of this formal system are still under development. One motivation for further innovation is to restore some of the metatheoretical properties of intentional dependent type theory, which as a foundation for constructive mathematics satisfies canonicity and normalization. In such a system a proof establishing the existence of an integer  $n$  with a certain property — such as famously Brunerie’s proof that  $\pi_4 S^3$  is  $\mathbb{Z}/n\mathbb{Z}$  for some  $n : \mathbb{Z}$  — can be compiled out to calculate the value of  $n$  [16, 53]. This motivated various *cubical* variants of homotopy type theory [13, 28, 4, 19], though there are still some open questions concerning the precise homotopy theoretic semantics of such systems [6, 21].

A related objective is to convert the equivalences characterizing identity types—such as those given by the structure-identity principle—into definitional equalities. Such a system, called *Higher Observational Type Theory*, is currently under development by Altenkirch, Kaposi, and Shulman, extending prior joint work on internal parametricity [3], and has an accompanying experimental proof assistant NARYA.

**8.2 Multimodal Simplicial HoTT.** Theorems about spaces that are not equivalence invariant cannot be correctly stated or proven in homotopy type theory for the reasons discussed in §4.3. Similarly, constructions involving categories that are not functorial or natural cannot be correctly stated or prove in simplicial type theory by Lemma 5.6 and Lemma 6.4. Thus, further axioms or extensions of this formal system are needed to redevelop the full analytic theory synthetically.

Work in progress towards this goal is being pursued by Cisinski, Cnossen, Nguyen, and Walde [25] and Gratzer, Weinberger, and Buchholtz [37, 38]. The latter project extends the simplicial type theory with various *modalities*, which for instance, might distinguish between contexts that are categorical or groupoidal, and limit the use of variables drawn from these contexts in certain circumstances.

**8.3 Synthetic mathematics.** Synthetic mathematics, in the tradition of Euclid, is experiencing a revival, perhaps in relation to recent advances in computer proof assistants, which can help mathematicians who are trained in one formal framework learn to reason in another [73]. A new proposed synthetic approach to algebraic geometry provides axioms for algebraic geometry, developed internal to the Zariski topos as a higher topos, so as to have direct access to the homotopy types of homotopy type theory to reason about cohomology [14, 23]. There are similar new proposed synthetic approaches to condensed mathematics intended to provide internal languages for the 1-topos of light condensed sets or the higher topos of light condensed anima developed in forthcoming work of Barton and Commelin and in [22].

**Acknowledgments.** Part of this text was originally prepared as lecture notes for a talk given at “A panorama of homotopy theory: a conference in honor of Mike Hopkins.” The author is grateful for support from the US National Science Foundation via the grant DMS-2507077 and the US Air Force Office of Scientific Research under award number FA9550-21-1-0009.

## References

- [1] A. A. ABOUNEGM, F. BAKKE, C. B. MARTÍNEZ, J. CAMPBELL, R. CARLIER, T. CHATZIDIAMANTIS-CHRISTOFORIDIS, A. ERGUS, M. HUTZLER, N. KUDASOV, K. MAILLARD, D. M. CARPENA, S. PRADAL, N. RASEKH, E. RIEHL, F. VERITY, T. WALDE, AND J. WEINBERGER, *Simplicial HoTT and synthetic  $\infty$ -categories*, <https://github.com/rzk-lang/rzk>. a formalization library.
- [2] B. AHRENS, P. R. NORTH, M. SHULMAN, AND D. TSEMENTZIS, *A higher structure identity principle*, in Proceedings of the 35th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS 2020), ACM, New York, [2020] ©2020, p. 14, <https://doi.org/10.1145/3373718.3394755>.

- [3] T. ALTENKIRCH, Y. CHAMOUN, A. KAPOSÍ, AND M. SHULMAN, *Internal parametricity, without an interval*, Proc. ACM Program. Lang., 8 (2024), <https://doi.org/10.1145/3632920>.
- [4] C. ANGIULI, G. BRUNERIE, T. COQUAND, R. HARPER, K.-B. HOU, AND D. R. LICATA, *Syntax and models of cartesian cubical type theory*, Mathematical Structures in Computer Science, 31 (2021), pp. 424–468, <https://doi.org/10.1017/S0960129521000347>.
- [5] O. ANTOLÍN CAMARENA, *A whirlwind tour of the world of  $(\infty, 1)$ -categories*, in Mexican mathematicians abroad: recent contributions, vol. 657 of Contemp. Math., Amer. Math. Soc., Providence, RI, 2016, pp. 15–61, <https://doi.org/10.1090/conm/657/13088>.
- [6] S. AWODEY, E. CAVALLO, T. COQUAND, E. RIEHL, AND C. SATTTLER, *The equivariant model structure on cartesian cubical sets*, 2025, <https://arxiv.org/abs/2406.18497>, <https://arxiv.org/abs/2406.18497>.
- [7] S. AWODEY AND M. A. WARREN, *Homotopy theoretic models of identity types*, Math. Proc. Cambridge Philos. Soc., 146 (2009), pp. 45–55, <https://doi.org/10.1017/S0305004108001783>.
- [8] C. BARWICK AND D. M. KAN, *Relative categories: another model for the homotopy theory of homotopy theories*, Indag. Math. (N.S.), 23 (2012), pp. 42–68, <https://doi.org/10.1016/j.indag.2011.10.002>.
- [9] J. E. BERGNER, *A model category structure on the category of simplicial categories*, Trans. Amer. Math. Soc., 359 (2007), pp. 2043–2058, <https://doi.org/10.1090/S0002-9947-06-03987-0>.
- [10] J. E. BERGNER, *Three models for the homotopy theory of homotopy theories*, Topology, 46 (2007), pp. 397–436, <https://doi.org/10.1016/j.top.2007.03.002>.
- [11] J. E. BERGNER, *The homotopy theory of  $(\infty, 1)$ -categories*, vol. 90 of London Mathematical Society Student Texts, Cambridge University Press, Cambridge, 2018.
- [12] M. BEZEM, U. BUCHHOLTZ, P. CAGNE, B. I. DUNDAS, AND D. R. GRAYSON, *Symmetry*. <https://github.com/UniMath/SymmetryBook>.
- [13] M. BEZEM, T. COQUAND, AND S. HUBER, *A Model of Type Theory in Cubical Sets*, in 19th International Conference on Types for Proofs and Programs (TYPES 2013), R. Matthes and A. Schubert, eds., vol. 26 of Leibniz International Proceedings in Informatics (LIPIcs), Dagstuhl, Germany, 2014, Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, pp. 107–128, <https://doi.org/10.4230/LIPIcs.TYPES.2013.107>.
- [14] I. BLECHSCHMIDT, *Using the internal language of toposes in algebraic geometry*, PhD thesis, Universität Augsburg, 2017.
- [15] J. M. BOARDMAN AND R. M. VOGT, *Homotopy invariant algebraic structures on topological spaces*, vol. 347 of Lecture Notes in Mathematics, Springer, 1973, <https://doi.org/10.1007/BFb0068547>.
- [16] G. BRUNERIE, *The James construction and  $\pi_4(\mathbb{S}^3)$  in homotopy type theory*, J. Automat. Reason., 63 (2019), pp. 255–284, <https://doi.org/10.1007/s10817-018-9468-2>.
- [17] U. BUCHHOLTZ, F. VAN DOORN, AND E. RIJKE, *Higher groups in homotopy type theory*, in Proceedings of the 33rd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS '18, New York, NY, USA, 2018, Association for Computing Machinery, p. 205–214, <https://doi.org/10.1145/3209108.3209150>.
- [18] U. BUCHHOLTZ AND J. WEINBERGER, *Synthetic fibered  $(\infty, 1)$ -category theory*, High. Struct., 7 (2023), pp. 74–165.
- [19] E. CAVALLO, A. MÖRTBERG, AND A. W. SWAN, *Unifying Cubical Models of Univalent Type Theory*, in 28th EACSL Annual Conference on Computer Science Logic (CSL 2020), M. Fernández and A. Muscholl, eds., vol. 152 of Leibniz International Proceedings in Informatics (LIPIcs), Dagstuhl, Germany, 2020, Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, pp. 14:1–14:17, <https://doi.org/10.4230/LIPIcs.CSL.2020.14>.
- [20] E. CAVALLO, E. RIEHL, AND C. SATTTLER, *Directed univalence for simplicial objects in an  $\infty$ -topos*. in preparation, 2025.

- [21] E. CAVALLO AND C. SATTler, *Relative elegance and cartesian cubes with one connection*, Canadian Journal of Mathematics, (2025), p. 1–64, <https://doi.org/10.4153/S0008414X25101466>.
- [22] F. CHERUBINI, T. COQUAND, F. GEERLIGS, AND H. MOENECLAËY, *A Foundation for Synthetic Stone Duality*, in 30th International Conference on Types for Proofs and Programs (TYPES 2024), R. E. Møgelberg and B. van den Berg, eds., vol. 336 of Leibniz International Proceedings in Informatics (LIPIcs), Dagstuhl, Germany, 2025, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, pp. 3:1–3:20, <https://doi.org/10.4230/LIPIcs.TYPES.2024.3>.
- [23] F. CHERUBINI, T. COQUAND, AND M. HUTZLER, *A foundation for synthetic algebraic geometry*, Mathematical Structures in Computer Science, 34 (2024), p. 1008–1053, <https://doi.org/10.1017/S0960129524000239>.
- [24] D.-C. CISINSKI, *Higher categories and homotopical algebra*, vol. 180 of Cambridge Studies in Advanced Mathematics, Cambridge University Press, Cambridge, 2019, <https://doi.org/10.1017/9781108588737>.
- [25] D.-C. CISINSKI, B. CNOSSEN, K. NGUYEN, AND T. WALDE, *Formalization of higher categories*. Book in progress, <https://drive.google.com/file/d/1lKaq7watGGl3xvjqw9qHjm6SDPFJ2-0o>.
- [26] D.-C. CISINSKI AND H. K. NGUYEN, *The universal cocartesian fibration*, 2022, <https://arxiv.org/abs/2210.08945>.
- [27] D. CLAUSEN AND P. SCHOLZE, *Lectures on analytic geometry*. lecture notes for course WS 19/20, 2020, <https://people.mpim-bonn.mpg.de/scholze/Analytic.pdf>.
- [28] C. COHEN, T. COQUAND, S. HUBER, AND A. MÖRTBERG, *Cubical Type Theory: A Constructive Interpretation of the Univalence Axiom*, in 21st International Conference on Types for Proofs and Programs (TYPES 2015), T. Uustalu, ed., vol. 69 of Leibniz International Proceedings in Informatics (LIPIcs), Dagstuhl, Germany, 2018, Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, pp. 5:1–5:34, <https://doi.org/10.4230/LIPIcs.TYPES.2015.5>, <http://drops.dagstuhl.de/opus/volltexte/2018/8475>.
- [29] T. COQUAND AND N. A. DANIELSSON, *Isomorphism is equality*, Indagationes Mathematicae, 24 (2013), pp. 1105–1120, <https://doi.org/https://doi.org/10.1016/j.indag.2013.09.002>. In memory of N.G. (Dick) de Bruijn (1918–2012).
- [30] W. G. DWYER, P. S. HIRSCHHORN, D. M. KAN, AND J. H. SMITH, *Homotopy limit functors on model categories and homotopical categories*, vol. 113 of Mathematical Surveys and Monographs, American Mathematical Society, Providence, RI, 2004, <https://doi.org/10.1090/surv/113>.
- [31] W. G. DWYER AND D. M. KAN, *Simplicial localizations of categories*, J. Pure Appl. Algebra, 17 (1980), pp. 267–284, [https://doi.org/10.1016/0022-4049\(80\)90049-3](https://doi.org/10.1016/0022-4049(80)90049-3).
- [32] S. EILENBERG AND J. A. ZILBER, *Semi-simplicial complexes and singular homology*, Ann. of Math. (2), 51 (1950), pp. 499–513, <https://doi.org/10.2307/1969364>.
- [33] P. FREYD, *Properties invariant within equivalence types of categories*, in Algebra, topology, and category theory (a collection of papers in honor of Samuel Eilenberg), Academic Press, New York-London, 1976, pp. 55–61.
- [34] P. GABRIEL AND M. ZISMAN, *Calculus of fractions and homotopy theory*, vol. Band 35 of Ergebnisse der Mathematik und ihrer Grenzgebiete [Results in Mathematics and Related Areas], Springer-Verlag New York, Inc., New York, 1967.
- [35] N. GAMBINO AND R. GARNER, *The identity type weak factorisation system*, Theoret. Comput. Sci., 409 (2008), pp. 94–109, <https://doi.org/10.1016/j.tcs.2008.08.030>.
- [36] N. GAMBINO AND C. SATTler, *The Frobenius condition, right properness, and uniform fibrations*, J. Pure Appl. Algebra, 221 (2017), pp. 3027–3068, <https://doi.org/10.1016/j.jpaa.2017.02.013>.

- [37] D. GRATZER, J. WEINBERGER, AND U. BUCHHOLTZ, *Directed univalence in simplicial homotopy type theory*, 2024, <https://arxiv.org/abs/2407.09146>.
- [38] D. GRATZER, J. WEINBERGER, AND U. BUCHHOLTZ, *The yoneda embedding in simplicial type theory*, 2025, <https://arxiv.org/abs/2501.13229>, <https://arxiv.org/abs/2501.13229>.
- [39] M. GROTH, *A short course on  $\infty$ -categories*, 2015, <https://arxiv.org/abs/1007.2925>.
- [40] A. GROTHENDIECK, *Sur quelques points d’algèbre homologique*, Tohoku Math. J. (2), 9 (1957), pp. 119–221, <https://doi.org/10.2748/tmj/1178244839>.
- [41] A. GROTHENDIECK, *Pursuing stacks (à la poursuite des champs). Vol. I*, vol. 20 of Documents Mathématiques (Paris) [Mathematical Documents (Paris)], Société Mathématique de France, Paris, [2022] ©2022.
- [42] V. HINICH, *Lectures on infinity categories*, 2018, <https://arxiv.org/abs/1709.06271>.
- [43] A. HIRSCHOWITZ AND C. SIMPSON, *Descente pour les  $n$ -champs (descent for  $n$ -stacks)*, 2001, <https://arxiv.org/abs/math/9807049>.
- [44] A. JOYAL, *Quasi-categories and Kan complexes*, vol. 175, 2002, pp. 207–222, [https://doi.org/10.1016/S0022-4049\(02\)00135-4](https://doi.org/10.1016/S0022-4049(02)00135-4). Special volume celebrating the 70th birthday of Professor Max Kelly.
- [45] A. JOYAL, *Notes on quasi-categories*. 2008, <https://www.math.uchicago.edu/~may/IMA/Joyal.pdf>.
- [46] A. JOYAL, *The theory of quasi-categories and its applications*. preprint, 2008, <https://mat.uab.cat/~kock/crm/hocat/advanced-course/Quadern45-2.pdf>.
- [47] A. JOYAL AND M. TIERNEY, *Quasi-categories vs Segal spaces*, in Categories in algebra, geometry and mathematical physics, vol. 431 of Contemp. Math., Amer. Math. Soc., Providence, RI, 2007, pp. 277–326, <https://doi.org/10.1090/conm/431/08278>.
- [48] D. M. KAN, *On  $c. s. s.$  complexes*, Amer. J. Math., 79 (1957), pp. 449–476, <https://doi.org/10.2307/2372558>.
- [49] K. KAPULKIN AND P. L. LUMSDAINE, *The simplicial model of univalent foundations (after Voevodsky)*, J. Eur. Math. Soc. (JEMS), 23 (2021), pp. 2071–2126, <https://doi.org/10.4171/JEMS/1050>.
- [50] N. KUDASOV, *RZK*, <https://github.com/rzk-lang/rzk>. An experimental proof assistant based on a type theory for synthetic  $\infty$ -categories.
- [51] N. KUDASOV, E. RIEHL, AND J. WEINBERGER, *Formalizing the  $\infty$ -categorical yoneda lemma*, in Proceedings of the 13th ACM SIGPLAN International Conference on Certified Programs and Proofs, CPP 2024, New York, NY, USA, 2024, Association for Computing Machinery, p. 274–290, <https://doi.org/10.1145/3636501.3636945>.
- [52] M. LAND, *Introduction to infinity-categories*, Compact Textbooks in Mathematics, Birkhäuser/Springer, Cham, [2021] ©2021, <https://doi.org/10.1007/978-3-030-61524-6>, <https://doi.org/10.1007/978-3-030-61524-6>.
- [53] A. LJUNGSTRÖM AND A. MÖRTBERG, *Formalizing  $\pi_4(\mathbb{S}^3) \cong \mathbb{Z}/2\mathbb{Z}$  and computing a Brunerie number in cubical Agda*, in 2023 38th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS), IEEE Comput. Soc. Press, Los Alamitos, CA, [2023] ©2023, p. 13.
- [54] J. LURIE, *Higher topos theory*, vol. 170 of Annals of Mathematics Studies, Princeton University Press, Princeton, NJ, 2009, <https://doi.org/10.1515/9781400830558>.
- [55] J. LURIE, *Kerodon*. <https://kerodon.net>, 2018.
- [56] S. MAC LANE AND I. MOERDIJK, *Sheaves in geometry and logic*, Universitext, Springer-Verlag, New York, 1994. A first introduction to topos theory, Corrected reprint of the 1992 edition.

- [57] M. MAKKAI, *First order logic with dependent sorts, with applications to category theory*, [www.math.mcgill.ca/makkai/](http://www.math.mcgill.ca/makkai/), 1995.
- [58] L. MARTINI, *Yoneda’s lemma for internal higher categories*, 2022, <https://arxiv.org/abs/2103.17141>.
- [59] L. MARTINI AND S. WOLF, *Colimits and cocompletions in internal higher category theory*, *High. Struct.*, 8 (2024), pp. 97–192.
- [60] J. P. NICHOLS-BARRER, *On Quasi-Categories as a Foundation for Higher Algebraic Stacks*, PhD thesis, Massachusetts Institute of Technology, 2007, <https://arxiv.org/abs/1721.1/39088>.
- [61] R. PELLISSIER, *Weak enriched categories - Categories enrichies faibles*, PhD thesis, 2003, <https://arxiv.org/abs/math/0308246>.
- [62] D. G. QUILLEN, *Homotopical algebra*, vol. No. 43 of Lecture Notes in Mathematics, Springer-Verlag, Berlin-New York, 1967.
- [63] C. REZK, *A model for the homotopy theory of homotopy theory*, *Trans. Amer. Math. Soc.*, 353 (2001), pp. 973–1007, <https://doi.org/10.1090/S0002-9947-00-02653-2>.
- [64] C. REZK, *Toposes and homotopy toposes*. notes based on lectures at UIUC in Fall 2005, 2005, <https://rezk.web.illinois.edu/homotopy-topos-sketch.pdf>.
- [65] E. RIEHL, *Could  $\infty$ -category theory be taught to undergraduates?*, *Notices Amer. Math. Soc.*, 70 (2023), pp. 727–736, <https://www.ams.org/journals/notices/202305/noti2692/noti2692.html>.
- [66] E. RIEHL, *On the  $\infty$ -topos semantics of homotopy type theory*, *Bull. Lond. Math. Soc.*, 56 (2024), pp. 461–517, <https://doi.org/10.1112/blms.12997>.
- [67] E. RIEHL AND M. SHULMAN, *A type theory for synthetic  $\infty$ -categories*, *High. Struct.*, 1 (2017), pp. 147–224, <https://doi.org/10.1007/s42001-017-0005-6>.
- [68] E. RIEHL AND D. VERITY, *Fibrations and Yoneda’s lemma in an  $\infty$ -cosmos*, *J. Pure Appl. Algebra*, 221 (2017), pp. 499–564, <https://doi.org/10.1016/j.jpaa.2016.07.003>.
- [69] E. RIJKE, *Introduction to Homotopy Type Theory*, Cambridge Studies in Advanced Mathematics, Cambridge University Press, 2025, <https://arxiv.org/abs/2212.11082>.
- [70] M. SHULMAN, *The univalence axiom for elegant Reedy presheaves*, *Homology Homotopy Appl.*, 17 (2015), pp. 81–106, <https://doi.org/10.4310/HHA.2015.v17.n2.a6>.
- [71] M. SHULMAN, *Homotopy type theory: a synthetic approach to higher equalities*, in *Categories for the working philosopher*, Oxford Univ. Press, Oxford, 2017, pp. 36–57.
- [72] M. SHULMAN, *All  $(\infty, 1)$ -toposes have strict univalent universes*, 2019, <https://arxiv.org/abs/1904.07004>.
- [73] M. SHULMAN, *Strange new universes: proof assistants and synthetic foundations*, *Bull. Amer. Math. Soc. (N.S.)*, 61 (2024), pp. 257–270, <https://doi.org/10.1090/bull/1830>, <https://doi.org/10.1090/bull/1830>.
- [74] C. SIMPSON, *Homotopy theory of higher categories*, vol. 19 of New Mathematical Monographs, Cambridge University Press, Cambridge, 2012.
- [75] N. E. STEENROD, *A convenient category of topological spaces*, *Michigan Math. J.*, 14 (1967), pp. 133–152, <http://projecteuclid.org/euclid.mmj/1028999711>.
- [76] R. STENZEL, *On univalence, Rezk completeness, and presentable quasi-categories*, PhD thesis, University of Leeds, 2019.
- [77] R. STREET, *Fibrations in bicategories*, *Cahiers Topologie Géom. Différentielle*, 21 (1980), pp. 111–160.

- [78] T. UNIVALENT FOUNDATIONS PROGRAM, *Homotopy Type Theory: Univalent Foundations of Mathematics*, <https://homotopytypetheory.org/book>, Institute for Advanced Study, 2013.
- [79] Y. VARSHAVSKIĬ I AND D. KAZHDAN, *The Yoneda lemma for complete Segal spaces*, Funktsional. Anal. i Prilozhen., 48 (2014), pp. 3–38, <https://doi.org/10.1007/s10688-014-0050-3>.
- [80] K. E. ČESNAVIČIUS AND P. SCHOLZE, *Purity for flat cohomology*, Ann. of Math. (2), 199 (2024), pp. 51–180, <https://doi.org/10.4007/annals.2024.199.1.2>.
- [81] J.-L. VERDIER, *Des catégories dérivées des catégories abéliennes*, Astérisque, (1996), pp. xii+253. With a preface by Luc Illusie, Edited and with a note by Georges Maltsiniotis.
- [82] D. R. B. VERITY, *Weak complicit sets. I. Basic homotopy theory*, Adv. Math., 219 (2008), pp. 1081–1149, <https://doi.org/10.1016/j.aim.2008.06.003>.
- [83] M. Z. WEAVER AND D. R. LICATA, *A constructive model of directed univalence in bicubical sets*, in Proceedings of the 35th Annual ACM/IEEE Symposium on Logic in Computer Science, LICS '20, New York, NY, USA, 2020, Association for Computing Machinery, p. 915–928, <https://doi.org/10.1145/3373718.3394794>.
- [84] J. WEINBERGER, *Strict stability of extension types*, 2022, <https://arxiv.org/abs/2203.07194>, <https://arxiv.org/abs/2203.07194>.
- [85] J. WEINBERGER, *Two-sided cartesian fibrations of synthetic  $(\infty, 1)$ -categories*, J. Homotopy Relat. Struct., 19 (2024), pp. 297–378, <https://doi.org/10.1007/s40062-024-00348-3>.