

ON THE ∞ -TOPOS SEMANTICS OF HOMOTOPY TYPE THEORY

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ABSTRACT. Many introductions to *homotopy type theory* and the *univalence axiom* neglect to explain what any of it means, glossing over the semantics of this new formal system in traditional set-based foundations. This series of talks will attempt to survey the state of the art, first presenting Voevodsky’s simplicial model of univalent foundations and then touring Shulman’s vast generalization, which provides an interpretation of homotopy type theory with strict univalent universes in any ∞ -topos. As we will explain, this achievement was the product of a community effort to abstract and streamline the original arguments as well as develop new lines of reasoning.

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Lecture I

1. INTRODUCTION

1.1. Why simplicial sets might model homotopy type theory. For any Kan complex A , there is a natural **path space factorization** of the diagonal map defined by exponentiation with the simplicial interval

$$\Delta^0 + \Delta^0 \xrightarrow{\sim} \Delta^1 \xrightarrow{\sim} \Delta^0 \quad \rightsquigarrow \quad A \xrightarrow{\sim} A^{\Delta^1} \twoheadrightarrow A \times A$$

In particular, the left map, 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 arbitrary Kan fibration:

$$\begin{array}{ccc} A & \xrightarrow{e} & E \\ r \downarrow \wr & \nearrow & \downarrow p \\ A^{\Delta^1} & \xrightarrow{b} & B \end{array} \quad \rightsquigarrow \quad \begin{array}{ccccc} A & \xrightarrow{d} & P & \xrightarrow{\quad} & E \\ r \downarrow \wr & \nearrow J & \downarrow \lrcorner & & \downarrow p \\ A^{\Delta^1} & \xlongequal{\quad} & A^{\Delta^1} & \xrightarrow{b} & B \end{array}$$

In particular, by pulling back along the codomain c it suffices to consider right lifting problems against Kan fibrations over the path space A^{Δ^1} , as displayed in the left-hand square of the rectangle above-right. This is the semantic interpretation of the homotopy type theoretic principle of **path induction**: given a type family $x : A, y : A, p : x =_A y \vdash P(x, y, p)$ and a family of terms $a : A \vdash d(a) : P(a, a, r_a)$ over the constant paths, there exists a section

$$x : A, y : A, p : x =_A y \vdash J_d(x, y, p) : P(x, y, p)$$

such that $a : A \vdash J_d(a, a, r_a) \equiv d(a) : P(a, a, r_a)$.

The homotopy type theoretic principle of path induction is stronger than this, because A might be a dependent type $\Gamma \vdash A$ in an arbitrary context Γ . But we can perform an analogous construction starting from an arbitrary Kan fibration $p : \Gamma.A \rightarrow \Gamma$ between Kan complexes. First form the path space factorizations for both $\Gamma.A$ and Γ

$$(1.1.1) \quad \begin{array}{ccccc} \Gamma.A & \xrightarrow{\sim} & (\Gamma.A)^{\Delta^1} & \twoheadrightarrow & \Gamma.A \times \Gamma.A \\ \wr \downarrow & \nearrow \wr & \downarrow \wr & & \downarrow \wr \\ \Delta^1 \wr_{\Gamma} (\Gamma.A) & \dashrightarrow & (\Gamma.A) \times_{\Gamma} (\Gamma.A) & & \\ \wr \downarrow & \nearrow \wr & \downarrow \wr & & \downarrow \wr \\ \Gamma & \xrightarrow{\sim} & \Gamma^{\Delta^1} & \twoheadrightarrow & \Gamma \times \Gamma \end{array}$$

and then pull back the top factorization so that it lies in the slice over Γ . This constructs a factorization of the relative diagonal, in the slice over Γ , using the cotensor with the simplicial interval in the slice over Γ . Once more the inclusion of constant paths is a trivial fibration so we have a lifting property exactly as above. Moreover, since pullback is a simplicially enriched right adjoint, this construction is stable under pullback along any $f : \Delta \rightarrow \Gamma$ between Kan complexes.

$$\begin{array}{ccccc} \Delta.f^*A & \xrightarrow{\sim} & \Gamma.A & \xrightarrow{\sim} & \Gamma.A \\ \wr \downarrow & \nearrow \wr & \downarrow \wr & & \downarrow \wr \\ \Delta^1 \wr_{\Delta} (\Delta.f^*A) & \dashrightarrow & \Delta^1 \wr_{\Gamma} (\Gamma.A) & & \\ \wr \downarrow & \nearrow \wr & \downarrow \wr & & \downarrow \wr \\ (\Delta.f^*A) \times_{\Delta} (\Delta.f^*A) & \dashrightarrow & (\Gamma.A) \times_{\Gamma} (\Gamma.A) & & \\ \wr \downarrow & \nearrow \wr & \downarrow \wr & & \downarrow \wr \\ \Delta & \xrightarrow{f} & \Gamma & & \end{array}$$

1.2. **Martin-Löf's Dependent Type Theory.** Here we use “homotopy type theory” and “univalent foundations” as synonyms for Martin-Löf's dependent type theory, with intensional identity types, together with Voevodsky's univalence axiom.

This type theory has four basic judgment forms:

$$\Gamma \vdash A \quad \Gamma \vdash a : A \quad \Gamma \vdash A \equiv B \quad \Gamma \vdash a \equiv b : A$$

asserting that A is a **type**, a is a **term** of type A , and that A and B or a and b are **judgmentally equal** types or terms, all in context Γ . Here Γ is shorthand for an arbitrary **context**, given by a sequence of variables of previously-defined types. Some types will be defined in the empty-context

$$\cdot \vdash \mathbb{N}$$

Such types then form contexts of length one $[n : \mathbb{N}]$. A type that is defined in a context of length one

$$n : \mathbb{N} \vdash \mathbb{R}^n$$

can then be used to **extend** the context to a context of length two $[n : \mathbb{N}, v : \mathbb{R}^n]$. Types definable using any subset of the previously-defined variables

$$n : \mathbb{N}, v : \mathbb{R}^n \vdash T_v \mathbb{R}^n$$

may then extend the context further $[n : \mathbb{N}, v : \mathbb{R}^n, \ell : T_v \mathbb{R}^n]$. Fully elaborated, the first two judgments take the form

$$\begin{aligned} x_1 : A_1, x_2 : A_1(x_1), \dots, x_n : A_n(x_1, \dots, x_{n-1}) &\vdash B(x_1, \dots, x_n) \\ x_1 : A_1, x_2 : A_1(x_1), \dots, x_n : A_n(x_1, \dots, x_{n-1}) &\vdash b(x_1, \dots, x_n) : B(x_1, \dots, x_n) \end{aligned}$$

We may think of such judgments as functions that take as input a sequence of typed variables and produce either a type or a term as output.

The **structural rules** of dependent type theory govern the variables and the judgmental equality relations. For instance, the **substitution rule** takes the form

$$\frac{\Gamma \vdash a : A \quad \Gamma, x : A, \Delta \vdash \mathcal{J}}{\Gamma, \Delta[a/x] \vdash \mathcal{J}[a/x]}$$

where \mathcal{J} can be the conclusion of any of the four judgment forms. This says that given any term $a : A$ defined in context Γ and any judgment whose context involves a variable $x : A$, there is a corresponding judgment that no longer involves a variable $x : A$ but instead substitutes the term a for x whenever that variable occurred.

The **variable rule** asserts the existence of projection functions

$$\overline{\Gamma, x : A, \Delta \vdash x : A}$$

that take any variable occurring in a context and providing it as a term of the corresponding type.

This base type theory then inherits a richer structure on account of various additional **logical rules** that can be used to form new types. These are called “logical rules” because the types themselves are used to encode mathematical statements, which are “grammatically correct” but are not necessarily provable or true. Such statements are then proven by constructing a term of the corresponding type.

For instance, given a context $\Gamma, x : A \vdash B(x)$ there is a **dependent pair type** and a **dependent function type** which in this case have the same **formation rules**:

$$\frac{\Gamma, x : A \vdash B(x)}{\Gamma \vdash \Sigma_{x:A} B(x)} \quad \frac{\Gamma, x : A \vdash B(x)}{\Gamma \vdash \Pi_{x:A} B(x)}$$

These types are distinguished by their **introduction rules**, which provide terms:

$$\frac{\Gamma, x : A \vdash B(x)}{\Gamma, a : A, b(a) : B(a) \vdash (a, b(a)) : \Sigma_{x:A} B(x)} \quad \frac{\Gamma, x : A \vdash B(x) \quad \Gamma, a : A \vdash b(a) : B(a)}{\Gamma \vdash \lambda x. b(x) : \Pi_{x:A} B(x)}$$

The **elimination rules** explain how generic terms $z : \Sigma_{x:A} B(x)$ and $f : \Pi_{x:A} B(x)$ can be used, while the **computation rules** describe the composites of the functions encoded by the introduction and elimination rules.

1.3. **Identity types.** Of the various logical rules that animate dependent type theory, Martin-Löf's rules for identity types are of paramount importance.

The **formation rule**

$$\frac{}{\Gamma, x : A, y : A \vdash x =_A y}$$

says that it is meaningful to inquire whether two terms belonging to a common type may be identifiable. The **introduction rule**

$$\frac{}{\Gamma, a : A \vdash \text{refl}_a : a =_A a}$$

guarantees that any term is automatically identifiable with itself, via “reflexivity.”

The **elimination rule** provides a version of Leibniz' indiscernability of identicals:

$$\frac{\Gamma, x : A, y : A, p : x =_A y \vdash P(x, y, p) \quad \Gamma, a : A \vdash d(a) : P(a, a, \text{refl}_a)}{\Gamma, x : A, y : A, p : x =_A y \vdash J_d(x, y, p) : P(x, y, p)}$$

Here P can be thought of as a predicate involving two terms of the same type and an identification between them, though the power of this rule derives from its applicability to arbitrary type families, not only the mere propositions. See [Ho, Ri] for a survey of its myriad consequences.

Finally, the **computation rule**

$$\frac{\Gamma, x : A, y : A, p : x =_A y \vdash P(x, y, p) \quad \Gamma, a : A \vdash d(a) : P(a, a, \text{refl}_a)}{\Gamma, a : A \vdash J_d(a, a, \text{refl}_a) \equiv d(a) : P(a, a, \text{refl}_a)}$$

is analogous to the computation rule for a recursively defined function.

1.4. **Extensionality vs intensionality.** By the structural rules for judgmental equality, if

$$\Gamma, x : A, y : A \vdash x \equiv y : A$$

then

$$\Gamma, x : A, y : A \vdash \text{refl}_x : x =_A y$$

Thus judgmentally equal terms are always identifiable.

The **extensional** form of Martin-Löf's identity types adds a converse implication:

$$\Gamma, x : A, y : A, p : x =_A y \vdash x \equiv y : A$$

while the **intensional** form of Martin-Löf's identity types does not add this implication.

2. A CATEGORICAL SEMANTICS OF DEPENDENT TYPE THEORY

2.1. **The category of contexts.** To interpret syntactic expressions in type theory as data in a category we must first build a category out of type theoretic syntax. A standard way to do this involves Cartmell's **contextual categories**.

Definition 2.1.1. Let \mathbf{T} be a type theory with the standard structural rules: variable, substitution, weakening, and the usual rules concerning judgmental equality of types and terms. Then the **category of contexts** $\mathcal{C}(\mathbf{T})$ is a category in which:

- objects are contexts $[x_1 : A_1, \dots, x_n : A_n]$ of arbitrary finite length up to definitional equality and renaming of free variables;
- maps of $\mathcal{C}(\mathbf{T})$ are **context morphisms** or **substitutions**, considered up to definitional equality and renaming of variables: a map

$$(2.1.2) \quad f = [f_1, \dots, f_m] : [x_1 : A_1, \dots, x_n : A_n] \rightarrow [y_1 : B_1, \dots, y_m : B_m]$$

is an equivalence class of term judgements

$$\begin{array}{c} x_1 : A_1, \dots, x_n : A_n \vdash f_1 : B_1 \\ \vdots \quad \vdots \\ x_1 : A_1, \dots, x_n : A_n \vdash f_m : B_m(f_1, \dots, f_{m-1}) \end{array}$$

- composition is given by substitution and the identity is defined by using variables as terms.
- The category of contexts has the following additional structures:
- $\mathcal{C}(\mathbf{T})$ has a terminal object corresponding to the empty context.
 - The objects are partitioned according to the length of the context

$$\text{ob } \mathcal{C}(\mathbf{T}) = \coprod_{n:\mathbb{N}} \text{ob}_n \mathcal{C}(\mathbf{T})$$

with the empty context being the only object of length 0.

- Each object of positive length has a **display map**

$$[x_1, \dots, x_n] : [x_1 : A_1, \dots, x_{n+1} : A_{n+1}] \rightarrow [x_1 : A_1, \dots, x_n : A_n]$$

namely the canonical projection away from the final type in the context. Writing Γ for the codomain context, we abbreviate this display map as

$$p_{A_{n+1}} : \Gamma.A_{n+1} \rightarrow \Gamma$$

and refer the domain of any display map over Γ as a **context extension** of Γ . We refer to composites

$$\Gamma.A.B \xrightarrow{p_B} \Gamma.A \xrightarrow{p_A} \Gamma \quad \text{or} \quad \Gamma.\Delta \xrightarrow{p} \Gamma$$

of display maps as **dependent projections**.

- For each substitution (2.1.2) and any context extension of its codomain, there is a **canonical pullback** defined by the context

$$[y_1 : B_1, \dots, y_m : B_m, y_{m+1} : A_{n+1}(f_1(\vec{y}), \dots, f_n(\vec{y}))]$$

together with a canonical pullback square

$$\begin{array}{ccc} \Delta.f^*A & \xrightarrow{q(f)} & \Gamma.A \\ p_{f^*A} \downarrow & \lrcorner & \downarrow p_A \\ \Delta & \xrightarrow{f} & \Gamma \end{array}$$

Moreover, these canonical pullbacks are *strictly stable under substitution*. Given any context morphism $g : \Theta \rightarrow \Delta$, $\Theta.g^*f^*A = \Theta.(f \cdot g)^*A$ and $q_f \cdot q_g = q_{f \cdot g}$; similarly $\Gamma.1^*A = \Gamma.A$.

Remark 2.1.3. A term $\Gamma \vdash a : A$ in a type A in context Γ is given by a section to the display map $p_A : \Gamma.A \rightarrow \Gamma$. Thus, the phrase “section” is typically reserved to mean section of a display map.

2.2. Homotopy theoretic models of identity types. The title of this section alludes to a famous paper of [AW] that described the homotopical semantics of identity types, but we instead focus on a result of Gambino and Garner inspired by it, constructing what they call the **identity type weak factorization system** on the category of contexts.

Theorem 2.2.1 ([GG]). *Let \mathbf{T} be a dependent type theory with intensional identity types. Then the category of contexts $\mathcal{C}(\mathbf{T})$ admits a weak factorization system whose left class is comprised of those maps that lift against the display maps.*

In the proof, Gambino and Garner construct the factorization of an arbitrary context morphism, but the main idea is illustrated effectively by the simplest non-trivial case: factoring the identity map on a context $[x : A]$ of length 1 as

$$\begin{array}{ccc} [a : A] & \xRightarrow{\quad} & [a : A] \\ [a, \text{refl}_a] \searrow & & \nearrow [y] \\ & [x : A, y : A, p : x =_A y] & \end{array}$$

The right factor is isomorphic in the category of contexts to a composite of display maps and hence belongs to the right class. To see that the left factor is in the left class, we must show it has the left lifting property with respect to an arbitrary display map $p_E : \Phi.E \rightarrow E$. By pulling back along the codomain of the lifting problem, we may assume that the codomain of this display map is the context $[x : A, y : A, p : x =_A y]$ presenting us with a lifting problem of the form below:

$$\begin{array}{ccc} [a : A] & \xrightarrow{[x, y, p, d(a)]} & [x : A, y : A, p : x =_A y, z : P(x, y, p)] \\ [a, a, \text{refl}_a] \downarrow & \nearrow [x, y, p, J_d(x, y, p)] & \downarrow p_P \\ [x : A, y : A, p : x =_A y] & \xlongequal{\quad} & [x : A, y : A, p : x =_A y] \end{array}$$

By the elimination rule for identity types, we can use the data provided by the lifting problem to define the term

$$x : A, y : A, p : x =_A y \vdash J_d(x, y, p) : P(x, y, p)$$

required to define a section of the display map associated to the type family

$$x : A, y : A, p : x =_A y \vdash P(x, y, p).$$

The top triangle commutes by the computation rule.

Remark 2.2.2. Unusually, this factorization is not *functorial*. Given a commutative rectangle involving the identity functions between three contexts of length one:

$$\begin{array}{ccccc} [a : A] & \xrightarrow{g} & [b : B] & \xrightarrow{f} & [c : C] \\ \parallel & & \parallel & & \parallel \\ [a : A] & \xrightarrow{g} & [b : B] & \xrightarrow{f} & [c : C] \end{array}$$

functoriality would demand that the induced substitutions between identity types commute. But as the maps induced by f , g , and $f \cdot g$ are defined by path induction (i.e., by the elimination rule of identity types) they only commute up to pointwise identification, not up to judgmental equality.

However, as these structures on the category of contexts are defined using the rules of type theory, they are strictly stable under substitution. The central components of the identity type weak factorization system equip the contextual category $\mathcal{C}(\mathbf{T})$ with what is called an “identity-type structure.”

Definition 2.2.3. An **identity type structure** on a contextual category consists of:

- for each object $\Gamma.A$, an object $\Gamma.A.A.\text{Id}_A$ extending the context defined by the canonical pullback:

$$\begin{array}{ccc} \Gamma.A.A & \longrightarrow & \Gamma.A \\ \downarrow & \lrcorner & \downarrow p_A \\ \Gamma.A & \xrightarrow{p_A} & \Gamma \end{array}$$

- for each $\Gamma.A$, a morphism

$$\begin{array}{ccc} & \Gamma.A.A.\text{Id}_A & \\ \text{refl}_A \nearrow & & \downarrow p_{\text{Id}_A} \\ \Gamma.A & \xrightarrow{(1,1)} & \Gamma.A.A \end{array}$$

lifting the relative diagonal; and

- for each $\Gamma.A.A.\text{Id}_A.P$ and solid-arrow commutative diagram

$$\begin{array}{ccc} \Gamma.A & \xrightarrow{d} & \Gamma.A.A.\text{Id}_A.P \\ \text{refl}_A \downarrow & \nearrow J & \downarrow p_P \\ \Gamma.A.A.\text{Id}_A & \xlongequal{\quad} & \Gamma.A.A.\text{Id}_A \end{array}$$

a section J of p_P so that $J \cdot \text{refl}_A = d$

so that all this structure is strictly stable under pullback along any substitution $f: \Delta \rightarrow \Gamma$.

2.3. Initiality. A **contextual functor** is a functor between contextual categories preserving all of the structure on the nose. In particular, if the contextual categories have additional logical structure, such as the identity type structure just defined, or the corresponding structures for Σ - or Π -types, then the contextual functor must preserve this as well, up to equality.

The category of contexts is intended to be the universal contextual category built from a type theory in the sense made precise by the following conjecture:

Conjecture 2.3.1 (initiality conjecture). *Let \mathbf{T} be a type theory given by the standard structural rules together with some collection of the logical rules alluded to above. Then the category of contexts $\mathcal{C}(\mathbf{T})$ is the initial contextual category with the corresponding extra structure.*

Then further models of \mathbf{T} in a category \mathcal{E} can be defined by turning \mathcal{E} into a contextual category with the appropriate logical structure: by initiality, this would induce a unique functor $\mathcal{C}(\mathbf{T}) \rightarrow \mathcal{E}$ providing an interpretation of the syntax of type theory in the category \mathcal{E} .

The difficulties with the initiality conjecture are multi-faceted. On the one hand:

The trouble with syntax is that it is very tricky to handle rigorously. Any full presentation must account for (among other complications) variable binding, capture-free substitution, and the possibility of multiple derivations of a judgment; and so any careful construction of an interpretation must deal with all of these, at the same time as tackling the details of the particular model in question. Contextual categories, by contrast, are a purely algebraic notion, with no such subtleties. [KL, 2075].

Another challenge is that there are many versions of type theory, determined by various collections of rules. Moreover, it's difficult to give a precise definition of what constitutes a type theory that is sufficiently general to cover all of the desired examples. An early version of initiality was proven for a type theory called the *calculus of constructions* by Streicher [Str1]. This has often been cited as evidence that initiality should be true for a much broader class of type theories, but at the time the simplicial “model” of homotopy type theory was being developed, Voevodsky argued that it was unacceptably unrigorous to assume initiality without proof.

While the general conjecture is still open, there have more recent efforts to at least prove initiality for the “Book-HoTT” version of homotopy type theory appearing in [Ho]. This was achieved in a 2020 PhD thesis of Menno de Boer [dB] based on parallel formalization efforts undertaken by Brunerie and de Boer in Agda and Lumsdaine and Mörtberg in Coq.

2.4. Contextual categories from universes. Even assuming initiality, it seems daunting to construct a model of type theory in a category \mathcal{E} , for one must still define a contextual category with suitable structures for all the type forming operations. By analyzing the type-forming operations, one can predict what sort of category might be suitable. For instance, a Π -type structure on a contextual category requires an operation that takes a composable pair of display maps as below-left to a display map as below-right:

$$\Gamma.A.B \xrightarrow{p_B} \Gamma.A \xrightarrow{p_A} \Gamma \quad \rightsquigarrow \quad \Gamma.\Pi_A B \xrightarrow{p_{\Pi_A B}} \Gamma$$

This, together with the fact that contextual categories must admit pullbacks of display maps, suggests that it would be reasonable to restrict to categories \mathcal{E} that are **locally cartesian closed**, meaning that for any $f: \Delta \rightarrow \Gamma$ the composition functor has two right adjoints

$$\begin{array}{ccc} & f_! & \\ \mathcal{E}_{/\Delta} & \begin{array}{c} \xleftarrow{f^*} \quad \xrightarrow{f_*} \\ \downarrow \perp \end{array} & \mathcal{E}_{/\Gamma} \\ & f_* & \end{array}$$

defined by pullback along f and pushforward along f , respectively. Note when \mathcal{E} has a terminal object 1 —as is required to model the empty context—this implies that $\mathcal{E} \cong \mathcal{E}_{/1}$ and indeed any slice $\mathcal{E}_{/\Gamma}$ is cartesian closed and has all finite limits.

Note, however, that the definition of a contextual category, implicitly given in Definition 2.1.1, requires strict stability of the canonical pullback squares. In addition, each logical structure, such as the identity

type structure of Definition 2.2.3, requires the pullbacks to preserve everything on the nose, up to equality of objects. Thus, the more categorically-natural requirement, that pullbacks preserve the various logical structures up to isomorphism, is not enough.

This leads to a massive coherence problem. It's not generally possible to choose strictly functorial pullbacks in a category with pullbacks, though it is possible to replace a category with pullbacks by an equivalent category with strictly functorial pullbacks.¹ But even after this is achieved, there remains the task of ensuring strict stability of all the logical structures.

Voevodsky's approach to the coherence problem makes use of a “universe” in a category, defined as follows:

Definition 2.4.1. A **universe** in a category \mathcal{E} consists of an object U , together with a morphism $\pi: \tilde{U} \rightarrow U$, and, for each map $A: \Gamma \rightarrow U$, a choice of pullback square

$$\begin{array}{ccc} (\Gamma; A) & \xrightarrow{q_A} & \tilde{U} \\ p_A \downarrow & \lrcorner & \downarrow \pi \\ \Gamma & \xrightarrow{A} & U \end{array}$$

Given a sequence of maps $A: \Gamma \rightarrow U$, $B: (\Gamma; A) \rightarrow U$, we write $(\Gamma; A, B)$ for $((\Gamma; A); B)$.

Definition 2.4.2 ([V1]). Given a category \mathcal{E} with a universe U and a terminal object 1 , define a contextual category \mathcal{E}_U as follows:

- The objects of \mathcal{E}_U are finite lists of morphisms as follows:

$$\text{ob}_n \mathcal{E}_U = \{(A_1, \dots, A_n) \in (\text{mor } \mathcal{E})^n \mid A_i: (1; A_1, \dots, A_{i-1}) \rightarrow U, \forall i\}.$$

- The morphisms between a pair of objects are defined by

$$\mathcal{E}_U((B_1, \dots, B_m), (A_1, \dots, A_n)) := \mathcal{E}((1; A_1, \dots, A_n), (1; B_1, \dots, B_m)).$$

- The terminal object is the empty sequence of morphisms.
- For any object (A_1, \dots, A_{n+1}) of positive length, its display map is provided by the universe structure:

$$(2.4.3) \quad \begin{array}{ccc} (1; A_1, \dots, A_{n+1}) & \longrightarrow & \tilde{U} \\ p_{A_{n+1}} \downarrow & \lrcorner & \downarrow \pi \\ (1; A_1, \dots, A_n) & \xrightarrow{A_{n+1}} & U \end{array}$$

- Finally the canonical pullback associated to a morphism $f: (B_1, \dots, B_m) \rightarrow (A_1, \dots, A_n)$ and a display map (2.4.3) is defined by factoring the chosen pullback square for the composite $A_{n+1} \cdot f$ through the pullback that defines the context extension (A_1, \dots, A_{n+1}) :

$$\begin{array}{ccccc} (1; B_1, \dots, B_m, f^* A_{n+1}) & \longrightarrow & (1; A_1, \dots, A_n, A_{n+1}) & \longrightarrow & \tilde{U} \\ p_{f^* A_{n+1}} \downarrow & \lrcorner & p_{A_{n+1}} \downarrow & \lrcorner & \downarrow \pi \\ (1; B_1, \dots, B_m) & \xrightarrow{f} & (1; A_1, \dots, A_n) & \xrightarrow{A_{n+1}} & U \end{array}$$

Indeed every small contextual category arises this way:

Proposition 2.4.4 ([V1]). Let \mathcal{C} be a small contextual category. Consider the universe U in the presheaf category $[\mathcal{C}^{\text{op}}, \text{Set}]$ given by

$$U(\Gamma) = \{\Gamma.A\} \quad \tilde{U}(\Gamma) = \{\text{sections } s: \Gamma \rightarrow \Gamma.A\}$$

with the evident projection map and any choice of pullbacks. Then $[\mathcal{C}^{\text{op}}, \text{Set}]_U$ is isomorphic, as a contextual category, to \mathcal{C} .

¹This can be achieved by applying the general techniques for replacing a fibration by a split fibration to the codomain-projection fibration $\text{cod}: \mathcal{E}^2 \rightarrow \mathcal{E}$; see mathoverflow.net/questions/144619/can-we-always-make-a-strictly-functorial-choice-of-pullbacks-re-indexing for a discussion.

When the original category \mathcal{E} is locally cartesian closed, it is possible to specify additional structure on the universe U that would equip the contextual category \mathcal{E}_U with the corresponding logical structure. The idea is that this introduces the desired structure in the universal case. To describe an identity structure on a universe, we require the following notion.

Digression 2.4.5. Recall that for maps $i: A \rightarrow B$ and $f: X \rightarrow Y$ in \mathcal{E} , a **lifting operation** witnessing a lifting property as below-left is a section to the map below-right:

$$\begin{array}{ccc} A & \xrightarrow{x} & X \\ i \downarrow & \nearrow & \downarrow f \\ B & \xrightarrow{y} & Y \end{array} \quad \mathcal{E}(B, X) \xrightarrow{(i^*, f_*)} \mathcal{E}(A, X) \times_{\mathcal{E}(A, Y)} \mathcal{E}(B, Y)$$

If \mathcal{E} is cartesian closed, an **internal lifting operation** is a section to the map

$$X^B \xrightarrow{(i^*, f_*)} X^A \times_{Y^A} Y^B$$

In the category of contexts $\mathcal{C}(\mathbf{T})$ associated to a type theory with identity types, the identity type over a type A in context Γ provides a factorization of the diagonal $\delta: A \rightarrow A \times_{\Gamma} A$ in the slice over Γ into a “stable trivial cofibration” followed by a dependent projection, where the phrase “stable trivial cofibration” refers to a map that admits an internal lifting operation against the dependent projects in the slice over Γ . Moreover, these structures are strictly stable under pullback.

We may obtain an analogous structure on the contextual category \mathcal{C}_U built from a universe $\pi: \tilde{U} \rightarrow U$ as follows. Firstly, note that since all display maps are pullbacks of π it suffices to consider orthogonality against π in the slice over U .

Definition 2.4.6. An **identity structure** on a universe $\pi: \tilde{U} \rightarrow U$ consists of a map

$$\text{Id}: \tilde{U} \times_U \tilde{U} \rightarrow U$$

together with a specified lift $r: \tilde{U} \rightarrow \text{Id}^* \tilde{U}$ of the relative diagonal:

$$\begin{array}{ccccc} & & \text{Id}^* \tilde{U} & \xrightarrow{\quad} & \tilde{U} \\ & \nearrow r & \downarrow & \lrcorner & \downarrow \pi \\ \tilde{U} & \xrightarrow{(1,1)} & \tilde{U} \times_U \tilde{U} & \xrightarrow{\text{Id}} & U \end{array}$$

together with an internal lifting operation J for r against $\pi \times U$ in $\mathcal{E}_{/U}$.

Theorem 2.4.7 ([V2]). *An identity structure on a universe U in \mathcal{E} induces an identity type structure on the contextual category \mathcal{E}_U .*

Of course, it remains to construct a suitable universe in our locally cartesian closed category. In part II, we’ll explain how this is done in the category of simplicial sets, leading to the simplicial model of univalent foundations.

Lecture II

3. A UNIVERSAL FIBRATION

Recall that Voevodsky defined a **universe** in a category \mathcal{E} to be a morphism $\pi: \tilde{U} \rightarrow U$ together with a chosen pullback along any $A: \Gamma \rightarrow U$. In the resulting contextual category, such a map encodes an extension of the context Γ by A with the chosen pullback of π defining the corresponding display map.

When \mathcal{E} is the category of simplicial sets, the intuitions developed in §1.1 suggest that we would like the display maps to be Kan fibrations, which we refer to simply as “fibrations” whenever there is no competing notion in sight. Thus, we would like the universe to be a simplicial set U that classifies Kan fibrations. By the Yoneda lemma, this suggests that U_n should be defined to be the set of fibrations over Δ^n , but there are two problems with this naïve construction:

- (i) Size: We must restrict to “small fibrations”—whose base and fibers are κ -small for some regular cardinal κ —and then ensure that we are taking a large set of all such, rather than proper classes.
- (ii) Coherence: The action of the simplicial operators $\alpha: \Delta^m \rightarrow \Delta^n$ by pullback is only functorial up to isomorphism, not on the nose.

We largely sweep the size issues under the rug—referring to a “set of *small* fibrations” without delving too deeply into its construction²—to reserve our attention for the coherence issues, which are quite interesting. This will give us more brain space to focus on the coherence issues, which are quite interesting.

3.1. What do fibrations form? The coherence issues derive from the fact that chosen pullbacks are not typically strictly functorial but rather *pseudofunctorial*. Put more precisely, in a category \mathcal{E} with pullbacks, there is a groupoid-valued pseudofunctor

$$\begin{array}{ccc} \mathcal{E}^{\text{op}} & \xrightarrow{\mathbb{E}} & \mathcal{GPD} \\ B & \longmapsto & (\mathcal{E}/_B)^\cong \\ f \uparrow & & \downarrow f^* \\ A & \longmapsto & (\mathcal{E}/_A)^\cong \end{array}$$

that sends an object B to the groupoid of morphisms with codomain B and acts on arrows by pullback. The pseudofunctor \mathbb{E} is called the **core of self-indexing** of \mathcal{E} , the “self-indexing” being the corresponding pseudofunctor $B \mapsto \mathcal{E}/_B: \mathcal{E}^{\text{op}} \rightarrow \mathcal{CAT}$. When \mathcal{E} has a pullback stable class of fibrations \mathcal{F} , they similarly assemble into a pseudofunctor

$$\begin{array}{ccc} \mathcal{E}^{\text{op}} & \xrightarrow{\mathbb{F}} & \mathcal{GPD} \\ B & \longmapsto & (\mathcal{F}/_B)^\cong \\ f \uparrow & & \downarrow f^* \\ A & \longmapsto & (\mathcal{F}/_A)^\cong \end{array}$$

defined by restricting $(\mathcal{F}/_B)^\cong \subset (\mathcal{E}/_B)^\cong$ to the full subgroupoid of fibrations over B .

By the bicategorical Yoneda lemma, a fibration $p: E \rightarrow B$ defines a pseudonatural transformation

$$\mathcal{E}(-, B) \xrightarrow{p} \mathbb{F}.$$

We might imagine that the *universal fibration* $\pi: \tilde{U} \rightarrow U$ is a representing element, defining a pseudonatural isomorphism $\mathcal{E}(B, U) \cong \mathbb{F}(B)$. But this can’t be, at least not if \mathcal{E} is very interesting:

- Since \mathcal{E} is a 1-category $\mathcal{E}(B, U)$ is a set, while $\mathbb{F}(B) := (\mathcal{F}/_B)^\cong$ is the groupoid of fibrations over B .
- Even ignoring this, we can see that the same fibration might be classified by multiple maps to U and the same map might classify multiple fibrations:

$$\begin{array}{ccccc} E & \xrightarrow{\cong} & E & \longrightarrow & \tilde{U} \\ p \downarrow \lrcorner & & p \downarrow \lrcorner & & \downarrow \pi \\ B & \xrightarrow{\cong} & B & \xrightarrow{\lrcorner p \lrcorner} & U \end{array} \qquad \begin{array}{ccccc} E' & \xrightarrow{\cong} & E & \longrightarrow & \tilde{U} \\ p' \downarrow \lrcorner & & p \downarrow \lrcorner & & \downarrow \pi \\ B & \xrightarrow{=} & B & \xrightarrow{\lrcorner p \lrcorner} & U \end{array}$$

In the definition of a contextual category from a universe, we choose a pullback for each map into U . Thus, we ask the universe to *weakly* classify the small fibrations, demanding that the pseudonatural transformation $\pi: \mathcal{E}(-, U) \rightarrow \mathbb{Fib}$ associated to $\pi: \tilde{U} \rightarrow U$ is surjective. Actually, we ask demand a bit more.

Definition 3.1.1. In a model category \mathcal{E} with all objects cofibrant, a fibration $\pi: \tilde{U} \rightarrow U$ is a **fibration classifier** if the pseudonatural transformation

$$\pi: \mathcal{E}(-, U) \rightarrow \mathbb{F}$$

²The original sources [KL] and [S] provide a precise accounting.

is a trivial fibration, meaning that for all cofibrations $i: A \rightarrowtail B$ in \mathcal{E} any strictly commutative square of pseudonatural transformations admits a lift:

$$\begin{array}{ccc} \mathcal{E}(-, A) & \xrightarrow{ho-} & \mathcal{E}(-, U) \\ i \circ - \downarrow & \nearrow k & \downarrow \pi \\ \mathcal{E}(-, B) & \xrightarrow{p} & \mathbb{F} \end{array}$$

The condition amounts to the following property:³ given any pair of pullback squares between fibrations as below

$$(3.1.2) \quad \begin{array}{ccccc} D & & & & \tilde{U} \\ & \lrcorner & & \nearrow & \\ & & E & & \\ q \downarrow & & p \downarrow & & \downarrow \pi \\ A & \xrightarrow{\quad} & U & & \\ & \lrcorner & & \nearrow & \\ & & B & & \\ & i \searrow & & \nearrow k & \end{array}$$

there exists an extension k of h along i factoring the back pullback square as a composite of pullbacks. This has been referred to as **strong gluing** by Angiuli and Sterling [AS], the **stratification property** by [Ste, 2.3.3], and **acyclicity** by Shulman [S1, S]. As our terminology suggests, a fibration weakly classifies fibrations, at least when all objects are cofibrant. Taking $A = \emptyset$, (3.1.2) implies that any $p: E \rightarrow B$ is classified by a pullback square into $\pi: \tilde{U} \rightarrow U$.

We'll explain the further relevance of this property below but first note that we've entirely sidestepped the question of how a fibration classifier might be constructed. It is to that subject that we now turn.

3.2. Hofmann-Streicher universes. There is a general method, due to Hofmann and Streicher [HS1], that defines a weak classifier for small maps in any presheaf category. Rather than introduce general notation for presheaf categories, we work in the category $\mathcal{E} = \hat{\Delta}$ of simplicial sets.

Let κ be an infinite regular cardinal,⁴ and write $\text{Set}_\kappa \subset \text{Set}$ for a full subcategory containing at least one set of each cardinality $\lambda < \kappa$. Write $\text{sSet}^\kappa \subset \text{sSet}$ for the category of κ -small simplicial sets. By regularity, a map $f: A \rightarrow B$ of simplicial sets lies in sSet^κ just when its base and fibers are κ -small.

The goal is to define $\pi: \tilde{V} \rightarrow V \in \mathcal{E}$ so that any small map $p: E \rightarrow B$ arises as a pullback of π along some classifying map $\ulcorner p \urcorner: B \rightarrow V$. As noted above, it's insufficient to define V_n to be the set of κ -small maps over Δ^n because the action of a simplicial operators $\alpha: \Delta^m \rightarrow \Delta^n$, by pullback, is only pseudofunctorial. However, under the equivalence of categories⁵

$$\begin{array}{ccc} \text{sSet}^\kappa_{/\Delta^n} & \simeq & \text{Set}_\kappa^{\Delta_{/[n]}^{\text{op}}} \\ \alpha^* \downarrow & & \downarrow - \circ \alpha_! \\ \text{sSet}^\kappa_{/\Delta^m} & \simeq & \text{Set}_\kappa^{\Delta_{/[m]}^{\text{op}}} \end{array}$$

the pullback action is replaced by precomposition with the composition functor $\alpha_!: \Delta_{/[m]} \rightarrow \Delta_{/[n]}$, which is strictly functorial. Thus

$$V_n := \text{ob}(\text{Set}_\kappa^{\Delta_{/[n]}^{\text{op}}})$$

³Adapting very similar terminology introduced by Stenzel [Ste, 2.3.3.].

⁴As the title of their article suggests, Hofmann and Streicher prefer to work with an inaccessible cardinal [HS1], but for the purposes of obtaining a κ -small map classifier it suffices to use a regular cardinal κ larger than the cardinality of the morphisms in the indexing category.

⁵More generally, the slice category over any presheaf X is equivalent to the category of presheaves on the category of elements of X . In particular, here " $\Delta_{/[n]}^{\text{op}}$ " should be read as an abbreviation for $(\Delta_{/[n]})^{\text{op}}$.

defines a large simplicial set $V \in \mathbf{sSet}$. An element $A: \Delta^n \rightarrow V$ defines a small map $\pi_A: \int A \rightarrow \Delta^n$ whose fiber over $\alpha \in (\Delta^n)_m$ is the set A_m together with specified pullback squares

$$\begin{array}{ccc} \alpha^* \int A & \longrightarrow & \int A \\ \pi_{A \cdot \alpha} \downarrow & \lrcorner & \downarrow \pi_A \\ \Delta^m & \xrightarrow{\alpha} & \Delta^n \end{array}$$

that are strictly functorial in Δ^{op} .

The simplicial set \tilde{V} is defined by

$$\tilde{V}_n := \text{ob}(\text{Set}_{*, \kappa}^{\Delta_{/[n]}^{\text{op}}})$$

where the presheaves now take values in small *pointed* sets. Since the indexing category $\Delta_{/[n]}$ has a terminal object $\text{id}_{[n]}$, an element $(A, a): \Delta^n \rightarrow \tilde{V}$ is equally given by the data of $A: \Delta^n \rightarrow V$ together with a global section $a \in A_{\text{id}_{[n]}}$ or equivalently by a section as below-left.

$$\begin{array}{ccc} \int A & & \int A \xrightarrow{a} \tilde{V} \\ \tilde{a} \downarrow \lrcorner \pi_A & & \downarrow \pi \\ \Delta^n & \xrightarrow{A} & V \end{array}$$

Writing $\pi: \tilde{V} \rightarrow V$ for the evident forgetful functor, we see that any small $A: \Delta^n \rightarrow V$ with fits into a pullback as above-right where the top map is determined by arbitrary choice of global section.

We prove that the evident forgetful functor $\pi: \tilde{V} \rightarrow V$ weakly classifies small maps in $\mathcal{E} = \hat{\Delta}$ with arbitrary codomain by proving that it has the acyclicity property (3.1.2) with respect to monomorphisms $i: A \rightarrowtail B$ and small maps over A and B , as observed in [Ci, 3.9] and [OP, 8.4].

Lemma 3.2.1. *The Hofmann Streicher universe $\pi: \tilde{V} \rightarrow V$ defines a trivial fibration*

$$\begin{array}{ccc} \mathcal{E}(-, A) & \xrightarrow{ho-} & \mathcal{E}(-, V) \\ i o - \downarrow & \nearrow k & \downarrow \pi \\ \mathcal{E}(-, B) & \xrightarrow{p} & \mathbb{E}_{\kappa} \end{array}$$

over the κ -small maps $\mathbb{E}_{\kappa} \subset \mathbb{E}$ in the core of self indexing. That is, given any pair of pullback squares between maps with κ -small fibers as below

$$\begin{array}{ccccc} D & \xrightarrow{\quad} & \tilde{V} & & \\ \downarrow q & \lrcorner \searrow & \downarrow \pi & & \\ & E & & & \\ \downarrow p & \lrcorner \searrow & & & \\ A & \xrightarrow{\quad} & V & & \\ \downarrow i & \nearrow k & \downarrow & & \\ & B & & & \end{array}$$

where $i: A \rightarrowtail B$ is a monomorphism, there exists an extension k of h along i factoring the back pullback square as a composite of pullbacks.

Proof. Since presheaf categories are locally cartesian closed, colimits in \mathcal{E} are *universal*, preserved by pullback along any map such as $\pi^*: \mathcal{E}_V \rightarrow \mathcal{E}_{\tilde{V}}$. Since any simplicial set is expressed canonically as a colimit of

it simplifies, this allows us to reduce to the case

$$\begin{array}{ccc}
 D & \xrightarrow{\quad} & \tilde{V} \\
 \downarrow q & \lrcorner & \downarrow \pi \\
 & E & \\
 \downarrow p & \lrcorner & \downarrow \pi \\
 C & \xrightarrow{\quad} & V \\
 \downarrow i & \lrcorner & \downarrow k \\
 & \Delta^n &
 \end{array}$$

where the monomorphism is given by a subcomplex of a simplex. Since E is a small map over Δ^n , we know that there is a classifying map $k': \Delta_{/[n]}^{\text{op}} \rightarrow \text{Set}_{*,\kappa}$ with the property that for each $\alpha: [m] \rightarrow [n]$ in C , the restriction $k' \circ \alpha: \Delta_{/[m]}^{\text{op}} \rightarrow \text{Set}_{*,\kappa}$ is naturally isomorphic to $h \circ \alpha: \Delta_{/[m]}^{\text{op}} \rightarrow \text{Set}_{*,\kappa}$. Using excluded middle, we define $k: \Delta_{/[n]}^{\text{op}} \rightarrow \text{Set}_{*,\kappa}$ by

$$k(\alpha) = \begin{cases} h \circ \alpha(\text{id}_{[m]}) & \alpha: [m] \rightarrow [n] \in S \\ k'(\alpha) & \alpha: [m] \rightarrow [n] \notin S \end{cases}$$

transporting the functorial action in k' along the isomorphism to k . This defines an extension of the classifying square for q to a classifying square for p , as desired. \square

4. THE SIMPLICIAL MODEL OF UNIVALENT FOUNDATIONS

The technique of Hofmann-Streicher universes can be used to define a universal Kan fibration, which is the key ingredient in the simplicial model of univalent foundations. This is not the approach taken to defining the universe in [KL] but was quickly noted as alternative possible route; see [Ci] or [Str2].

4.1. A fibration classifier. The Hofmann-Streicher universe

$$\tilde{V}_n := \text{ob}(\text{Set}_{*,\kappa}^{\Delta_{/[n]}^{\text{op}}}) \quad V_n := \text{ob}(\text{Set}_{\kappa}^{\Delta_{/[n]}})$$

may be restricted to define the universal Kan fibration by specifying

$$U_n := \left\{ A \in \text{ob}(\text{Set}_{\kappa}^{\Delta_{/[n]}^{\text{op}}}) \mid \int A \Big|_{\pi_A \downarrow \Delta^n} \text{ is a Kan fibration} \right\},$$

and by defining $\pi: \tilde{U} \rightarrow U$ to be the pullback

$$(4.1.1) \quad \begin{array}{ccc} \tilde{U} & \longrightarrow & \tilde{V} \\ \pi \downarrow & \lrcorner & \downarrow \pi \\ U & \longrightarrow & V \end{array}$$

Crucially, the Kan fibrations of simplicial sets are **local**: a map $p: E \rightarrow B$ is a fibration if and only if for all n and all $b: \Delta^n \rightarrow B$, the pullback defines a Kan fibration. This follows from the fact that the fibrations are characterized by a right lifting property against maps with representable codomains:

$$\begin{array}{ccccc}
 \Lambda_k^n & \longrightarrow & \bullet & \longrightarrow & E \\
 \downarrow \wr & \nearrow & \downarrow & \lrcorner & \downarrow p \\
 \Delta^n & \xlongequal{\quad} & \Delta^n & \xrightarrow{b} & B
 \end{array}$$

Consequently:

Corollary 4.1.2. $\pi: \tilde{U} \rightarrow U$ is a Kan fibration.

Proof. By construction, each pullback

$$\begin{array}{ccc} E & \longrightarrow & \tilde{U} \\ p \downarrow & \lrcorner & \downarrow \pi \\ \Delta^n & \xrightarrow{\lrcorner p^\top} & B \end{array}$$

is a Kan fibration. □

Another reflection of this locality is the following:

Lemma 4.1.3. *Let $p: E \rightarrow B$ be a small map and consider any classifying square*

$$\begin{array}{ccc} E & \longrightarrow & \tilde{V} \\ p \downarrow & \lrcorner & \downarrow \pi \\ B & \xrightarrow{\lrcorner p^\top} & V \end{array}$$

Then p is a Kan fibration if and only if the classifying square factors through (4.1.1).

Proof. If p is a pullback of $\pi: \tilde{U} \rightarrow U$ it is clearly a Kan fibration. Conversely, if p is a Kan fibration then so is its restriction along any $b: \Delta^n \rightarrow B$. Recall U is defined as a simplicial subset of V , so $\lrcorner p^\top: B \rightarrow V$ factors through $U \hookrightarrow V$ just when each for each $b: \Delta^n \rightarrow B$ the corresponding map $\lrcorner p^\top \cdot b: \Delta^n \rightarrow V$ so factors. But since a Kan fibration pulls back to Kan fibrations, this means the corresponding elements are in the simplicial subset. □

Put more abstractly, the locality we have shown that there is a pullback square

$$\begin{array}{ccc} \mathcal{E}(-, U) & \hookrightarrow & \mathcal{E}(-, V) \\ \pi \downarrow & \lrcorner & \downarrow \pi \\ \mathbb{F}_\kappa & \hookrightarrow & \mathbb{E}_\kappa \end{array}$$

in the category of groupoid-valued pseudofunctors and pseudonatural transformations between them. Thus the acyclicity condition of Definition 3.1.1 follows from the corresponding result for Hofmann-Streicher universes

Corollary 4.1.4. *The Kan fibration $\pi: \tilde{U} \rightarrow U$ is a κ -small Kan fibration classifier.*

Proof. For any lifting problem as presented by the left-hand square, the dashed lift exists by Lemma 3.2.1.

$$\begin{array}{ccccc} \mathcal{E}(-, A) & \longrightarrow & \mathcal{E}(-, U) & \hookrightarrow & \mathcal{E}(-, V) \\ i_0 \downarrow & \nearrow \gamma & \pi \downarrow & \lrcorner & \downarrow \pi \\ \mathcal{E}(-, B) & \longrightarrow & \mathbb{F}_\kappa & \hookrightarrow & \mathbb{E}_\kappa \end{array}$$

On account of the pullback established by Lemma 4.1.3, this induces the required dotted lift. □

Since the cofibrations in the category of simplicial sets are the monomorphisms, all simplicial sets are cofibrant. Thus taking $A = \emptyset$ we see that:

Corollary 4.1.5. *Any Kan fibration $p: E \rightarrow B$ with small fibers is classified by a pullback square*

$$\begin{array}{ccc} E & \longrightarrow & \tilde{U} \\ p \downarrow & \lrcorner & \downarrow \pi \\ B & \xrightarrow{\lrcorner p^\top} & U \end{array} \quad \square$$

4.2. Fibrancy of the universe. In the simplicial model of univalent foundations, types are meant to correspond to Kan complexes. One use of the acyclicity property is proving that U is a Kan complex. Recall that Kan complexes of simplicial sets are characterized by right lifting against the **acyclic cofibrations**, monomorphisms that also define weak homotopy equivalences

$$\begin{array}{ccc} A & \xrightarrow{h} & U \\ j \downarrow \wr & \nearrow & \\ B & & \end{array}$$

If the universe U strictly classified small fibrations, this would unravel to the following:

Definition 4.2.1. The fibrations in a model category \mathcal{E} satisfy the **fibration extension property** if for all small fibrations $q: D \rightarrow A$ and all trivial cofibrations $j: A \rightarrowtail B$, there exists a small fibration $p: E \rightarrow B$ that pulls back along j to q .

$$\begin{array}{ccc} D & \dashrightarrow & E \\ q \downarrow \wr & \lrcorner & \downarrow p \\ A & \xrightarrow{\sim} & B \\ & j & \end{array}$$

Note that Definition 4.2.1 makes no reference to a particular universe U . Nevertheless, when $\pi: \tilde{U} \rightarrow U$ is a fibration classifier, satisfying the acyclicity property (3.1.2), the fibration extension property encodes the fibrancy of U .

Lemma 4.2.2. Suppose $\pi: \tilde{U} \rightarrow U$ is a fibration classifier in a model category \mathcal{E} . Then U is fibrant if and only if \mathcal{E} satisfies the fibration extension property.

Proof. Suppose \mathcal{E} satisfies the fibration extension property and consider a lifting problem:

$$\begin{array}{ccc} A & \xrightarrow{h} & U \\ j \downarrow \wr & \nearrow & \\ B & & \end{array}$$

Define a fibration $q: D \rightarrow A$ by pulling back π along h . Then use the fibration extension property to extend this to a fibration $p: E \rightarrow B$ that pulls back along j to q . By acyclicity property, it follows that the classifying map h extends along j to a classifying map k for p so that $k \cdot j = h$, solving the lifting problem. This proves that the fibration extension property implies fibrancy of the universe.

Conversely, if U is fibrant and we are given a small fibration $q: D \rightarrow A$, we may use Corollary 4.1.5 to choose a classifying pullback square. In particular, this choice defines a classifying map and thus a lifting problem

$$\begin{array}{ccc} A & \xrightarrow{\ulcorner q \urcorner} & U \\ j \downarrow \wr & \nearrow & \\ B & & \end{array}$$

which admits a solution. The pullback of π along this map, displayed below-right, defines a small fibration over B . The pullback square for q factors through the one for p defining the desired extension square:

$$\begin{array}{ccccc} D & \dashrightarrow & E & \xrightarrow{\quad} & \tilde{U} \\ q \downarrow \wr & \lrcorner & p \downarrow \wr & \lrcorner & \downarrow \pi \\ A & \xrightarrow{j} & B & \xrightarrow{\ulcorner p \urcorner} & U \\ & \searrow & \nearrow & \lrcorner & \\ & & & \ulcorner q \urcorner & \end{array}$$

□

Thus, to show that U is a Kan complex, we need only verify the fibration extension property in the category of simplicial sets. Since the Kan complexes are detected by right lifting against the simplicial

horn inclusion $\Lambda_k^n \xrightarrow{\sim} \Delta^n$, it suffices to consider extensions of fibrations along such maps as the proof just given reveals.

Theorem 4.2.3. *The category of simplicial sets satisfies the fibration extension property.*

Proof. By Lemma 4.2.2, it suffices to extension a Kan fibration over a horn Λ_k^n to a Kan fibration over the simplex Δ^n in such a way that the latter pulls back to the former. To do so, we use a result of Quillen [Q2] to factor $q: E \rightarrow \Lambda_k^n$ as a trivial fibration followed by a minimal fibration. Since the base of the minimal fibration is contractible, it is isomorphic to a projection map $F \times \Lambda_k^n \rightarrow \Lambda_k^n$ for some Kan complex F and thus extends as displayed:

$$\begin{array}{ccc} E & \xrightarrow{\quad\quad\quad} & E' \\ \downarrow \wr & \lrcorner & \downarrow \wr \\ F \times \Lambda_k^n & \longrightarrow & F \times \Delta^n \\ \downarrow \wr & \lrcorner & \downarrow \wr \\ \Lambda_k^n & \hookrightarrow & \Delta^n \end{array}$$

Thus it remains only to extend the trivial fibration, but this can be achieved defining $E' \xrightarrow{\sim} F \times \Delta^n$ to be the pushforward of $E \xrightarrow{\sim} F \times \Lambda_k^n$ along the monomorphism $F \times \Lambda_k^n \hookrightarrow F \times \Delta^n$. Since monomorphisms are stable under pullback, the trivial fibrations are stable under pushforward. Finally, the pushforward along a monomorphism pulls back along that monomorphism to a map isomorphic to the original, the since the left adjoints of these functors compose to a functor isomorphic to the identity. \square

4.3. Univalence. We now explain the interpretation of the univalence axiom in a model category \mathcal{E} , for instance the model category of simplicial sets that presents the ∞ -topos of spaces. Our exposition follows [S1], which explains univalence as follows:

The univalence axiom, when interpreted in a model category, is a statement about a “universe object” U , which is fibrant and comes equipped with a fibration $\pi: \tilde{U} \rightarrow U$ that is generic, in the sense that any fibration with “small fibers” is a pullback of π In homotopy theory, it would be natural to ask for the stronger property that U is a classifying space for small fibrations, i.e. that homotopy classes of maps $A \rightarrow U$ are in bijection with (rather than merely surjecting onto) equivalence classes of small fibrations over A . The univalence axiom is a further strengthening of this: it says that the path space of U is equivalent to the “universal space of equivalences” between fibers of π ... In particular, therefore, if two pullbacks of π are equivalent, then their classifying maps are homotopic. [S1]

The univalence axiom concerns the object $\text{Eq}(\tilde{U}) \rightarrow U \times U$ of equivalences defined for the universal fibration $\pi: \tilde{U} \rightarrow U$. The idea is that a generalized element

$$\begin{array}{ccc} B & \xrightarrow{\quad \ulcorner \epsilon \urcorner \quad} & \text{Eq}(\tilde{U}) \\ & \searrow (\ulcorner E \urcorner, \ulcorner E' \urcorner) & \downarrow \\ & & U \times U \end{array}$$

should represent a fibered equivalence $\epsilon: E \simeq E'$ between the fibrations over B classified by these maps.

We explain how to construct the simplicial set $\text{Eq}(\tilde{U})$ via a construction that would work in any simplicially locally cartesian closed, right proper, simplicial model category \mathcal{E} whose cofibrations are the monomorphisms. As recalled above, local cartesian closure provides adjunctions

$$(4.3.1) \quad \begin{array}{ccc} & \Sigma_f & \\ \mathcal{E}_{/B} & \xleftarrow{\quad \perp \quad} & \mathcal{E}_{/A} \\ & \xrightarrow{\quad \perp \quad} & \\ & \Pi_f & \end{array}$$

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for any $f: A \rightarrow B$ defined respectively by composition, pullback, and pushforward; here we prefer notation that reflects the type theoretic analogues of these constructions. Since the cofibrations are the monomorphisms, pushforward along any map preserves trivial fibrations. Since the model category is right proper, pushforward along a fibration also preserves fibrations. Since the model category is simplicial, we may form the **fibred path space** factorization (1.1.1) of any fibration $p: E \twoheadrightarrow B$ between fibrant objects through the **fibred path space** $P_B E$ defined by the pullback:

$$(4.3.2) \quad \begin{array}{ccccc} E & \xrightarrow{\sim} & E^{\Delta^1} & \twoheadrightarrow & E \times E \\ \downarrow p & \nearrow P_B E & \downarrow p^{\Delta^1} & \nearrow & \downarrow p \times p \\ & E \times_B E & & & \\ & \downarrow & & & \\ B & \xrightarrow{\sim} & B^{\Delta^1} & \twoheadrightarrow & B \times B \end{array}$$

As noted above, this construction has the following properties:

Proposition 4.3.3. *For any fibration between fibrant objects $p: E \twoheadrightarrow B$, the natural maps*

$$E \xrightarrow{\sim} P_B E \xrightarrow{(e_0, e_1)} E \times_B E$$

give a factorization of the relative diagonal map $(1, 1): E \rightarrow E \times_B E$ over B as a trivial cofibration followed by a fibration, and this construction is weakly stable over B in that the pullback along any $f: A \rightarrow B$ is again such a factorization.

Proof. Since \mathcal{E} is a simplicial model category and $p: E \twoheadrightarrow B$ is a fibration between fibrant objects, the maps depicted as fibrations in (4.3.2) are all fibrations. The map r is a monomorphism, since it is the left factor of a monomorphism, and is a weak equivalence by the 2-of-3 property and right properness. For the pullback stability of this construction, it's helpful to note that $P_B E \cong \Delta^1 \pitchfork_B E$ is the simplicial cotensor of $p: E \twoheadrightarrow B$ by Δ^1 in the slice $\mathcal{E}_{/B}$. Simplicial cartesian closure demands that the adjunctions (4.3.1) are simplicially enriched, and in particular that the right adjoint $f^*: \mathcal{E}_{/B} \rightarrow \mathcal{E}_{/A}$ preserves these simplicial cotensors. \square

Digression 4.3.4. In homotopy type theory the object of equivalences between types in the universe \mathcal{U} is

$$\Sigma_{(A,B): \mathcal{U} \times \mathcal{U}} \Sigma_{f: A \rightarrow B} \text{isEquiv}(f)$$

where

$$\text{isEquiv}(f) := \Sigma_{b: B} \text{isContr}(P f_b)$$

where

$$\text{isContr}(C) := \Sigma_{c: C} \prod_{x: C} c =_C x$$

and

$$P f_b := \Sigma_{a: A} f a =_B b$$

is the homotopy fiber of f over b .

A fibration $p: E \twoheadrightarrow B$ is a weak equivalence if and only if it is a trivial fibration. Between cofibrant objects this is the case if and only if it admits a section $s: B \rightarrow E$ together with a homotopy $\gamma: sp \sim 1_E$ over B . Such data in particular chooses a center of contraction $s(b) \in E_b$ in the fiber over each $b: 1 \rightarrow B$ and also provides a contracting homotopy, proving the contractibility of the fibers of p .

The data of such a homotopy is encoded by a dashed lift

$$\begin{array}{ccc} & & P_B E \\ & \nearrow \gamma & \downarrow \\ E & \xrightarrow{(sp, 1_E)} & E \times_B E \\ \downarrow p & \lrcorner & \downarrow \pi_1 \\ B & \xrightarrow{s} & E \end{array}$$

Since the map $(sp, 1_E)$ is a pullback of s along π_1 , this lift is equally encoded by a lift of $s: B \rightarrow E$ along $\Pi_{\pi_1} P_B E \rightarrow E$. And thus a section of the composite $\Sigma_p \Pi_{\pi_1} P_B E \rightarrow B$ provides the data of both the section s and the homotopy γ . Thus we define

$$\text{isContr}_B(E) := \Sigma_p \Pi_{\pi_1} P_B E \in \mathcal{E}_B,$$

which is the B -indexed object of spaces internalizing the assertion that for each $b \in B$, the fiber E_b is contractible. By construction:

Lemma 4.3.5. *A fibration $p: E \rightarrow B$ between fibrant objects is a trivial fibration if and only if $\text{isContr}_B(E) \rightarrow B$ has a section.* \square

Now a map $f: E_1 \rightarrow E_2$ over B is a weak equivalence if and only if its replacement by an equivalent fibration over E_2 is a trivial fibration. This replacement is the map $p: P_B f \rightarrow E_2$ defined by the pullback of the fibered path space of E_2 over B

$$\begin{array}{ccc} E_1 & \xrightarrow{f} & E_2 \\ \downarrow \langle 1, f \rangle & \searrow \sim & \downarrow \\ & P_B f & \longrightarrow P_B E_2 \\ & \downarrow \langle q, p \rangle & \downarrow \\ E_1 \times_B E_2 & \xrightarrow{f \times 1} & E_2 \times_B E_2 \end{array}$$

By Lemma 4.3.5, the map $p: P_B f \rightarrow E_2$ is a trivial fibration if and only if $\text{isContr}_{E_2}(P_B f) \rightarrow E_2$ has a section, or equivalently if and only if the pushforward along $p_2: E_2 \rightarrow B$ has a section over B . Thus we define

$$\text{isEquiv}_B(f) := \Pi_{p_2} \text{isContr}_{E_2}(P_B f) \in \mathcal{E}_B.$$

By construction:

Lemma 4.3.6. *A map $f: E_1 \rightarrow E_2$ between fibrations over a fibrant object B is a weak equivalence if and only if $\text{isEquiv}_B(f) \rightarrow B$ has a section.* \square

Finally the slice category \mathcal{E}_B has an internal hom $\text{map}_B(E_1, E_2)$. The counit $\epsilon: \text{map}_B(E_1, E_2) \times_B E_1 \rightarrow E_2$ pulls back to define a map

$$\mu: \text{map}_B(E_1, E_2) \times_B E_1 \rightarrow \text{map}_B(E_1, E_2) \times_B E_2$$

over $\text{map}_B(E_1, E_2)$. The fiber over an element $f: X \rightarrow \text{map}_B(E_1, E_2)$ over $b: X \rightarrow B$ is the map $f_b: (E_1)_b \rightarrow (E_2)_b$.

$$\begin{array}{ccccc} (E_1)_b & \xrightarrow{\quad} & \text{map}_B(E_1, E_2) \times_B E_1 & \xrightarrow{\quad} & E_1 \\ \downarrow f_b & \lrcorner & \downarrow & \searrow \mu & \downarrow \epsilon \\ (E_2)_b & \xrightarrow{\quad} & \text{map}_B(E_1, E_2) \times_B E_2 & \xrightarrow{\quad} & E_2 \\ \downarrow & \lrcorner & \downarrow & \searrow & \downarrow \\ X & \xrightarrow{f} & \text{map}_B(E_1, E_2) & \xrightarrow{\quad} & B \\ & \searrow b & & & \end{array}$$

Thus we define

$$\text{Equiv}_B(E_1, E_2) := \Sigma_{\text{map}_B(E_1, E_2)} \text{isEquiv}_{\text{map}_B(E_1, E_2)(\epsilon)} \in \mathcal{E}_B$$

so that a section provides a map $E_1 \rightarrow E_2$ over B that is an equivalence. More generally:

Lemma 4.3.7. *Given fibrations $p_1: E_1 \rightarrow B$ and $p_2: E_2 \rightarrow B$ between fibrant objects over B , any lift of $b: X \rightarrow B$ to $\text{Equiv}_B(E_1, E_2)$ provides a map $b^* E_1 \rightarrow b^* E_2$ over X that is an equivalence.* \square

Finally, given a universe $\pi: \tilde{U} \rightarrow U$ define

$$\text{Eq}(\tilde{U}) := \text{Equiv}_{U \times U}(\pi_1^* \tilde{U}, \pi_2^* \tilde{U}) \in \mathcal{E}_{U \times U}.$$

By construction:

Lemma 4.3.8. *Given a fibrant object B and a map $(p_1, p_2): B \rightarrow U \times U$ classifying fibrations $p_1: E_1 \rightarrow B$ and $p_2: E_2 \rightarrow B$ over B , a lift to $\text{Eq}(\tilde{U})$ provides an equivalence $E_1 \simeq E_2$ over B .*

Proof. By Lemma 4.3.7, a lift of $(p_1, p_2): B \rightarrow U \times U$ to $\text{Eq}(\tilde{U})$ provides map from $(p_1, p_2)^* \pi_1^* \tilde{U} \cong p_1^* \tilde{U} \cong E_1$ to $(p_1, p_2)^* \pi_2^* \tilde{U} \cong p_2^* \tilde{U} \cong E_2$ over B that is an equivalence. \square

In particular, there is a lift

$$\begin{array}{ccc} & & \text{Eq}(\tilde{U}) \\ & \text{id} \nearrow & \downarrow \\ U & \xrightarrow{(1,1)} & U \times U \end{array}$$

classifying the identity equivalence $\tilde{U} \cong \tilde{U}$ over U . We may now state the model categorical version of Voevodsky's univalence axiom.

Definition 4.3.9. The *univalence axiom*, for the universal fibration $\pi: \tilde{U} \rightarrow U$, asserts that the comparison map defined by any solution to the lifting problem

$$\begin{array}{ccc} U & \xrightarrow{\text{id}} & \text{Eq}(\tilde{U}) \\ \text{refl} \downarrow & \text{id-to-equiv} \nearrow & \downarrow \\ PU & \longrightarrow & U \times U \end{array}$$

from the path object to the object of equivalences is an equivalence.

By the 2-of-3 property, $\text{id-to-equiv}: PU \rightarrow \text{Eq}(\tilde{U})$ is a weak equivalence if and only if $\text{id}: U \rightarrow \text{Eq}(\tilde{U})$ is a weak equivalence, which is the case if and only if either projection $\text{Eq}(\tilde{U}) \rightarrow U$ is a trivial fibration. As with the fibrancy of the universe, this can be expressed as a property of the model category \mathcal{E} that does not refer explicitly to the universal Kan fibration $\pi: \tilde{U} \rightarrow U$.

Definition 4.3.10. The **equivalence extension property** states that given a cofibration $i: A \hookrightarrow B$, an equivalence $w: E_1 \xrightarrow{\sim} E_2$ of small fibrations over A and a fibration D_2 over B that pulls back along i to E_2 , there exists a small fibration D_1 over B and an equivalence $v: D_1 \xrightarrow{\sim} D_2$ over B that pulls back along i to the equivalence w .

$$\begin{array}{ccccc} E_1 & \xrightarrow{\sim} & D_1 & & \\ \downarrow w & \searrow & \downarrow v & \searrow & \\ E_2 & \xrightarrow{\sim} & D_2 & & \\ \downarrow & \searrow & \downarrow & \searrow & \\ A & \xrightarrow{i} & B & & \end{array}$$

As with Lemma 4.2.2, there is a slightly delicate argument necessary to prove that the equivalence extension property implies univalence of the fibration $\pi: \tilde{U} \rightarrow U$ as stated in Definition 4.3.9. Suppose the equivalence extension property holds and consider a commutative square

$$\begin{array}{ccc} A & \xrightarrow{w} & \text{Eq}(\tilde{U}) \\ i \downarrow & \text{id-to-equiv} \nearrow & \downarrow p_1 \\ B & \xrightarrow{D_2} & U \end{array}$$

By the equivalenc extension property, $w: E_1 \simeq E_2$ extends to an equivalence $v: D_1 \simeq D_2$ between fibrations over B . By the acyclicity property, there is a classifying map for D_1 extending the classifying map for E_1 .

$$\begin{array}{ccccc}
 E_1 & \xrightarrow{\quad} & \tilde{U} & & \\
 \downarrow p_1 & \lrcorner & \downarrow \pi & & \\
 & & D_1 & \xrightarrow{\quad} & U \\
 & \lrcorner & \downarrow q_1 & \lrcorner & \downarrow p_0 w \\
 A & \xrightarrow{\quad} & B & \xrightarrow{\quad} & U \\
 \downarrow i & \lrcorner & \downarrow & \lrcorner & \downarrow \\
 & & B & \xrightarrow{\quad} & B
 \end{array}$$

This defines a new lifting problem as below-left together with the data of an equivalence $v: D_1 \simeq D_2$ over B extending $w: E_1 \simeq E_2$. Unraveling the definitions, this gives us the lifting problem below-center and then below-right:

$$\begin{array}{ccc}
 A \xrightarrow{w} \text{Eq}(\tilde{U}) & A \xrightarrow{w=i^*u} \text{Equiv}_B(D_1, D_2) & A \xrightarrow{w} \text{isEquiv}_B(v) \\
 \downarrow i & \downarrow i & \downarrow i \\
 B \xrightarrow{(D_1, D_2)} U \times U & B \xrightarrow{v} \text{map}_B(D_1, D_2) & B \xrightarrow{=} B
 \end{array}$$

Since v is a fibration, the map $\text{isEquiv}_B(v) \rightarrow B$ is a trivial fibration.⁶ so there exists a lift in the right-hand square which induces one in the middle square and then in the left-hand square. In particular, this final lift solves the original lifting problem, proving univalence.

Thus, we have reduced the verification of the univalence axiom to proving the equivalence extension property for Kan fibrations of simplicial sets. We define D_1 and v by the pullback

$$\begin{array}{ccc}
 D_1 & \dashrightarrow & \Pi_i E_1 \\
 \downarrow v & \lrcorner & \downarrow \Pi_i w \\
 D_2 & \xrightarrow{\eta} & \Pi_i E_2
 \end{array}$$

and leave the rest of the verification to the original sources.

Remark 4.3.11. Note that fibrancy of U was not required to prove the equivalence extension property, and in fact follows from it by an argument due to Stenzel [Ste, 2.4.3]. We must construct a lift

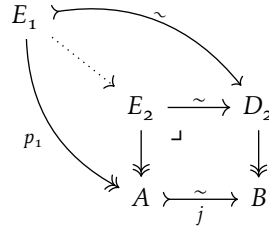
$$\begin{array}{ccc}
 A & \xrightarrow{h} & U \\
 \downarrow i & \lrcorner & \downarrow \\
 B & \xrightarrow{k} & U
 \end{array}$$

that is, we must extend a fibration as indicated:

$$\begin{array}{ccc}
 E_1 & \dashrightarrow & D_1 \\
 \downarrow p_1 & \lrcorner & \downarrow \\
 A & \xrightarrow{j} & B
 \end{array}$$

⁶We proved a bit less; see [S1, §4] for more.

Factor the composite $j \cdot p_1$ into an acyclic cofibration followed by a fibration and pull the fibration back:



By right properness, j pulls back to a weak equivalence and thus the induced map to the pullback is an equivalence between fibrations over A . Now the equivalence extension property can be used to extend the fibration E_1 as desired.

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