

Inductive Types in Homotopy Type Theory

STEVE AWODEY, Carnegie Mellon University
 NICOLA GAMBINO, Institute for Advanced Study
 KRISTINA SOJAKOVA, Carnegie Mellon University

Homotopy type theory is an interpretation of Martin-Löf's constructive type theory into abstract homotopy theory. There results a link between constructive mathematics and algebraic topology, providing topological semantics for intensional systems of type theory as well as a computational approach to algebraic topology via type theory-based proof assistants such as Coq.

The present work investigates inductive types in this setting. Modified rules for inductive types, including types of well-founded trees, or W-types, are presented, and the basic homotopical semantics of such types are determined. Proofs of all results have been formally verified by the Coq proof assistant, and the proof scripts for this verification form an essential component of this research.

Categories and Subject Descriptors: F.4.1 [Mathematical Logic and Formal Languages]: Mathematical Logic

General Terms: Theory, Verification

Additional Key Words and Phrases: Homotopy type theory, homotopy-initial algebras, inductive types

ACM Reference Format:

Steve Awodey, Nicola Gambino, and Kristina Sojakova, 2014. Inductive Types in Homotopy Type Theory. *J. ACM* V, N, Article A (January YYYY), 36 pages.
 DOI : <http://dx.doi.org/10.1145/0000000.0000000>

1. INTRODUCTION

The general topic of Homotopy Type Theory is concerned with the study of the constructive type theories of Martin-Löf under their new interpretation into abstract homotopy theory and higher-dimensional category theory. Martin-Löf type theories are foundational systems which have been used to formalize large parts of constructive mathematics, and also for the development of high-level programming languages [Martin-Löf 1982]. They are prized for their combination of expressive strength and desirable proof-theoretic properties. One aspect of these type theories that has led to special difficulties in providing semantics is the intensional character of equality. In recent work [Awodey and Warren 2009; Voevodsky 2009; van den Berg and Garner 2012; Awodey 2010], it has emerged that the topological notion of *homotopy* provides an adequate basis for the semantics of intensionality. This extends the paradigm of computability as continuity, familiar from domain theory, beyond the simply-typed λ -calculus to dependently-typed theories involving:

Author's addresses: S. Awodey, Philosophy Department, Carnegie Mellon University; N. Gambino, (Current address) School of Mathematics, University of Leeds; K. Sojakova, Computer Science Department, Carnegie Mellon University.

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies show this notice on the first page or initial screen of a display along with the full citation. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, to republish, to post on servers, to redistribute to lists, or to use any component of this work in other works requires prior specific permission and/or a fee. Permissions may be requested from Publications Dept., ACM, Inc., 2 Penn Plaza, Suite 701, New York, NY 10121-0701 USA, fax +1 (212) 869-0481, or permissions@acm.org.

© YYYY ACM 0004-5411/YYYY/01-ARTA \$15.00
 DOI : <http://dx.doi.org/10.1145/0000000.0000000>

- (i) dependent sums $(\Sigma x : A)B(x)$ and dependent products $(\Pi x : A)B(x)$, modelled respectively by the total space and the space of sections of the fibration modelling the dependency of $B(x)$ over $x : A$;
- (ii) and, crucially, including the identity type constructor $\text{Id}_A(a, b)$, interpreted as the space of all *paths* in A between points a and b .

In the present work, we build on this homotopical interpretation to study inductive types, such as the natural numbers, Booleans, lists, and W-types. Within extensional type theories, W-types can be used to provide a constructive counterpart of the classical notion of a well-ordering [Martin-Löf 1984] and to uniformly define a variety of inductive types [Dybjer 1997]. However, most programming languages and proof assistants, such as Coq [Bertot and Castéran 2004], Agda [Norell 2007] and Epigram [McBride and McKinna 2004] use schematic inductive definitions [Coquand and Paulin-Mohring 1990; Paulin-Mohring 1993] rather than W-types to define inductive types. This is due in part to the practical convenience of the schematic approach, but it is also a matter of necessity; these systems are based on intensional rather than extensional type theories, and in the intensional theory the usual reductions of inductive types to W-types fail [Dybjer 1997; McBride 2010]. Nonetheless, W-types retain great importance from a theoretical perspective, since they allow us to internalize in type theory arguments about inductive types. Furthermore, as we will see in Section ??, a limited form of extensionality licensed by the homotopical interpretation suffices to develop the theory of W-types in a satisfactory way. In particular, we shall make use of ideas from higher category theory and homotopy theory to understand W-types as “homotopy-initial” algebras of an appropriate kind.

In intensional type theories, inductive types cannot be characterized by standard category-theoretic universal properties. For instance, in this setting it is not possible to show that there exists a definitionally-unique function out of the empty type with rules as in [Nordstrom et al. 2000, Section 5.2], thus making it impossible to prove that the empty type provides an initial object. Another consequence of this fact is that, if we attempt to define the type of natural numbers as a W-type in the usual way, then the usual elimination and computation rules for it are no longer derivable [Dybjer 1997]. Similarly, it is not possible to show the uniqueness of recursively-defined functions out of W-types. When interpreted categorically, the uniqueness of such functions translates into the initiality property of the associated polynomial functor algebra, which is why the correspondence between W-types and initial algebras fails in the intensional setting.

Due to this sort of poor behaviour of W-types, and other constructions, in the purely intensional setting, that system is often augmented by other extensionality principles that are somewhat weaker than the Reflection rule, such as Streicher’s K-rule or the Uniqueness of Identity Proofs (UIP) [Streicher 1993], which has recently been reconsidered in the context of Observational Type Theory [Altenkirch et al. 2007]. Inductive types in such intermediate systems are somewhat better behaved, but still exhibit some undesirable properties, making them less useful for practical purposes than one might wish [McBride 2010]. Moreover, these intermediate systems seem to lack a clear conceptual basis: they neither intend to formalize constructive sets (like the extensional theory) nor is there a principled reason to choose these particular extensionality rules, beyond their practical advantages.

2. THE DEPENDENT TYPE THEORIES \mathcal{H} AND \mathcal{H}_{EXT}

We work here with type theories that have the four standard forms of judgement

$$A : \text{type}, \quad A = B : \text{type}, \quad a : A, \quad a = b : A.$$

We refer to the equality relation in these judgements as *definitional equality*, which should be contrasted with the notion of *propositional equality* recalled below. Such a judgement J can be made also relative to a *context* Γ of variable declarations, a situation that we indicate by writing $\Gamma \vdash J$. When stating deduction rules we make use of standard conventions to simplify the exposition, such as omitting the mention of a context that is common to premisses and conclusions of the rule. The rules for identity types in intensional type theories are given in [Nordstrom et al. 2000, Section 5.5]. We recall them here in a slightly different, but equivalent, formulation.

— Id-formation rule.

$$\frac{A : \text{type} \quad a : A \quad b : A}{\text{Id}_A(a, b) : \text{type}}$$

— Id-introduction rule.

$$\frac{a : A}{\text{refl}(a) : \text{Id}_A(a, a)}$$

— Id-elimination rule.

$$\frac{\begin{array}{l} x, y : A, u : \text{Id}_A(x, y) \vdash C(x, y, u) : \text{type} \\ x : A \vdash c(x) : C(x, x, \text{refl}(x)) \end{array}}{x, y : A, u : \text{Id}_A(x, y) \vdash \text{idrec}(x, y, u, c) : C(x, y, u)}$$

— Id-computation rule.

$$\frac{\begin{array}{l} x, y : A, u : \text{Id}_A(x, y) \vdash C(x, y, u) : \text{type} \\ x : A \vdash c(x) : C(x, x, \text{refl}(x)) \end{array}}{x : A \vdash \text{idrec}(x, x, \text{refl}(x), c) = c(x) : C(x, x, \text{refl}(x))}.$$

As usual, we say that two elements $a, b : A$ are *propositionally equal* if the type $\text{Id}(a, b)$ is inhabited. Most work on W-types to date (e.g. [Dybjer 1997; Moerdijk and Palmgren 2000; Abbott et al. 2005]) has been in the setting of extensional type theories, in which the following rule, known as the *identity reflection rule*, is also assumed:

$$\frac{p : \text{Id}_A(a, b)}{a = b : A} \tag{1}$$

This rule collapses propositional equality with definitional equality, thus making the overall system somewhat simpler to work with. However, it destroys the constructive character of the intensional system, since it makes type-checking undecidable [Hofmann 1997]. For this reason, it is not assumed in the most recent formulations of Martin-Löf type theories [Nordstrom et al. 2000] or in automated proof assistants like Coq [Bertot and Castéran 2004].

2.1. The system \mathcal{H}

We here take a different approach to inductive types in the intensional setting, namely, one motivated by the homotopical interpretation. It involves working over a dependent type theory \mathcal{H} which has the following deduction rules on top of the standard structural rules:

- rules for identity types as stated above;
- rules for Σ -types as in [Nordstrom et al. 2000, Section 5.8];
- rules for Π -types as in [Garner 2009, Section 3.2];
- the Function Extensionality axiom (FE), *i.e.* the axiom asserting that for every $f, g : A \rightarrow B$, the type

$$(\Pi x : A) \text{ld}_B(\text{ap}(f, x), \text{ap}(g, x)) \rightarrow \text{ld}_{A \rightarrow B}(f, g)$$

is inhabited.

Here, we have used the notation $A \rightarrow B$ to indicate function types, defined via Π -types in the usual way. Similarly, we will write $A \times B$ to denote the binary product of two types as usually defined via Σ -types.

Remarks

- (i) The rules for Π -types of \mathcal{H} are derivable from those in [Nordstrom et al. 2000, Section 5.4]. For simplicity, we will write $f(a)$ or fa instead of $\text{ap}(f, a)$.
- (ii) As shown in [Voevodsky 2010a], the principle of propositional function extensionality stated above implies the corresponding principle for dependent functions, *i.e.*

$$(\Pi x : A) \text{ld}_{B(x)}(fx, gx) \rightarrow \text{ld}_{(\Pi x : A)B(x)}(f, g).$$

- (iii) The following form of the η -rule for Σ -types is derivable:

$$\frac{c : (\Sigma x : A)B(x)}{\eta_\Sigma(c) : \text{ld}(c, \text{pair}(\pi_1 c, \pi_2 c))},$$

where π_1 and π_2 are the projections. This can be proved by Σ -elimination, without FE.

- (iv) The following form of the η -rule for Π -types is derivable:

$$\frac{f : (\Pi x : A)B(x)}{\eta_\Pi(f) : \text{ld}(f, \lambda x. fx)}$$

This is an immediate consequence of FE and clearly implies the corresponding η -rule for function types.

- (v) \mathcal{H} does *not* include the η -rules as definitional equalities, either for Σ -types or for Π -types (as is done in [Goguen and Luo 1993]).
- (vi) The type theory \mathcal{H} will serve as the background theory for our study of inductive types and W-types. For this reason, we need not assume it to have any primitive types.

This particular combination of rules is motivated by the fact that \mathcal{H} has a clear homotopy-theoretic semantics. Indeed, the type theory \mathcal{H} is a subsystem of the type theory used in Voevodsky's Univalent Foundations library [Voevodsky 2010a]. In particular, the Function Extensionality axiom is formally implied by Voevodsky's Univalence axiom [Voevodsky 2009], which is also valid in homotopy-theoretic models, but will not be needed here. Note that, while the Function Extensionality axiom is valid also in set-theoretic models, the Univalence axiom is not. Although \mathcal{H} has a straightforward set-theoretical semantics, we stress that it does not have any global extensionality rules, like the identity reflection rule, K, or UIP. This makes it also compatible with “higher-dimensional” interpretations such as the groupoid model [Hofmann and Streicher 1998], in which the rules of \mathcal{H} are also valid.

2.2. Homotopy-theoretic notions in type theory

The homotopical semantics of \mathcal{H} is based on the idea that an identity term $p : \text{Id}_A(a, b)$ is (interpreted as) a path $p : a \rightsquigarrow b$ between the points a and b in the space A . More generally, the interpretations of terms $a(x)$ and $b(x)$ with free variables will be continuous functions into the space A , and an identity term $p(x) : \text{Id}_A(a(x), b(x))$ is then a continuous family of paths, *i.e.* a homotopy between the continuous functions. Now, the main import of the Id -elimination rule is that type dependency must respect identity, in the following sense: given a dependent type

$$x : A \vdash B(x) : \text{type}, \quad (2)$$

and $p : \text{Id}_A(a, b)$, there is then a *transport* function

$$p_! : B(a) \rightarrow B(b),$$

which is defined by Id -elimination, taking for $x : A$ the function $\text{refl}(x)_! : B(x) \rightarrow B(x)$ to be the identity on $B(x)$. Semantically, given that an identity term $p : \text{Id}_A(a, b)$ is interpreted as a path $p : a \rightsquigarrow b$, this means that a dependent type as in (2) must be interpreted as a space $B \rightarrow A$, fibered over the space A , and that the judgement

$$x, y : A \vdash \text{Id}_A(x, y) : \text{type}$$

is interpreted as the canonical fibration $A^I \rightarrow A \times A$ of the path space A^I over $A \times A$. For a more detailed overview of the homotopical interpretation, see [Awodey 2010].

Independently of this interpretation, each type A can be shown to carry the structure of a weak ω -groupoid in the sense of [Batanin 1998; Leinster 2004] with the elements of A as objects, identity proofs $p : \text{Id}_A(a, b)$ as morphisms and elements of iterated identity types as n -cells [van den Berg and Garner 2011; Lumsdaine 2010b]. Furthermore, \mathcal{H} determines a weak ω -category $\mathcal{C}(\mathcal{H})$ having types as 0-cells, elements $f : A \rightarrow B$ as 1-cells, and elements of (iterated) identity types as n -cells [Lumsdaine 2010a]. The relation between the weak ω -category structure of $\mathcal{C}(\mathcal{H})$ and the homotopical interpretation of intensional type theories closely mirrors that between higher category theory and homotopy theory in modern algebraic topology, and some methods developed in the latter setting are also applicable in type theory. For instance, the topological notion of contractibility admits the following type-theoretic counterpart, originally introduced by Voevodsky in [Voevodsky 2010a].

Definition 2.1. A type A is called *contractible* if the type

$$\text{is-contr}(A) := (\Sigma x : A)(\Pi y : A)\text{Id}_A(x, y) \quad (3)$$

is inhabited.

The type $\text{is-contr}(A)$ can be seen as the propositions-as-types translation of the formula stating that A has a unique element. However, its homotopical interpretation is as a space that is inhabited if and only if the space interpreting A is contractible in the usual topological sense. The notion of contractibility can be used to articulate the world of types into different homotopical dimensions, or *h-levels* [Voevodsky 2010a]. This classification has proven to be quite useful in understanding intensional type theory. For example, it permits the definition of new notions of *proposition* and *set* which provide a useful alternative to the standard approach to formalization of mathematics in type theory [Voevodsky 2010a].

Remark 2.2. If A is a contractible type, then for every $a, b : A$, the type $\text{Id}_A(a, b)$ is again contractible. This can be proved by Id -elimination [Awodey et al. 2011].

Let us also recall from [Voevodsky 2010a] the notions of weak equivalence and homotopy equivalence. To do this, we need to fix some notation. For $f : A \rightarrow B$ and $y : B$,

define the type

$$\text{hfiber}(f, y) := (\Sigma x : A) \text{ld}_B(fx, y).$$

We refer to this type as the *homotopy fiber* of f at y .

Definition 2.3. Let $f : A \rightarrow B$.

— We say that f is a *weak equivalence* if the type

$$\text{isweq}(f) := (\Pi y : B) \text{is-contr}(\text{hfiber}(f, y))$$

is inhabited.

— We say that f is a *homotopy equivalence* if there exist a function $g : B \rightarrow A$ and elements

$$\begin{aligned} \eta &: (\Pi x : A) \text{ld}(gfx, x), \\ \varepsilon &: (\Pi y : B) \text{ld}(fgy, y). \end{aligned}$$

It is an *adjoint homotopy equivalence* if there are also terms

$$\begin{aligned} p &: (\Pi x : A) \text{ld}(\varepsilon_{fx}, f \eta_x), \\ q &: (\Pi y : B) \text{ld}(\eta_{gy}, g \varepsilon_y), \end{aligned}$$

where the same notation for both function application and the action of a function on an identity proof (which is easily definable by ld -elimination), and we write α_x instead of $\alpha(x)$ for better readability.

The type $\text{isweq}(f)$ can be seen as the propositions-as-types translation of the formula asserting that f is bijective, while homotopy equivalence is evidently a form of isomorphism. Thus it is a pleasant fact that a function is a weak equivalence if and only if it is a homotopy equivalence [Voevodsky 2010a]. We also note that all type-theoretic constructions are homotopy invariant, in the sense that they respect this relation of equivalence, a fact which is exploited by the Univalence axiom [Voevodsky 2009].

In Section ?? below, these and related homotopy-theoretic insights will be used to study inductive types, but first we must briefly review some basic facts about inductive types in the extensional setting.

3. SIMPLE INDUCTIVE TYPES

3.1. Extensional case

The type 2 is not a W-type, but can be formulated as an inductive type in the familiar way by means of formation, introduction, elimination, and computation rules:

— 2-formation rule.

$$2 : \mathcal{U}_i.$$

— 2-introduction rules.

$$0 : 2, \quad 1 : 2.$$

— 2-elimination rule (“induction”).

$$\frac{x : 2 \vdash E(x) : \mathcal{U}_i \quad e_0 : E(0) \quad e_1 : E(1) \quad b : 2}{2\text{ind}_{\mathcal{U}_i}(x.E, e_0, e_1, b) : E(b)}$$

— 2-computation rules.

$$\frac{x : 2 \vdash E(x) : \mathcal{U}_i \quad e_0 : E(0) \quad e_1 : E(1)}{\begin{cases} 2\text{ind}_{\mathcal{U}_i}(x.E, e_0, e_1, 0) \equiv e_0 : E(0), \\ 2\text{ind}_{\mathcal{U}_i}(x.E, e_0, e_1, 1) \equiv e_1 : E(1). \end{cases}}$$

The above rules imply a non-dependent (simple) version of elimination and the corresponding computation rules:

— Simple 2-elimination rule (“recursion”).

$$\frac{C : \mathcal{U}_i \quad c_0 : C \quad c_1 : C \quad b : 2}{2\text{rec}_{\mathcal{U}_i}(C, c_0, c_1, b) : C}$$

— Simple 2-computation rules.

$$\frac{C : \mathcal{U}_i \quad c_0 : C \quad c_1 : C}{\begin{cases} 2\text{rec}_{\mathcal{U}_i}(C, c_0, c_1, 0) \equiv c_0 : C, \\ 2\text{rec}_{\mathcal{U}_i}(C, c_0, c_1, 1) \equiv c_1 : C. \end{cases}}$$

Furthermore, the induction principle implies the following uniqueness principles, which state that any two functions out of 2 which agree on the constructors are (point-wise) equal:

— 2-uniqueness principle.

$$\frac{\begin{array}{l} b : 2 \quad x : 2 \vdash E(x) : \mathcal{U}_i \quad e_0 : E(0) \quad e_1 : E(1) \\ x : 2 \vdash f(x) : E(x) \quad f(0) \equiv e_0 \quad f(1) \equiv e_1 \\ x : 2 \vdash g(x) : E(x) \quad g(0) \equiv e_0 \quad g(1) \equiv e_1 \end{array}}{f(b) \equiv g(b) : E(b)}$$

— Simple 2-uniqueness principle.

$$\frac{\begin{array}{l} b : 2 \quad C : \mathcal{U}_i \quad c_0 : C \quad c_1 : C \\ x : 2 \vdash f(x) : C \quad f(0) \equiv c_0 \quad f(1) \equiv c_1 \\ x : 2 \vdash g(x) : C \quad g(0) \equiv c_0 \quad g(1) \equiv c_1 \end{array}}{f(b) \equiv g(b) : C}$$

Remark: In this particular case, we could also write $f(0) \equiv g(0) : E(0)$ and $f(1) \equiv g(1) : E(1)$ in the premises, avoiding the mention of e_0 and e_1 altogether (and similarly for the simple uniqueness principle). However, the form we chose follows a general schema (see Defs. 3.4 and 3.8) which scales to more complicated inductive types.

We can prove the dependent uniqueness principle by using the induction principle with the type family $x \mapsto f(x) =_{E(x)} g(x)$; the cases when $x := 0$ and $x := 1$ are straightforward. This gives us pointwise propositional equality between f and g ; we appeal to the identity reflection rule to finish the proof. The simple uniqueness principle clearly follows from the dependent one.

We now introduce some terminology in order to talk about the above rules more economically. The elimination and computation rules motivate the following definitions:

Definition 3.1. Define the type of 2-algebras on a universe \mathcal{U}_i as

$$2\text{-Alg}_{\mathcal{U}_i} := \Sigma_{C:\mathcal{U}_i} C \times C$$

Definition 3.2. Define the type of *fibred 2-algebras* on a universe \mathcal{U}_j over $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ by

$$2\text{-Fib-Alg}_{\mathcal{U}_j}(C, c_0, c_1) := \Sigma_{E:C \rightarrow \mathcal{U}_j} E(c_0) \times E(c_1)$$

Definition 3.3. Given algebras $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ and $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$, define the type of *2-homomorphisms* from \mathcal{X} to \mathcal{Y} by

$$2\text{-Hom}(C, c_0, c_1)(D, d_0, d_1) := \Sigma_{f:C \rightarrow D} (f(c_0) = d_0) \times (f(c_1) = d_1)$$

Definition 3.4. Given algebras $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ and $\mathcal{Y} : 2\text{-Fib-Alg}_{\mathcal{U}_j}$, define the type of *fibred 2-homomorphisms* from \mathcal{X} to \mathcal{Y} by

$$2\text{-Fib-Hom}(C, c_0, c_1)(E, e_0, e_1) := \Sigma_{(f:\Pi_{x:C} E(x))} (f(c_0) = e_0) \times (f(c_1) = e_1)$$

We note that in order to form the type of homomorphisms, we had to use propositional rather than definitional equality. Of course, in the setting of an extensional type theory this distinction is immaterial; however, it will become important in Chpt. ??.

Definition 3.5. An algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ *satisfies the recursion principle* on a universe \mathcal{U}_j if for any algebra $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$ there exists a 2-homomorphism between \mathcal{X} and \mathcal{Y} :

$$\text{has-2-rec}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:2\text{-Alg}_{\mathcal{U}_j})} 2\text{-Hom } \mathcal{X} \mathcal{Y}$$

Definition 3.6. An algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ *satisfies the induction principle* on a universe \mathcal{U}_j if for any fibred algebra $\mathcal{Y} : 2\text{-Fib-Alg}_{\mathcal{U}_j}$ \mathcal{X} there exists a fibred 2-homomorphism between \mathcal{X} and \mathcal{Y} :

$$\text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:2\text{-Fib-Alg}_{\mathcal{U}_j})} 2\text{-Fib-Hom } \mathcal{X} \mathcal{Y}$$

The uniqueness principles motivate the following definitions:

Definition 3.7. An algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ *satisfies the recursion uniqueness principle* on a universe \mathcal{U}_j if for any algebra $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$ any two 2-homomorphisms between \mathcal{X} and \mathcal{Y} are equal:

$$\text{has-2-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:2\text{-Alg}_{\mathcal{U}_j})} \text{is-prop}(2\text{-Hom } \mathcal{X} \mathcal{Y})$$

Definition 3.8. An algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ *satisfies the induction uniqueness principle* on a universe \mathcal{U}_j if for any fibred algebra $\mathcal{Y} : 2\text{-Fib-Alg}_{\mathcal{U}_j}$ \mathcal{X} any two fibred 2-homomorphisms between \mathcal{X} and \mathcal{Y} are equal:

$$\text{has-2-ind-uniq}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:2\text{-Fib-Alg}_{\mathcal{U}_j})} \text{is-prop}(2\text{-Fib-Hom } \mathcal{X} \mathcal{Y})$$

The uniqueness principles as in definitions 3.7, 3.8 require that any two homomorphisms $\mu := (f, \gamma_0, \gamma_1)$ and $\nu := (g, \delta_0, \delta_1)$ be equal as *tuples*; however, in the presence of the UIP axiom this is equivalent to saying that their first components agree, i.e., $f = g$ (and hence $f \equiv g$).

Definition 3.9. An algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ is *initial* on a universe \mathcal{U}_j if for any algebra $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$ there exists a unique 2-homomorphism between \mathcal{X} and \mathcal{Y} :

$$\text{is-2-init}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:2\text{-Alg}_{\mathcal{U}_j})} \text{is-contr}(2\text{-Hom } \mathcal{X} \mathcal{Y})$$

The contractibility requirement precisely captures the notion of initiality: in the presence of the identity reflection rule, a contractible type is one which contains a definitionally unique element.

The following lemma in particular implies that it is not necessary to have a “fibered” version of the initiality property, which quantifies over all fibered algebras $\mathcal{Y} : 2\text{-Fib-Alg}_{\mathcal{U}_j}$.

LEMMA 3.10. *In \mathcal{H}_{ext} , if an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ satisfies the induction principle on the universe \mathcal{U}_j , it also satisfies the induction uniqueness principle on \mathcal{U}_j . In other words, we have*

$$\text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X}) \rightarrow \text{has-2-ind-uniq}_{\mathcal{U}_j}(\mathcal{X})$$

PROOF. Let an algebra $(C, c_0, c_1) : 2\text{-Alg}_{\mathcal{U}_i}$ be given. To prove the induction uniqueness principle, take any algebra $(E, e_0, e_1) : 2\text{-Fib-Alg}_{\mathcal{U}_j}(C, c_0, c_1)$ and homomorphisms $(f, \gamma_0, \gamma_1), (g, \delta_0, \delta_1) : 2\text{-Fib-Hom}(C, c_0, c_1)(E, e_0, e_1)$. Because of UIP, showing $(f, \gamma_0, \gamma_1) = (g, \delta_0, \delta_1)$ is equivalent to showing $f = g$. For the latter, we use the induction principle with the fibered algebra $(x \mapsto f(x) = g(x), \text{refl}(f(c_0)), \text{refl}(g(c_0)))$. This is indeed well-typed since γ_0, δ_0 give us $f(c_0) = e_0 = g(c_0)$ and γ_1, δ_1 give us $f(c_1) = e_1 = g(c_1)$.

The first component of the resulting homomorphism together with the function extensionality principle then give us $f = g$. \square

COROLLARY 3.11. *In \mathcal{H}_{ext} , if an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ satisfies the induction principle on the universe \mathcal{U}_j , it is initial on \mathcal{U}_j . In other words, we have*

$$\text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X}) \rightarrow \text{is-2-init}_{\mathcal{U}_j}(\mathcal{X})$$

LEMMA 3.12. *In \mathcal{H}_{ext} , if an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_j and $j \geq i$, then it satisfies the induction principle on \mathcal{U}_j . In other words, we have*

$$\text{has-2-rec}_{\mathcal{U}_j}(\mathcal{X}) \times \text{has-2-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) \rightarrow \text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X})$$

provided $j \geq i$.

PROOF. Let algebras $(C, c_0, c_1) : 2\text{-Alg}_{\mathcal{U}_i}$ and $(E, e_0, e_1) : 2\text{-Fib-Alg}_{\mathcal{U}_j}(C, c_0, c_1)$ be given. We use the recursion principle with the algebra $(\Sigma_{x:C} E(x), (c_0, e_0), (c_1, e_1))$. We note that the carrier type belongs to \mathcal{U}_j as $i \leq j$. This gives us a homomorphism (u, θ_0, θ_1) , where $u : C \rightarrow \Sigma_{x:C} E(x)$, $\theta_0 : u(c_0) = (c_0, e_0)$, and $\theta_1 : u(c_1) = (c_1, e_1)$. We can now form two homomorphisms $(\text{fst} \circ u, \text{refl}(c_0), \text{refl}(c_1)), (\text{id}_C, \text{refl}(c_0), \text{refl}(c_1)) : 2\text{-Hom}(C, c_0, c_1)(C, c_0, c_1)$; the former type-checks due to θ_0, θ_1 . The recursion uniqueness principle tells us that these homomorphisms are equal. Thus, we have $\text{fst} \circ u = \text{id}_C$ and in particular $\text{fst} \circ u \equiv \text{id}_C$.

We can thus define the desired fibered homomorphism as $(\text{snd} \circ u, \text{refl}(e_0), \text{refl}(e_1)) : 2\text{-Fib-Hom}(C, c_0, c_1)(E, e_0, e_1)$. \square

COROLLARY 3.13. *In \mathcal{H}_{ext} , the following conditions on an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ are equivalent:*

- (1) \mathcal{X} satisfies the induction principle on the universe \mathcal{U}_j
- (2) \mathcal{X} satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_j
- (3) \mathcal{X} is initial on the universe \mathcal{U}_j

for $j \geq i$. In other words, we have

$$\text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X}) \simeq \text{has-2-rec}_{\mathcal{U}_j}(\mathcal{X}) \times \text{has-2-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) \simeq \text{is-2-init}_{\mathcal{U}_j}(\mathcal{X})$$

provided $j \geq i$. Furthermore, all 3 conditions are mere propositions.

PROOF. Conditions (1) and (3) are mere propositions by Lem. ??¹ (for the latter), EdN:1
Lem. ??², 3.10 (for the former), and the fact that a family of mere propositions is itself EdN:2
a mere proposition. \square

We can thus characterize the type 2 using the universal property of initiality as follows.

COROLLARY 3.14. *In \mathcal{H}_{ext} extended with the type 2, the algebra $(2, 0, 1) : 2\text{-Alg}_{\mathcal{U}_0}$ is initial on any universe \mathcal{U}_j .*

COROLLARY 3.15. *In \mathcal{H}_{ext} extended with an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_0}$ which is initial on any universe \mathcal{U}_j , the type 2 is definable.*

PROOF. We have an algebra $\cdot \vdash \mathcal{X} : 2\text{-Alg}_{\mathcal{U}_0}$ such that for any j , there exists a term $\cdot \vdash h_j : \text{is-2-init}_{\mathcal{U}_j}(\mathcal{X})$. Since the requirement $j \geq 0$ always holds, Cor. 3.13 implies that for any j , we have a term $\cdot \vdash r_j : \text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X})$. This implies that the type 2 is definable. \square

3.2. Intensional case

3.3. The type 2

Although the rules for the type 2 as presented in section 3.1 are the natural ones to consider in the setting of homotopy type theory, they do not imply a strict universal property. For example, given a type $C : \mathcal{U}_i$ and elements $c_0, c_1 : C$, the function $\lambda x. 2\text{rec}_{\mathcal{U}_i}(C, c_0, c_1, x) : 2 \rightarrow C$ cannot, in general, be shown to be definitionally unique among the functions $f : 2 \rightarrow C$ with the property that $f(0) \equiv c_0 : C$ and $f(1) \equiv c_1 : C$.³ EdN:3
The best that one can do is to show that it is unique among all such maps up to a path, which itself is unique up to a higher path, which in turn is unique up to a yet higher path, etc. This sort of “homotopy” ω -universality, which apparently involves infinitely much data, can nonetheless be captured directly within the system of type theory (without resorting to coinduction) using ideas from higher category theory. To obtain a full characterization of the type 2 using this alternate universal condition, we relax the computation rules from section 3.1 to involve propositional, rather than definitional, equality:

— Propositional 2-computation rules.

$$\frac{x : 2 \vdash E(x) : \mathcal{U}_i \quad e_0 : E(0) \quad e_1 : E(1)}{\begin{cases} 2\text{ind-comp}0_{\mathcal{U}_i}(x.E, e_0, e_1) : 2\text{ind}_{\mathcal{U}_i}(0) = e_0, \\ 2\text{ind-comp}1_{\mathcal{U}_i}(x.E, e_0, e_1) : 2\text{ind}_{\mathcal{U}_i}(1) = e_1. \end{cases}}$$

— Simple propositional 2-computation rules.

$$\frac{C : \mathcal{U}_i \quad c_0 : C \quad c_1 : C \quad b : 2}{\begin{cases} 2\text{rec-comp}0_{\mathcal{U}_i}(C, c_0, c_1) : 2\text{rec}_{\mathcal{U}_i}(0) = c_0, \\ 2\text{rec-comp}1_{\mathcal{U}_i}(C, c_0, c_1) : 2\text{rec}_{\mathcal{U}_i}(1) = c_1. \end{cases}}$$

As discussed above, the uniqueness principles can still be shown to hold, albeit in a propositional form:

¹EDNOTE: Which says $\text{is-prop}(\text{is-contr}(A))$

²EDNOTE: Which says $\text{is-prop}(A) \simeq A \rightarrow \text{is-prop}(A)$

³EDNOTE: Do we need a reference for this?

— Propositional 2-uniqueness principle.

$$\frac{\begin{array}{c} b : 2 \quad x : 2 \vdash E(x) : \mathcal{U}_i \quad e_0 : E(0) \quad e_1 : E(1) \\ x : 2 \vdash f(x) : E(x) \quad \gamma_0 : f(0) = e_0 \quad \gamma_1 : f(1) = e_1 \\ x : 2 \vdash g(x) : E(x) \quad \delta_0 : g(0) = e_0 \quad \delta_1 : g(1) = e_1 \end{array}}{2\text{ind-uniq}_{\mathcal{U}_i}(x.E, e_0, e_1, x.f, \gamma_0, \gamma_1, x.g, \delta_0, \delta_1, b) : f(b) = g(b)}$$

— Simple propositional 2-uniqueness principle.

$$\frac{\begin{array}{c} b : 2 \quad C : \mathcal{U}_i \quad c_0 : C \quad c_1 : C \\ x : 2 \vdash f(x) : C \quad \gamma_0 : f(0) = c_0 \quad \gamma_1 : f(1) = c_1 \\ x : 2 \vdash g(x) : C \quad \delta_0 : g(0) = c_0 \quad \delta_1 : g(1) = c_1 \end{array}}{2\text{rec-uniq}_{\mathcal{U}_i}(C, c_0, c_1, x.f, \gamma_0, \gamma_1, x.g, \delta_0, \delta_1, b) : f(b) = g(b)}$$

The witness terms will be shortened to $2\text{ind-uniq}(b)$, $2\text{rec-uniq}(b)$ where appropriate. In showing the above laws, we proceed analogously to the extensional case: we use the induction principle with the type family $x \mapsto f(x) =_{E(x)} g(x)$ and for the cases $x := 0$, $x := 1$ we supply the paths $\gamma_0 \cdot \delta_0^{-1}$ and $\gamma_1 \cdot \delta_1^{-1}$ respectively. This gives us a pointwise propositional equality between f and g as desired. The simple uniqueness principle follows at once from the dependent one.

Unlike in the extensional setting, however, $2\text{ind-uniq}(b)$ will generally not be an identity path. The natural question to ask is how $2\text{ind-uniq}(-)$ behaves on the constructors 0, 1. Since $2\text{ind-uniq}(b)$ was constructed using the 2-induction principle, we invoke the corresponding (propositional) computation rules to get the following coherence rules:

— Propositional 2-coherence principles.

$$\frac{\begin{array}{c} x : 2 \vdash E(x) : \mathcal{U}_i \quad e_0 : E(0) \quad e_1 : E(1) \\ x : 2 \vdash f(x) : E(x) \quad \gamma_0 : f(0) = e_0 \quad \gamma_1 : f(1) = e_1 \\ x : 2 \vdash g(x) : E(x) \quad \delta_0 : g(0) = e_0 \quad \delta_1 : g(1) = e_1 \end{array}}{\begin{cases} 2\text{ind-coh0}_{\mathcal{U}_i}(x.E, e_0, e_1, x.f, \gamma_0, \gamma_1, x.g, \delta_0, \delta_1) : 2\text{ind-uniq}(0) = \gamma_0 \cdot \delta_0^{-1}, \\ 2\text{ind-coh1}_{\mathcal{U}_i}(x.E, e_0, e_1, x.f, \gamma_0, \gamma_1, x.g, \delta_0, \delta_1) : 2\text{ind-uniq}(1) = \gamma_1 \cdot \delta_1^{-1}. \end{cases}}$$

— Simple propositional 2-coherence principles.

$$\frac{\begin{array}{c} C : \mathcal{U}_i \quad c_0 : C \quad c_1 : C \\ x : 2 \vdash f(x) : C \quad \gamma_0 : f(0) = c_0 \quad \gamma_1 : f(1) = c_1 \\ x : 2 \vdash g(x) : C \quad \delta_0 : g(0) = c_0 \quad \delta_1 : g(1) = c_1 \end{array}}{\begin{cases} 2\text{rec-coh0}_{\mathcal{U}_i}(C, c_0, c_1, x.f, \gamma_0, \gamma_1, x.g, \delta_0, \delta_1) : 2\text{rec-uniq}(0) = \gamma_0 \cdot \delta_0^{-1}, \\ 2\text{rec-coh1}_{\mathcal{U}_i}(C, c_0, c_1, x.f, \gamma_0, \gamma_1, x.g, \delta_0, \delta_1) : 2\text{rec-uniq}(1) = \gamma_1 \cdot \delta_1^{-1}. \end{cases}}$$

This motivates the following definitions.

Definition 3.16. For $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$, $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$ and homomorphisms $\mu, \nu : 2\text{-Hom } \mathcal{X} \mathcal{Y}$, define the type of *2-cells* between μ and ν by

$$\begin{aligned} 2\text{-Cell } (C, c_0, c_1) (D, d_0, d_1) (f, \gamma_0, \gamma_1) (g, \delta_0, \delta_1) &:= \\ 2\text{-Fib-Hom } (C, c_0, c_1) (f \sim g, \gamma_0 \cdot \delta_0^{-1}, \gamma_1 \cdot \delta_1^{-1}) & \end{aligned}$$

Definition 3.17. For $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$, $\mathcal{Y} : 2\text{-Fib-Alg}_{\mathcal{U}_j}$ \mathcal{X} and fibered homomorphisms $\mu, \nu : 2\text{-Fib-Hom } \mathcal{X} \mathcal{Y}$, define the type of *fibered 2-cells* between μ and ν by

$$\begin{aligned} 2\text{-Fib-Cell } (C, c_0, c_1) (E, e_0, e_1) (f, \gamma_0, \gamma_1) (g, \delta_0, \delta_1) &:= \\ 2\text{-Fib-Hom } (C, c_0, c_1) (f \sim g, \gamma_0 \cdot \delta_0^{-1}, \gamma_1 \cdot \delta_1^{-1}) & \end{aligned}$$

For brevity, we will often leave out the first two arguments.

We also need to update some of our previous terminology: it is a misnomer to call an algebra \mathcal{X} *initial* if the type of homomorphisms from \mathcal{X} to any other algebra \mathcal{Y} is contractible, since a contractible type may contain more than one element. Instead, an algebra with this property will be called *homotopy-initial*; by Lem. ?? the contractibility requirement exactly captures the notion that there exists a homomorphism which is unique up to a path, which itself is unique up to a higher path, and so on.

Definition 3.18. An algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ is *homotopy-initial* on a universe \mathcal{U}_j if for any algebra $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$, the type of 2-homomorphisms between \mathcal{X} and \mathcal{Y} is contractible:

$$\text{is-2-hinit}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:2\text{-Alg}_{\mathcal{U}_j})} \text{is-contr}(2\text{-Hom } \mathcal{X} \ \mathcal{Y})$$

In certain respects, algebras and algebra homomorphisms behave much like objects and morphisms in a category:

Definition 3.19. For any $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ there is a designated *identity* homomorphism from \mathcal{X} to itself, defined by

$$2\text{-Id-Hom } (C, c_0, c_1) := (\text{id}_C, \text{refl}(c_0), \text{refl}(c_1))$$

We often denote this homomorphism by $1_{\mathcal{X}}$.

Definition 3.20. For algebras $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$, $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$, $\mathcal{Z} : 2\text{-Alg}_{\mathcal{U}_k}$ and homomorphisms $\mu : 2\text{-Hom } \mathcal{X} \ \mathcal{Y}$, $\nu : 2\text{-Hom } \mathcal{Y} \ \mathcal{Z}$, the *composition* of μ and ν is a homomorphism from \mathcal{X} to \mathcal{Z} defined by

$$2\text{-Comp-Hom } (C, c_0, c_1) \ (D, d_0, d_1) \ (E, e_0, e_1) \ (f, \gamma_0, \gamma_1) \ (g, \delta_0, \delta_1) := \\ (g \circ f, g(\gamma_0) \cdot \delta_0, g(\gamma_1) \cdot \delta_1)$$

We often leave out the first three arguments and denote the composition by $\nu \circ \mu$.

Definition 3.21. For $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$, $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$ we define the type of *isomorphisms* between \mathcal{X} and \mathcal{Y} as

$$2\text{-Alg-Iso } \mathcal{X} \ \mathcal{Y} := \Sigma_{(\rho:2\text{-Hom } \mathcal{X} \ \mathcal{Y})} \left(\Sigma_{(\mu:2\text{-Hom } \mathcal{Y} \ \mathcal{X})} \mu \circ \rho = 1_{\mathcal{X}} \right) \times \left(\Sigma_{(\nu:2\text{-Hom } \mathcal{Y} \ \mathcal{X})} \rho \circ \nu = 1_{\mathcal{Y}} \right)$$

LEMMA 3.22. For $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$, $\mathcal{Y} : 2\text{-Fib-Alg}_{\mathcal{U}_j}$ \mathcal{X} and $\mu, \nu : 2\text{-Fib-Hom } \mathcal{X} \ \mathcal{Y}$, the *path space* $\mu = \nu$ is equivalent to the space of fibered 2-cells between μ and ν :

$$\mu = \nu \simeq 2\text{-Fib-Cell } \mu \ \nu$$

PROOF. Let algebras $(C, c_0, c_1) : 2\text{-Alg}_{\mathcal{U}_i}$, $(E, e_0, e_1) : 2\text{-Fib-Alg}_{\mathcal{U}_j}$ (C, c_0, c_1) and homomorphisms $(f, \gamma_0, \gamma_1), (g, \delta_0, \delta_1) : 2\text{-Fib-Hom } (C, c_0, c_1) \ (E, e_0, e_1)$ be given. We have

$$\begin{aligned} (f, \gamma_0, \gamma_1) &= (g, \delta_0, \delta_1) && \simeq \\ \Sigma_{\alpha:f=g} \left((\gamma_0, \gamma_1) &= \text{tr}_{h \mapsto h(c_0)=d_0 \times h(c_1)=d_1}^{-1} (\alpha) \ (\delta_0, \delta_1) \right) && \simeq \\ \Sigma_{\alpha:f=g} \left((\gamma_0, \gamma_1) &= (= \text{Eq}^{\Pi}(\alpha, c_0) \cdot \delta_0, = \text{Eq}^{\Pi}(\alpha, c_1) \cdot \delta_1) \right) && \simeq \\ \Sigma_{\alpha:f=g} \left(\gamma_0 &= = \text{Eq}^{\Pi}(\alpha, c_0) \cdot \delta_0 \right) \times \left(\gamma_1 = = \text{Eq}^{\Pi}(\alpha, c_1) \cdot \delta_1 \right) && \simeq \\ \Sigma_{\alpha:f \sim g} \left(\gamma_0 &= \alpha(c_0) \cdot \delta_0 \right) \times \left(\gamma_1 = \alpha(c_1) \cdot \delta_1 \right) && \simeq \\ \Sigma_{\alpha:f \sim g} \left(\alpha(c_0) &= \gamma_0 \cdot \delta_0^{-1} \right) \times \left(\alpha(c_1) = \gamma_1 \cdot \delta_1^{-1} \right) && \equiv \\ 2\text{-Fib-Cell } (f, \gamma_0, \gamma_1) &(g, \delta_0, \delta_1) \end{aligned}$$

□

COROLLARY 3.23. *For $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$, $\mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_j}$ and $\mu, \nu : 2\text{-Hom } \mathcal{X} \mathcal{Y}$, the path space $\mu = \nu$ is equivalent to the space of 2-cells between μ and ν :*

$$\mu = \nu \simeq 2\text{-Cell } \mu \nu$$

LEMMA 3.24. *For $\mathcal{X}, \mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_i}$, the path space $\mathcal{X} = \mathcal{Y}$ is equivalent to the space of isomorphisms between \mathcal{X} and \mathcal{Y} :*

$$\mathcal{X} = \mathcal{Y} \simeq 2\text{-Alg-Iso } \mathcal{X} \mathcal{Y}$$

PROOF. Let algebras $(C, c_0, c_1), (D, d_0, d_1) : 2\text{-Alg}_{\mathcal{U}_i}$ be given. We have

$$\begin{aligned} 2\text{-Alg-Iso } (C, c_0, c_1) (D, d_0, d_1) &\equiv \\ \Sigma_{\rho: (\Sigma_{f: C \rightarrow D} f(c_0)=d_0 \times f(c_1)=d_1)} \left(\Sigma_{\mu: (\Sigma_{g: D \rightarrow C} g(d_0)=c_0 \times g(d_1)=c_1)} \mu \circ \rho = 1_{(C, c_0, c_1)} \right) \times \\ &\quad \left(\Sigma_{\nu: (\Sigma_{h: D \rightarrow C} h(d_0)=c_0 \times g(d_1)=c_1)} \rho \circ \nu = 1_{(D, d_0, d_1)} \right) \simeq \\ \Sigma_{f: C \rightarrow D} \Sigma_{\epsilon_0: f(c_0)=d_0} \Sigma_{\epsilon_1: f(c_1)=d_1} \left(\Sigma_{g: D \rightarrow C} \Sigma_{\gamma_0: g(d_0)=c_0} \Sigma_{\gamma_1: g(d_1)=c_1} P_{f, \epsilon_0, \epsilon_1, g, \gamma_0, \gamma_1} \right) \times \\ &\quad \left(\Sigma_{h: D \rightarrow C} \Sigma_{\delta_0: h(d_0)=c_0} \Sigma_{\delta_1: h(d_1)=c_1} Q_{f, \epsilon_0, \epsilon_1, h, \delta_0, \delta_1} \right) \end{aligned}$$

where

$$\begin{aligned} P_{f, \epsilon_0, \epsilon_1, g, \gamma_0, \gamma_1} &:= (g \circ f, \text{ap}_g(\epsilon_0) \cdot \gamma_0, \text{ap}_g(\epsilon_1) \cdot \gamma_1) = (\text{id}_C, \text{refl}_{c_0}, \text{refl}_{c_1}) \\ Q_{f, \epsilon_0, \epsilon_1, h, \delta_0, \delta_1} &:= (f \circ h, \text{ap}_f(\delta_0) \cdot \epsilon_0, \text{ap}_f(\delta_1) \cdot \epsilon_1) = (\text{id}_D, \text{refl}_{d_0}, \text{refl}_{d_1}) \end{aligned}$$

Now we have

$$\begin{aligned} P_{f, \epsilon_0, \epsilon_1, g, \gamma_0, \gamma_1} &\equiv \\ (g \circ f, \text{ap}_g(\epsilon_0) \cdot \gamma_0, \text{ap}_g(\epsilon_1) \cdot \gamma_1) &\simeq \\ \Sigma_{\alpha: g \circ f = \text{id}_C} (\text{ap}_g(\epsilon_0) \cdot \gamma_0, \text{ap}_g(\epsilon_1) \cdot \gamma_1) &= \text{tr}_{i \mapsto i(c_0)=c_0 \times i(c_1)=c_1}^{-1}(\alpha) (\text{refl}_{c_0}, \text{refl}_{c_1}) \simeq \\ \Sigma_{\alpha: g \circ f = \text{id}_C} (\text{ap}_g(\epsilon_0) \cdot \gamma_0, \text{ap}_g(\epsilon_1) \cdot \gamma_1) &= ({}^{\text{Eq}}\Pi(\alpha, c_0) \cdot \text{refl}_{c_0}, {}^{\text{Eq}}\Pi(\alpha, c_1) \cdot \text{refl}_{c_1}) \simeq \\ \Sigma_{\alpha: g \circ f = \text{id}_C} (\text{ap}_g(\epsilon_0) \cdot \gamma_0 = {}^{\text{Eq}}\Pi(\alpha, c_0) \cdot \text{refl}_{c_0}) &\times (\text{ap}_g(\epsilon_1) \cdot \gamma_1 = {}^{\text{Eq}}\Pi(\alpha, c_1) \cdot \text{refl}_{c_1}) \simeq \\ \Sigma_{\alpha: g \circ f \sim \text{id}_C} (\text{ap}_g(\epsilon_0) \cdot \gamma_0 = \alpha(c_0) \cdot \text{refl}_{c_0}) &\times (\text{ap}_g(\epsilon_1) \cdot \gamma_1 = \alpha(c_1) \cdot \text{refl}_{c_1}) \simeq \\ \Sigma_{\alpha: g \circ f \sim \text{id}_C} (\alpha(c_0) = \text{ap}_g(\epsilon_0) \cdot \gamma_0) &\times (\alpha(c_1) = \text{ap}_g(\epsilon_1) \cdot \gamma_1) \end{aligned}$$

and analogously

$$Q_{f, \epsilon_0, \epsilon_1, h, \delta_0, \delta_1} \simeq \Sigma_{\beta: f \circ h \sim \text{id}_D} (\beta(d_0) = \text{ap}_f(\delta_0) \cdot \epsilon_0) \times (\beta(d_1) = \text{ap}_f(\delta_1) \cdot \epsilon_1)$$

Thus we can express $2\text{-Alg-Iso } (C, c_0, c_1) (D, d_0, d_1)$ equivalently as the type

$$\begin{aligned} \Sigma_{f: C \rightarrow D} \Sigma_{\epsilon_0: f(c_0)=d_0} \Sigma_{\epsilon_1: f(c_1)=d_1} \Sigma_{g: D \rightarrow C} \Sigma_{\alpha: g \circ f \sim \text{id}_C} \Sigma_{h: D \rightarrow C} \Sigma_{\beta: f \circ h \sim \text{id}_D} \\ (\Sigma_{\gamma_0: g(d_0)=c_0} \alpha(c_0) = \text{ap}_g(\epsilon_0) \cdot \gamma_0) \times (\Sigma_{\gamma_1: g(d_1)=c_1} \alpha(c_1) = \text{ap}_g(\epsilon_1) \cdot \gamma_1) \times \\ (\Sigma_{\delta_0: h(d_0)=c_0} \beta(d_0) = \text{ap}_f(\delta_0) \cdot \epsilon_0) \times (\Sigma_{\delta_1: h(d_1)=c_1} \beta(d_1) = \text{ap}_f(\delta_1) \cdot \epsilon_1) \end{aligned}$$

Now we have

$$\Sigma_{\gamma_0: g(d_0)=c_0} \left(\alpha(c_0) = \mathsf{ap}_g(\epsilon_0) \cdot \gamma_0 \right) \simeq \Sigma_{\gamma_0: g(d_0)=c_0} \left(\gamma_0 = \mathsf{ap}_g(\epsilon_0)^{-1} \cdot \alpha(c_0) \right) \simeq 1$$

by Lem. ??⁴. Similarly, $\Sigma_{\gamma_1: g(d_1)=c_1} \left(\alpha(c_1) = \mathsf{ap}_g(\epsilon_1) \cdot \gamma_1 \right)$ is equivalent to 1. We also have EdN:4

$$\Sigma_{\delta_0: h(d_0)=c_0} \left(\beta(d_0) = \mathsf{ap}_f(\delta_0) \cdot \epsilon_0 \right) \simeq \Sigma_{\delta_0: h(d_0)=c_0} \left(\mathsf{ap}_f(\delta_0) = \beta(d_0) \cdot \epsilon_0^{-1} \right) \simeq 1$$

by Lem. ??⁵, ??⁶, and the fact that g, α, h, β make f into an equivalence. Similarly, EdN:5
 $\Sigma_{\delta_1: h(d_1)=c_1} \left(\beta(d_1) = \mathsf{ap}_f(\delta_1) \cdot \epsilon_1 \right)$ is equivalent to 1. Thus, we have EdN:6

$$\begin{aligned} & 2\text{-Alg-Iso } (C, c_0, c_1) (D, d_0, d_1) \simeq \\ & \Sigma_{f: C \rightarrow D} \Sigma_{g: D \rightarrow C} \Sigma_{\alpha: g \circ f \sim \text{id}_C} \Sigma_{h: D \rightarrow C} \Sigma_{\beta: f \circ h \sim \text{id}_D} \left(f(c_0) = d_0 \right) \times \left(f(c_1) = d_1 \right) \simeq \\ & \Sigma_{f: C \rightarrow D} \text{is-equiv}(f) \times \left(f(c_0) = d_0 \right) \times \left(f(c_1) = d_1 \right) \simeq \\ & \Sigma_{p: C \simeq D} \left(\text{fst}(p) \ c_0 = d_0 \right) \times \left(\text{fst}(p) \ c_1 = d_1 \right) \simeq \\ & \Sigma_{p: C \simeq D} \left(\text{fst}(p) \ c_0, \text{fst}(p) \ c_1 \right) = (d_0, d_1) \simeq \\ & \Sigma_{p: C = D} \left(\text{fst}(\text{Eq}^\sim(p)) \ c_0, \text{fst}(\text{Eq}^\sim(p)) \ c_1 \right) = (d_0, d_1) \simeq \\ & \Sigma_{p: C = D} \left(\text{tr}_{X \mapsto X \times X}(p) \ (c_0, c_1) = (d_0, d_1) \right) \simeq \\ & (C, c_0, c_1) = (D, d_0, d_1) \end{aligned}$$

□

As desired, the analogues of the lemmas from section 3.1 still hold in the setting of homotopy type theory:

LEMMA 3.25. *In \mathcal{H} , if an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ satisfies the induction principle on the universe \mathcal{U}_j , it also satisfies the induction uniqueness principle on \mathcal{U}_j . In other words, we have*

$$\text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X}) \rightarrow \text{has-2-ind-uniq}_{\mathcal{U}_j}(\mathcal{X})$$

PROOF. Let an algebra $(C, c_0, c_1) : 2\text{-Alg}_{\mathcal{U}_i}$ be given. To prove the induction uniqueness principle, take any algebra $(E, e_0, e_1) : 2\text{-Fib-Alg}_{\mathcal{U}_j}(C, c_0, c_1)$ and homomorphisms $(f, \gamma_0, \gamma_1), (g, \delta_0, \delta_1) : 2\text{-Fib-Hom}(C, c_0, c_1)(E, e_0, e_1)$. By Lem. 3.22, to show $(f, \gamma_0, \gamma_1) = (g, \delta_0, \delta_1)$ it suffices to exhibit a fibered 2-cell between (f, γ_0, γ_1) and (g, δ_0, δ_1) . For this we use the induction principle with the fibered algebra $(f \sim g, \gamma_0 \cdot \delta_0^{-1}, \gamma_1 \cdot \delta_1^{-1})$ and we are done. □

COROLLARY 3.26. *In \mathcal{H} , if an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ satisfies the induction principle on the universe \mathcal{U}_j , it is homotopy-initial on \mathcal{U}_j . In other words, we have*

$$\text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X}) \rightarrow \text{is-2-hinit}_{\mathcal{U}_j}(\mathcal{X})$$

⁴EdNOTE: Which says $\text{is-contr}(\Sigma_{x:A} x = y)$

⁵EdNOTE: Which says $\text{is-contr}(\Sigma_{x:A} f(x) =_B y)$ if $f : A \rightarrow B$ is an equivalence

⁶EdNOTE: Which says $\text{ap}_f : x =_A y \rightarrow f(x) =_B f(y)$ is equivalence if $f : A \rightarrow B$ is

LEMMA 3.27. *In \mathcal{H} , if an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_j and $j \geq i$, then it satisfies the induction principle on \mathcal{U}_j . In other words, we have*

$$\text{has-2-rec}_{\mathcal{U}_j}(\mathcal{X}) \times \text{has-2-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) \rightarrow \text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X})$$

provided $j \geq i$.

PROOF. Let algebras $(C, c_0, c_1) : 2\text{-Alg}_{\mathcal{U}_i}$ and $(E, e_0, e_1) : 2\text{-Fib-Alg}_{\mathcal{U}_j}$ (C, c_0, c_1) be given. We use the recursion principle with the algebra $(\Sigma_{x:C} E(x), (c_0, e_0), (c_1, e_1))$. We note that the carrier type belongs to \mathcal{U}_j as $i \leq j$. This gives us a homomorphism (u, θ_0, θ_1) , where $u : C \rightarrow \Sigma_{x:C} E(x)$, $\theta_0 : u(c_0) = (c_0, e_0)$, and $\theta_1 : u(c_1) = (c_1, e_1)$. We can now form two homomorphisms

$$\left(\text{fst} \circ u, \text{fst}(=\text{Eq}^\Sigma(\theta_0)), \text{fst}(=\text{Eq}^\Sigma(\theta_1)) \right), \left(\text{id}_C, \text{refl}_{c_0}, \text{refl}_{c_1} \right) : 2\text{-Hom}(C, c_0, c_1)(C, c_0, c_1)$$

The recursion uniqueness principle tells us that these homomorphisms are equal. By Cor. 3.23 this means there exists a 2-cell (α, η_0, η_1) between them, i.e., we have

$$\begin{aligned} \alpha : \text{fst} \circ u &\sim \text{id}_C \\ \eta_0 : \alpha(c_0) &= \text{fst}(=\text{Eq}^\Sigma(\theta_0)) \cdot \text{refl}_{c_0} \\ \eta_1 : \alpha(c_1) &= \text{fst}(=\text{Eq}^\Sigma(\theta_1)) \cdot \text{refl}_{c_1} \end{aligned}$$

We can thus define the desired fibered homomorphism as

$$(x \mapsto \text{tr}_E(\alpha(x)) \text{ snd}(u(x)), \phi_0, \phi_1) : 2\text{-Fib-Hom}(C, c_0, c_1)(E, e_0, e_1)$$

where ϕ_0 is the path

$$\begin{array}{c} \text{tr}_E(\alpha(c_0)) \text{ snd}(u(c_0)) \\ \downarrow \text{via } \eta_0 \\ \text{tr}_E(\text{fst}(=\text{Eq}^\Sigma(\theta_0)) \cdot \text{refl}_{c_0}) \text{ snd}(u(c_0)) \\ \downarrow \\ \text{tr}_E(\text{fst}(=\text{Eq}^\Sigma(\theta_0))) \text{ snd}(u(c_0)) \\ \downarrow \text{snd}(=\text{Eq}^\Sigma(\theta_0)) \\ e_0 \end{array}$$

and ϕ_1 is defined analogously. \square

COROLLARY 3.28. *In \mathcal{H} , the following conditions on an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_i}$ are equivalent:*

- (1) \mathcal{X} satisfies the induction principle on the universe \mathcal{U}_j
- (2) \mathcal{X} satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_j
- (3) \mathcal{X} is homotopy-initial on the universe \mathcal{U}_j

for $j \geq i$. In other words, we have

$$\text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X}) \simeq \text{has-2-rec}_{\mathcal{U}_j}(\mathcal{X}) \times \text{has-2-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) \simeq \text{is-2-hinit}_{\mathcal{U}_j}(\mathcal{X})$$

provided $j \geq i$. Furthermore, all 3 conditions are mere propositions.

PROOF. Conditions (1) and (3) are mere propositions by Lem. ?? (for the latter), Lem. ??, 3.25 (for the former), and the fact that a family of mere propositions is itself a mere proposition. \square

Furthermore, we have the following corollary which does *not* have an analogue in the extensional case:

COROLLARY 3.29. *In \mathcal{H} , any two algebras $\mathcal{X}, \mathcal{Y} : 2\text{-Alg}_{\mathcal{U}_i}$ which are homotopy-initial on \mathcal{U}_i are equal:*

$$\text{is-2-hinit}_{\mathcal{U}_i}(\mathcal{X}) \rightarrow \text{is-2-hinit}_{\mathcal{U}_i}(\mathcal{Y}) \rightarrow \mathcal{X} = \mathcal{Y}$$

PROOF. By Lem. 3.24 it suffices to construct an isomorphism between \mathcal{X} and \mathcal{Y} . Since \mathcal{X} and \mathcal{Y} are both homotopy-initial on \mathcal{U}_i , there exist homomorphisms $\mu : 2\text{-Hom } \mathcal{X} \mathcal{Y}$ and $\nu : 2\text{-Hom } \mathcal{Y} \mathcal{X}$. Again by homotopy-initiality, we have $\nu \circ \mu = 1_{\mathcal{X}}$ and $\mu \circ \nu = 1_{\mathcal{Y}}$, which gives us the desired isomorphism. \square

We can thus characterize the type 2 using the universal property of homotopy-initiality as follows.

COROLLARY 3.30. *In \mathcal{H} extended with the type 2, the algebra $(2, 0, 1) : 2\text{-Alg}_{\mathcal{U}_0}$ is homotopy-initial on any universe \mathcal{U}_j .*

COROLLARY 3.31. *In \mathcal{H} extended with an algebra $\mathcal{X} : 2\text{-Alg}_{\mathcal{U}_0}$ which is homotopy-initial on any universe \mathcal{U}_j , the type 2 with propositional computation rules is definable.*

PROOF. We have an algebra $\cdot \vdash \mathcal{X} : 2\text{-Alg}_{\mathcal{U}_0}$ such that for any j , there exists a term $\cdot \vdash h_j : \text{is-2-hinit}_{\mathcal{U}_j}(\mathcal{X})$. Since the requirement $j \geq 0$ always holds, Cor. 3.28 implies that for any j , we have a term $\cdot \vdash r_j : \text{has-2-ind}_{\mathcal{U}_j}(\mathcal{X})$. This implies that the type 2 with propositional computation rules is definable. \square

Corollaries 3.31 and 3.30 are the analogue in Homotopy Type Theory of the characterization of 2 as a strict coproduct $1 + 1$ in extensional type theory. It makes precise the rough idea that, in intensional type theory, 2 is a kind of homotopy coproduct or weak ω -coproduct in the weak ω -category $\mathcal{C}(\mathcal{H})$ of types, terms, identity terms, higher identity terms, \dots . It is worth emphasizing that homotopy-initiality is a purely type-theoretic notion; despite having an obvious semantic interpretation, it is formulated in terms of inhabitation of specific, definable types. Indeed, Corollary 3.28 and its proof have been completely formalized in the Coq proof assistant [Awodey et al. 2011].

4. W-TYPES

4.1. Extensional case

We recall the rules for W-types from [Martin-Löf 1984]; to state them more conveniently, we sometimes write W instead of $W_{x:A}^{\mathcal{U}_i} B(x)$; $\text{sup}(a, t)$ instead of $\text{sup}_{\mathcal{U}_i}^{A, x.B}(a, t)$; and $\text{wind}(m)$ instead of $\text{wind}_{\mathcal{U}_j}^{A, x.B}(w.E, a.t.s.e, m)$.

— W-formation rule.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i}{W_{x:A}^{\mathcal{U}_i} B(x)}$$

— W-introduction rule.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad a : A \quad t : B(a) \rightarrow W}{\text{sup}_{\mathcal{U}_i}^{A, x.B}(a, t) : W}$$

— W-elimination rule.

$$\frac{w : W \vdash E(w) : \mathcal{U}_j \quad \begin{array}{c} A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad m : W \\ x : A, p : B(x) \rightarrow W, r : \prod_{b:B(x)} E(p\ b) \vdash e(x, p, r) : E(\sup(x, p)) \end{array}}{\text{wind}_{\mathcal{U}_j}^{A, x.B}(w.E, x.p.r.e, m) : E(m)}$$

— W-computation rule.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad a : A \quad t : B(a) \rightarrow W \quad w : W \vdash E(w) : \mathcal{U}_j \quad x : A, p : B(x) \rightarrow W, r : \prod_{b:B(x)} E(p\ b) \vdash e(x, p, r) : E(\sup(x, p))}{\text{wind}(\sup(a, t)) \equiv e(a, t, \lambda_{b:B(a)} \text{wind}(t\ b)) : E(\sup(a, t))}$$

W-types can be seen informally as the free algebras for signatures with operations of possibly infinite arity, but no equations. Indeed, the premises of the formation rule above can be thought of as specifying a signature that has the elements of A as operations and in which the arity of $a : A$ is the cardinality of the type $B(a)$. Then, the introduction rule specifies the canonical way of forming an element of the free algebra, and the elimination rule can be seen as the propositions-as-types translation of the appropriate induction principle.

As before, the above rules imply a non-dependent version of elimination and the corresponding computation rule, where we write $\text{wrec}(m)$ instead of $\text{wrec}_{\mathcal{U}_j}^{A, x.B}(C, x.r.c, m)$ where appropriate.

— Simple W-elimination rule.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad m : W \quad C : \mathcal{U}_j \quad x : A, r : B(x) \rightarrow C \vdash c(x, r) : C}{\text{wrec}_{\mathcal{U}_j}^{A, x.B}(C, x.r.c, m) : C}$$

— Simple W-computation rule.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad a : A \quad t : B(a) \rightarrow W \quad C : \mathcal{U}_j \quad x : A, r : B(x) \rightarrow C \vdash c(x, r) : C}{\text{wrec}(\sup(a, t)) \equiv c(a, \lambda_{b:B(a)} \text{wrec}(t\ b)) : C}$$

The induction principle also implies the following uniqueness principles, which state that any two functions out of W which satisfy the same recurrence are pointwise equal:

— W-uniqueness principle.

$$\frac{\begin{array}{c} A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad m : W \\ w : W \vdash E(w) : \mathcal{U}_j \quad x : A, p : B(x) \rightarrow W, r : \prod_{b:B(x)} E(p\ b) \vdash e(x, p, r) : E(\sup(x, p)) \\ w : W \vdash f(w) : E(w) \quad x : A, p : B(x) \rightarrow W \vdash f(\sup(x, p)) \equiv e(x, p, \lambda_{b:B(x)} f(p\ b)) \\ w : W \vdash g(w) : E(w) \quad x : A, p : B(x) \rightarrow W \vdash g(\sup(x, p)) \equiv e(x, p, \lambda_{b:B(x)} g(p\ b)) \end{array}}{f(m) \equiv g(m) : E(m)}$$

— Simple W-uniqueness principle.

$$\frac{\begin{array}{c} A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad m : W \quad C : \mathcal{U}_j \quad x : A, r : B(x) \rightarrow C \vdash c(x, r) : C \\ w : W \vdash f(w) : C \quad x : A, p : B(x) \rightarrow W \vdash f(\sup(x, p)) \equiv c(x, \lambda_{b:B(x)} f(p\ b)) \\ w : W \vdash g(w) : C \quad x : A, p : B(x) \rightarrow W \vdash g(\sup(x, p)) \equiv c(x, \lambda_{b:B(x)} g(p\ b)) \end{array}}{f(m) \equiv g(m) : C}$$

As before, we can prove the dependent uniqueness principle by using the induction principle with the type family $w \mapsto f(w) =_{E(w)} g(w)$. For this we need to show that for any x, p we have $f(\sup(x, p)) = g(\sup(x, p))$ under the induction hypothesis $\Pi_{b:B(x)} f(p \ b) = g(p \ b)$. Using this hypothesis with function extensionality we get $\lambda_{b:B(x)} f(p \ b) = \lambda_{b:B(x)} g(p \ b)$. Together with the premises of the uniqueness rule this gives us $f(\sup(a, t)) = g(\sup(a, t))$ as desired. The induction principle thus gives us pointwise propositional equality between f and g and we appeal to the identity reflection rule to finish the proof. The simple uniqueness principle again follows from the dependent one.

We can now formulate the notions of algebras, homomorphisms, etc. accordingly:

Definition 4.1. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i$, define the type of *W-algebras* on a universe \mathcal{U}_j as

$$\mathbf{W-Alg}_{\mathcal{U}_j}(A, B) := \Sigma_{C:\mathcal{U}_j} \Pi_{a:A} (B(a) \rightarrow C) \rightarrow C$$

Definition 4.2. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i$, define the type of *fibred W-algebras* on a universe \mathcal{U}_k over $\mathcal{X} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B)$ by

$$\mathbf{W-Fib-Alg}_{\mathcal{U}_k}(A, B) (C, c) := \Sigma_{E:C \rightarrow \mathcal{U}_k} \Pi_{a:A} \Pi_{t:B(a) \rightarrow C} (\Pi_{b:B(a)} E(t \ b)) \rightarrow E(c(a, t))$$

Definition 4.3. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i, \mathcal{X} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B), \mathcal{Y} : \mathbf{W-Alg}_{\mathcal{U}_k}(A, B)$, define the type of *W-homomorphisms* from \mathcal{X} to \mathcal{Y} by

$$\mathbf{W-Hom} (C, c) (D, d) := \Sigma_{f:C \rightarrow D} \Pi_{a:A} \Pi_{t:B(a) \rightarrow C} f(c(a, t)) = d(a, \lambda_{b:B(a)} f(t \ b))$$

Definition 4.4. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i, \mathcal{X} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B), \mathcal{Y} : \mathbf{W-Fib-Alg}_{\mathcal{U}_k}(A, B)$, define the type of *fibred W-homomorphisms* from \mathcal{X} to \mathcal{Y} by

$$\mathbf{W-Fib-Hom} (C, c) (E, e) := \Sigma_{(f:\Pi_{x:C} E(x))} \Pi_{a:A} \Pi_{t:B(a) \rightarrow C} f(c(a, t)) = e(a, t, \lambda_{b:B(a)} f(t \ b))$$

Definition 4.5. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i$, an algebra $\mathcal{X} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B)$ *satisfies the recursion principle* on a universe \mathcal{U}_k if for any algebra $\mathcal{Y} : \mathbf{W-Alg}_{\mathcal{U}_k}(A, B)$ there exists a W-homomorphism between \mathcal{X} and \mathcal{Y} :

$$\mathbf{has-W-rec}_{\mathcal{U}_k}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbf{W-Alg}_{\mathcal{U}_k}(A, B))} \mathbf{W-Hom} \ \mathcal{X} \ \mathcal{Y}$$

Definition 4.6. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i$, an algebra $\mathcal{X} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B)$ *satisfies the induction principle* on a universe \mathcal{U}_k if for any fibred algebra $\mathcal{Y} : \mathbf{W-Fib-Alg}_{\mathcal{U}_k}(A, B)$ \mathcal{X} there exists a fibred W-homomorphism between \mathcal{X} and \mathcal{Y} :

$$\mathbf{has-W-ind}_{\mathcal{U}_k}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbf{W-Fib-Alg}_{\mathcal{U}_k}(A, B))} \mathbf{W-Fib-Hom} \ \mathcal{X} \ \mathcal{Y}$$

Definition 4.7. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i$, an algebra $\mathcal{X} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B)$ *satisfies the recursion uniqueness principle* on a universe \mathcal{U}_k if for any algebra $\mathcal{Y} : \mathbf{W-Alg}_{\mathcal{U}_k}(A, B)$ any two W-homomorphisms between \mathcal{X} and \mathcal{Y} are equal:

$$\mathbf{has-W-rec-uniq}_{\mathcal{U}_k}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbf{W-Alg}_{\mathcal{U}_k}(A, B))} \mathbf{is-prop}(\mathbf{W-Hom} \ \mathcal{X} \ \mathcal{Y})$$

Definition 4.8. For $A : \mathcal{U}_i$ and $B : A \rightarrow \mathcal{U}_i$, an algebra $\mathcal{X} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B)$ *satisfies the induction uniqueness principle* on a universe \mathcal{U}_k if for any fibred algebra $\mathcal{Y} : \mathbf{W-Fib-Alg}_{\mathcal{U}_k}(A, B)$ \mathcal{X} any two fibred W-homomorphisms between \mathcal{X} and \mathcal{Y} are equal:

$$\mathbf{has-W-ind-uniq}_{\mathcal{U}_k}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbf{W-Fib-Alg}_{\mathcal{U}_k}(A, B))} \mathbf{is-prop}(\mathbf{W-Fib-Hom} \ \mathcal{X} \ \mathcal{Y})$$

Definition 4.9. For $A : \mathcal{U}_i$ and $B : A \rightarrow \mathcal{U}_i$, an algebra $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ is *initial* on a universe \mathcal{U}_k if for any algebra $\mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_k}(A, B)$ there exists a unique \mathbf{W} -homomorphism between \mathcal{X} and \mathcal{Y} :

$$\text{is-W-init}_{\mathcal{U}_k}(\mathcal{X}) := \Pi_{(\mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_k}(A, B))} \text{is-contr}(\mathbf{W}\text{-Hom } \mathcal{X} \mathcal{Y})$$

As before, the induction principle implies induction uniqueness:

LEMMA 4.10. *In \mathcal{H}_{ext} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ satisfies the induction principle on the universe \mathcal{U}_k , it also satisfies the induction uniqueness principle on \mathcal{U}_k . In other words, we have*

$$\text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X}) \rightarrow \text{has-W-ind-uniq}_{\mathcal{U}_k}(\mathcal{X})$$

PROOF. Let an algebra $(C, c) : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ be given. To prove the induction uniqueness principle, take any algebra $(E, e) : \mathbf{W}\text{-Fib}\text{-Alg}_{\mathcal{U}_k}(C, c)$ and homomorphisms $(f, \gamma), (g, \delta) : \mathbf{W}\text{-Fib}\text{-Hom } (C, c) (E, e)$. Because of UIP, showing $(f, \gamma) = (g, \delta)$ is equivalent to showing $f = g$. For the latter, we use the induction principle with the fibered algebra $(x \mapsto f(x) = g(x); a, t, s \mapsto \text{refl}(f(c(a, t))))$. This is indeed well-typed since $\gamma(a, t)$ gives us $f(c(a, t)) = e(a, t, \lambda_{b:B(a)} f(t b))$; $\delta(a, t)$ gives us $g(c(a, t)) = e(a, t, \lambda_{b:B(a)} g(t b))$; and s together with function extensionality gives us $\lambda_{b:B(a)} f(t b) = \lambda_{b:B(a)} g(t b)$.

The first component of the resulting homomorphism together with the function extensionality principle then give us $f = g$. \square

COROLLARY 4.11. *In \mathcal{H}_{ext} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ satisfies the induction principle on the universe \mathcal{U}_k , it is initial on \mathcal{U}_k . In other words, we have*

$$\text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X}) \rightarrow \text{is-W-init}_{\mathcal{U}_k}(\mathcal{X})$$

LEMMA 4.12. *In \mathcal{H}_{ext} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_k and $k \geq j$, then it satisfies the induction principle on \mathcal{U}_k . In other words, we have*

$$\text{has-W-rec}_{\mathcal{U}_k}(\mathcal{X}) \times \text{has-W-rec-uniq}_{\mathcal{U}_k}(\mathcal{X}) \rightarrow \text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X})$$

provided $k \geq j$.

PROOF. Let algebras $(C, c) : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ and $(E, e) : \mathbf{W}\text{-Fib}\text{-Alg}_{\mathcal{U}_k}(C, c)$ be given. We use the recursion principle with the algebra $(\Sigma_{x:C} E(x); a, s \mapsto d(a, s))$ where

$$d(a, s) := \left(c(a, \lambda_{b:B(a)} \text{fst}(s b)), e(a, \lambda_{b:B(a)} \text{fst}(s b), \lambda_{b:B(a)} \text{snd}(s b)) \right)$$

We note that the carrier type belongs to \mathcal{U}_k as $j \leq k$. This gives us a homomorphism (u, θ) , where $u : C \rightarrow \Sigma_{x:C} E(x)$ and $\theta : \Pi_a \Pi_t u(c(a, t)) = d(a, \lambda_{b:B(a)} u(t b))$. We can now form two homomorphisms

$$(\text{fst} \circ u; a, t \mapsto \text{refl}_{c(a, \lambda_{b:B(a)} u(t b))}), (\text{id}_C; a, t \mapsto \text{refl}_{c(a, t)}) : \mathbf{W}\text{-Hom } (C, c) (C, c)$$

The first one type-checks due to θ . The recursion uniqueness principle tells us that these homomorphisms are equal. Thus, $\text{fst} \circ u = \text{id}_C$ and in particular $\text{fst} \circ u \equiv \text{id}_C$.

We can thus define the desired fibered homomorphism as

$$(\text{snd} \circ u; a, t \mapsto \text{refl}(e(a, t, \lambda_{b:B(a)} \text{snd}(u(t b))))) : \mathbf{W}\text{-Fib}\text{-Hom } (C, c) (E, e)$$

which type-checks due to θ and the fact that $\text{fst} \circ u \equiv \text{id}_C$. \square

COROLLARY 4.13. *In \mathcal{H}_{ext} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, the following conditions on an algebra $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ are equivalent:*

- (1) \mathcal{X} satisfies the induction principle on the universe \mathcal{U}_k
- (2) \mathcal{X} satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_k
- (3) \mathcal{X} is initial on the universe \mathcal{U}_k

for $k \geq j$. In other words, we have

$$\text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X}) \simeq \text{has-W-rec}_{\mathcal{U}_k}(\mathcal{X}) \times \text{has-W-rec-uniq}_{\mathcal{U}_k}(\mathcal{X}) \simeq \text{is-W-init}_{\mathcal{U}_k}(\mathcal{X})$$

provided $k \geq j$. Furthermore, all 3 conditions are mere propositions.

PROOF. Conditions (1) and (3) are mere propositions by Lem. ?? (for the latter), Lem. ??, 3.10 (for the former), and the fact that a family of mere propositions is itself a mere proposition. \square

We can thus characterize W-types using the universal property of initiality as follows.

COROLLARY 4.14. In \mathcal{H}_{ext} with W-types, for any $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, the algebra

$$\left(\text{W}_{x:A}^{\mathcal{U}_i} B(x), \lambda_a \lambda_t \sup_{\mathcal{U}_i}^{A, x.B(x)}(a, t) \right) : \text{W-Alg}_{\mathcal{U}_i}(A, B)$$

is initial on any universe \mathcal{U}_j .

COROLLARY 4.15. In \mathcal{H}_{ext} extended with an algebra $\mathcal{X}_{\mathcal{U}_i}(A, B) : \text{W-Alg}_{\mathcal{U}_i}(A, B)$ for any \mathcal{U}_i , $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, which is initial on any universe \mathcal{U}_j , Martin-Löf's W-types are definable.

PROOF. For any i , the algebra $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i \vdash \mathcal{X}_{\mathcal{U}_i}(A, B) : \text{W-Alg}_{\mathcal{U}_i}(A, B)$ is such that for any j , there exists a term $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i \vdash h_j^i : \text{is-W-init}_{\mathcal{U}_j}(\mathcal{X}_{\mathcal{U}_i}(A, B))$. By Cor. 3.13, for any $j \geq i$ there is a term $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i \vdash r_j^i : \text{has-W-ind}_{\mathcal{U}_j}(\mathcal{X}_{\mathcal{U}_i}(A, B))$. Since universes are cumulative, this implies that such a term r_j^i exists for any j . This in turn implies that W-types are definable. \square

We conclude by the type-theoretic analogue of Lambek's lemma for W-types, which asserts that the structure map of an initial algebra is an equivalence. In \mathcal{H}_{ext} any equivalence is also a type isomorphism, which then gives us the more familiar formulation of Lambek's lemma.

LEMMA 4.16. Over \mathcal{H}_{ext} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $(C, c) : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ is initial on \mathcal{U}_j and $j \geq i$, then the map from $\Sigma_{x:A} B(x) \rightarrow C$ to C given by c is an equivalence.

PROOF. By abuse of notation we refer to both the curried and uncurried versions of the structure map by c . Since (C, c) is initial on \mathcal{U}_j , it satisfies the recursion principle on \mathcal{U}_j . We use it with the algebra

$$\left(\Sigma_{x:A} B(x) \rightarrow C; a, s \mapsto (a, \lambda_{b:B(a)} c(s \, b)) \right)$$

We note that the carrier type belongs to \mathcal{U}_j as $i \leq j$. This gives us a homomorphism (u, θ) where $u : C \rightarrow (\Sigma_{x:A} B(x) \rightarrow C)$ and $\theta : \Pi_a \Pi_t u(c(a, t)) = (a, \lambda_{b:B(a)} c(u(t \, b)))$. We can now form two homomorphisms

$$(c \circ u; a, t \mapsto \text{refl}_{c(a, \lambda_{b:B(a)} u(t \, b))}), (\text{id}_C; a, t \mapsto \text{refl}_{c(a, t)}) : \text{W-Hom}(C, c)(C, c)$$

where the first one type-checks due to θ . Since (C, c) is initial on \mathcal{U}_j , it satisfies the recursion uniqueness principle on \mathcal{U}_j , thus the above homomorphisms are equal. Thus, we have $c \circ u = \text{id}_C$, hence $c \circ u \sim \text{id}_C$ and also $c \circ u \equiv \text{id}_C$. The latter together with θ implies that for any a, t , we have $u(c(a, t)) \equiv (a, t)$. Thus $u \circ c \sim \text{id}_{\Sigma_{x:A} B(x) \rightarrow C}$. \square

COROLLARY 4.17. *Over \mathcal{H}_{ext} , given $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$ and $a_1, a_2 : A$, $t_1 : B(a_1) \rightarrow W$, $t_2 : B(a_2) \rightarrow W$ we have*

$$\sup(a_1, t_1) = \sup(a_2, t_2) \simeq (a_1, t_1) = (a_2, t_2)$$

PROOF. By Lem. 4.16 and Cor. 4.14, the structure map \sup defines an equivalence between $\Sigma_{x:A} B(x) \rightarrow W$ and W . The rest follows from Lem. ??⁷. \square

EdN:7

4.2. Intensional case

Although it is more elaborate to state (and difficult to prove) owing to the presence of recursively generated data, our main result on W-types is analogous to the foregoing example in the following respect: rather than being strict initial algebras, as in the extensional case, W-types with propositional computation rules are instead homotopy-initial algebras. This fact can again be stated entirely syntactically, as an equivalence between the definability of W-types with propositional computation rules (which we spell out below) and the existence of a suitable family of homotopy-initial algebras. Moreover, as in the simple case of the type 2 above, the proof is again entirely constructive.

The propositional computation rules for W-types are as follows:

— Propositional W-computation rule.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad a : A \quad t : B(a) \rightarrow W \quad w : W \vdash E(w) : \mathcal{U}_j \quad x : A, p : B(x) \rightarrow W, r : \Pi_{b:B(x)} E(p\ b) \vdash e(x, p, r) : E(\sup(x, p))}{\text{wind-comp}_{\mathcal{U}_i}(A, x.B, w.E, x.p.r.e, a, t) : \text{wind}(\sup(a, t)) = e(a, t, \lambda_{b:B(a)} \text{wind}(t\ b))}$$

— Simple propositional W-computation rule.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad a : A \quad t : B(a) \rightarrow W \quad C : \mathcal{U}_j \quad x : A, r : B(x) \rightarrow C \vdash c(x, r) : C}{\text{wrec-comp}_{\mathcal{U}_i}(A, x.B, C, x.r.c, a, t) : \text{wrec}(\sup(a, t)) = c(a, \lambda_{b:B(a)} \text{wrec}(t\ b))}$$

Remark 4.18. One interesting aspect of this group of rules is that, unlike the standard rules for W-types, they are invariant under equivalence, and propositional equality in particular. If $A : \mathcal{U}_i$ and $x : A \vdash B(x) : \mathcal{U}_i$ and we have a type $W : \mathcal{U}_i$ such that $W \simeq W_{x:A}^{\mathcal{U}_i} B(x)$, then W can be shown to satisfy the same rules as $W_{x:A}^{\mathcal{U}_i} B(x)$, in the sense that there are definable terms playing the role of the primitive constants that appear in the rules for $W_{x:A}^{\mathcal{U}_i} B(x)$.

We again have uniqueness principles, in the propositional form:

— Propositional W-uniqueness principle.

$$\frac{A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad m : W \quad w : W \vdash E(w) : \mathcal{U}_j \quad x : A, p : B(x) \rightarrow W, r : \Pi_{b:B(x)} E(p\ b) \vdash e(x, p, r) : E(\sup(x, p)) \quad w : W \vdash f(w) : E(w) \quad w : W \vdash g(w) : E(w) \quad x : A, p : B(x) \rightarrow W \vdash \gamma(x, p) : f(\sup(x, p)) = e(x, p, \lambda_{b:B(x)} f(p\ b)) \quad x : A, p : B(x) \rightarrow W \vdash \delta(x, p) : g(\sup(x, p)) = e(x, p, \lambda_{b:B(x)} g(p\ b))}{\text{wind-uniq}_{\mathcal{U}_i}(A, x.B, w.E, x.p.r.e, w.f, x.p.\gamma, w.g, x.p.\delta, m) : f(m) = g(m)}$$

⁷EDNOTE: Which says that $a = b$ is equivalent to $f(a) = f(b)$ if f is an equivalence

— Simple propositional W-uniqueness principle.

$$\frac{\begin{array}{l} A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad m : W \quad C : \mathcal{U}_j \quad x : A, r : B(x) \rightarrow C \vdash c(x, r) : C \\ w : W \vdash f(w) : C \quad x : A, p : B(x) \rightarrow W \vdash \gamma(x, p) : f(\sup(x, p)) = c(x, \lambda_{b:B(x)} f(p \, b)) \\ w : W \vdash g(w) : C \quad x : A, p : B(x) \rightarrow W \vdash \delta(x, p) : g(\sup(x, p)) = c(x, \lambda_{b:B(x)} g(p \, b)) \end{array}}{\text{wrec-uniq}_{\mathcal{U}_i}(A, x.B, C, x.r.c, w.f, x.p.\gamma, w.g, x.p.\delta, m) : f(m) = g(m)}$$

The witness terms will be shortened to $\text{wind-uniq}(m)$, $\text{wrec-uniq}(m)$ where appropriate. In showing the above laws, we proceed analogously to the extensional case: we use the induction principle with the type family $x \mapsto f(w) =_{E(w)} g(w)$. For this we need to show that for any x, p we have $f(\sup(x, p)) = g(\sup(x, p))$ under the induction hypothesis $h : \Pi_{b:B(x)} f(p \, b) = g(p \, b)$. We can construct this path explicitly as

$$\gamma(x, p) \cdot \text{ap}_{e(x, p, -)}(\Pi \text{Eq}^=(h)) \cdot \delta(x, p)^{-1}$$

The simple uniqueness rule again follows from the dependent one. Invoking the corresponding (propositional) computation rule, we get the following coherence principles for W-types:

— Propositional W-coherence principle.

$$\frac{\begin{array}{l} A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \quad a : A \quad t : B(a) \rightarrow W \\ w : W \vdash E(w) : \mathcal{U}_j \quad x : A, p : B(x) \rightarrow W, r : \Pi_{b:B(x)} E(p \, b) \vdash e(x, p, r) : E(\sup(x, p)) \\ w : W \vdash f(w) : E(w) \quad w : W \vdash g(w) : E(w) \\ x : A, p : B(x) \rightarrow W \vdash \gamma(x, p) : f(\sup(x, p)) = e(x, p, \lambda_{b:B(x)} f(p \, b)) \\ x : A, p : B(x) \rightarrow W \vdash \delta(x, p) : g(\sup(x, p)) = e(x, p, \lambda_{b:B(x)} g(p \, b)) \end{array}}{\begin{array}{l} \text{wind-coh}_{\mathcal{U}_i}(A, x.B, w.E, x.p.r.e, w.f, x.p.\gamma, w.g, x.p.\delta, a, t) : \\ \text{wind-uniq}(\sup(a, t)) = \gamma(a, t) \cdot \text{ap}_{e(a, t, -)}(\Pi \text{Eq}^=(\lambda_{b:B(a)} \text{wind-uniq}(t \, b))) \cdot \delta(a, t)^{-1} \end{array}}$$

— Simple propositional W-coherence principle.

$$\frac{\begin{array}{l} A : \mathcal{U}_i \quad x : A \vdash B(x) : \mathcal{U}_i \\ a : A \quad t : B(a) \rightarrow W \quad C : \mathcal{U}_j \quad x : A, r : B(x) \rightarrow C \vdash c(x, r) : C \\ w : W \vdash f(w) : C \quad x : A, p : B(x) \rightarrow W \vdash \gamma(x, p) : f(\sup(x, p)) = c(x, \lambda_{b:B(x)} f(p \, b)) \\ w : W \vdash g(w) : C \quad x : A, p : B(x) \rightarrow W \vdash \delta(x, p) : g(\sup(x, p)) = c(x, \lambda_{b:B(x)} g(p \, b)) \end{array}}{\begin{array}{l} \text{wrec-coh}_{\mathcal{U}_i}(A, x.B, C, x.r.c, w.f, x.p.\gamma, w.g, x.p.\delta, a, t) : \\ \text{wrec-uniq}(\sup(a, t)) = \gamma(a, t) \cdot \text{ap}_{c(a, -)}(\Pi \text{Eq}^=(\lambda_{b:B(a)} \text{wrec-uniq}(t \, b))) \cdot \delta(a, t)^{-1} \end{array}}$$

This motivates the following definitions:

Definition 4.19. For $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, $\mathcal{X} : \text{W-Alg}_{\mathcal{U}_j}(A, B)$, $\mathcal{Y} : \text{W-Alg}_{\mathcal{U}_k}(A, B)$ and homomorphisms $\mu, \nu : \text{W-Hom } \mathcal{X} \, \mathcal{Y}$, define the type of *2-cells* between μ and ν by

$$\begin{aligned} \text{W-Cell } (C, c) (D, d) (f, \gamma) (g, \delta) := \\ \text{W-Fib-Hom } (C, c) \left(f \sim g; x, p, r \mapsto \gamma(x, p) \cdot \text{ap}_{d(x)}(\Pi \text{Eq}^=(r)) \cdot \delta(x, p)^{-1} \right) \end{aligned}$$

Definition 4.20. For $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, $\mathcal{X} : \text{W-Alg}_{\mathcal{U}_j}(A, B)$, $\mathcal{Y} : \text{W-Fib-Alg}_{\mathcal{U}_k}(A, B)$ \mathcal{X} and fibered homomorphisms $\mu, \nu : \text{W-Fib-Hom } \mathcal{X} \, \mathcal{Y}$, define the type of *fibered 2-cells* between μ and ν by

$$\begin{aligned} \text{W-Fib-Cell } (C, c) (E, e) (f, \gamma) (g, \delta) := \\ \text{W-Fib-Hom } (C, c) \left(f \sim g; x, p, r \mapsto \gamma(x, p) \cdot \text{ap}_{e(x, p)}(\Pi \text{Eq}^=(r)) \cdot \delta(x, p)^{-1} \right) \end{aligned}$$

For brevity, we will often leave out the first two arguments. As expected, we have:

Definition 4.21. Given $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i$, an algebra $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ is called *homotopy-initial* on a universe \mathcal{U}_k if for any algebra $\mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_k}(A, B)$, the type of \mathbf{W} -homomorphisms between \mathcal{X} and \mathcal{Y} is contractible:

$$\text{is-W-hinit}_{\mathcal{U}_k}(\mathcal{X}) := \Pi_{(\mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_k}(A, B))} \text{is-contr}(\mathbf{W}\text{-Hom } \mathcal{X} \mathcal{Y})$$

Definition 4.22. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i, \mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ there is a designated *identity* homomorphism from \mathcal{X} to itself, defined by

$$\mathbf{W}\text{-Id-Hom } (C, c) := (\text{id}_C; a, t \mapsto \text{refl}_{c(a, t)})$$

As before, we denote this homomorphism by $1_{\mathcal{X}}$.

Definition 4.23. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i, \mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B), \mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_k}(A, B), \mathcal{Z} : \mathbf{W}\text{-Alg}_{\mathcal{U}_l}(A, B)$ and homomorphisms $\mu : \mathbf{W}\text{-Hom } \mathcal{X} \mathcal{Y}, \nu : \mathbf{W}\text{-Hom } \mathcal{Y} \mathcal{Z}$, the *composition* of μ and ν is a homomorphism from \mathcal{X} to \mathcal{Z} defined by

$$\mathbf{W}\text{-Comp-Hom } (C, c) (D, d) (E, e) (f, \gamma) (g, \delta) := (g \circ f; a, t \mapsto \text{ap}_g(\gamma(a, t)) \cdot \delta(a, f \circ t))$$

As before, we often leave out the first three arguments and denote the composition by $\nu \circ \mu$.

Definition 4.24. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i, \mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B), \mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_k}(A, B)$ we define the type of *isomorphisms* between \mathcal{X} and \mathcal{Y} as

$$\mathbf{W}\text{-Alg-Iso } \mathcal{X} \mathcal{Y} := \Sigma_{(\rho : \mathbf{W}\text{-Hom } \mathcal{X} \mathcal{Y})} \left(\Sigma_{(\mu : \mathbf{W}\text{-Hom } \mathcal{Y} \mathcal{X})} \mu \circ \rho = 1_{\mathcal{X}} \right) \times \left(\Sigma_{(\nu : \mathbf{W}\text{-Hom } \mathcal{Y} \mathcal{X})} \rho \circ \nu = 1_{\mathcal{Y}} \right)$$

LEMMA 4.25. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i, \mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B), \mathcal{Y} : \mathbf{W}\text{-Fib-Alg}_{\mathcal{U}_k}(A, B)$ \mathcal{X} and $\mu, \nu : \mathbf{W}\text{-Fib-Hom } \mathcal{X} \mathcal{Y}$, the path space $\mu = \nu$ is equivalent to the space of fibered 2-cells between μ and ν :

$$\mu = \nu \simeq \mathbf{W}\text{-Fib-Cell } \mu \nu$$

PROOF. Let algebras $(C, c) : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B), (E, e) : \mathbf{W}\text{-Fib-Alg}_{\mathcal{U}_k}(A, B)$ (C, c) and homomorphisms $(f, \gamma), (g, \delta) : \mathbf{W}\text{-Fib-Hom } (C, c) (E, e)$ be given. We have

$$\begin{aligned} (f, \gamma) &= (g, \delta) && \simeq \\ \Sigma_{\alpha : f=g} \left(\delta = \text{tr}_{(h \mapsto \Pi_a \Pi_t h(c(a, t)) = e(a, t, \lambda_b h(t, b)))} (\alpha) \gamma \right) && \simeq \\ \Sigma_{\alpha : f=g} \left(\delta = \lambda_a \lambda_t \text{Eq}^{\Pi}(\alpha, c(a, t))^{-1} \cdot \gamma(a, t) \cdot \text{ap}_{e(a, t)}(\text{Eq}^{\Pi}(\lambda_b \text{Eq}^{\Pi}(\alpha, t, b))) \right) && \simeq \\ \Sigma_{\alpha : f \sim g} \left(\delta = \lambda_a \lambda_t \alpha(c(a, t))^{-1} \cdot \gamma(a, t) \cdot \text{ap}_{e(a, t)}(\text{Eq}^{\Pi}(\lambda_b \alpha(t, b))) \right) && \simeq \\ \Sigma_{\alpha : f \sim g} \Pi_a \Pi_t \left(\delta(a, t) = \alpha(c(a, t))^{-1} \cdot \gamma(a, t) \cdot \text{ap}_{e(a, t)}(\text{Eq}^{\Pi}(\lambda_b \alpha(t, b))) \right) && \simeq \\ \Sigma_{\alpha : f \sim g} \Pi_a \Pi_t \left(\alpha(c(a, t)) = \gamma(a, t) \cdot \text{ap}_{e(a, t)}(\text{Eq}^{\Pi}(\lambda_b \alpha(t, b))) \cdot \delta(a, t)^{-1} \right) && \equiv \\ \mathbf{W}\text{-Fib-Cell } (f, \gamma) (g, \delta) && \end{aligned}$$

□

COROLLARY 4.26. For $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i, \mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B), \mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_k}(A, B)$ and $\mu, \nu : \mathbf{W}\text{-Hom } \mathcal{X} \mathcal{Y}$, the path space $\mu = \nu$ is equivalent to the space of 2-cells between μ and ν :

$$\mu = \nu \simeq \mathbf{W}\text{-Cell } \mu \nu$$

LEMMA 4.27. *Given $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$ and $\mathcal{X}, \mathcal{Y} : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B)$, the path space $\mathcal{X} = \mathcal{Y}$ is equivalent to the space of isomorphisms between \mathcal{X} and \mathcal{Y} :*

$$\mathcal{X} = \mathcal{Y} \simeq \mathbf{W-Alg-Iso} \mathcal{X} \mathcal{Y}$$

PROOF. Let algebras $(C, c), (D, d) : \mathbf{W-Alg}_{\mathcal{U}_j}(A, B)$ be given. We have

$$\begin{aligned} \mathbf{W-Alg-Iso} (C, c) (D, d) & \equiv \\ \Sigma_{\rho: (\Sigma_{f: C \rightarrow D} \Pi_a \Pi_t f(c(a, t)) = d(a, f \circ t))} \left(\Sigma_{\mu: (\Sigma_{g: D \rightarrow C} \Pi_a \Pi_s g(d(a, s)) = c(a, g \circ s))} \mu \circ \rho = 1_{(C, c)} \right) \times \\ & \left(\Sigma_{\nu: (\Sigma_{h: D \rightarrow C} \Pi_a \Pi_s h(d(a, s)) = c(a, h \circ s))} \rho \circ \nu = 1_{(D, d)} \right) \simeq \\ \Sigma_{f: C \rightarrow D} \Sigma_{\epsilon: (\Pi_a \Pi_t f(c(a, t)) = d(a, f \circ t))} \left(\Sigma_{g: D \rightarrow C} \Sigma_{\gamma: (\Pi_a \Pi_s g(d(a, s)) = c(a, g \circ s))} P_{f, \epsilon, g, \gamma} \right) \times \\ & \left(\Sigma_{h: D \rightarrow C} \Sigma_{\delta: (\Pi_a \Pi_s h(d(a, s)) = c(a, h \circ s))} Q_{f, \epsilon, h, \delta} \right) \end{aligned}$$

where

$$\begin{aligned} P_{f, \epsilon, g, \gamma} & := (g \circ f; a, t \mapsto \mathbf{ap}_g(\epsilon(a, t)) \cdot \gamma(a, f \circ t)) = (\mathbf{id}_C; a, t \mapsto \mathbf{refl}_{c(a, t)}) \\ Q_{f, \epsilon, h, \delta} & := (f \circ h; a, s \mapsto \mathbf{ap}_f(\delta(a, s)) \cdot \epsilon(a, h \circ s)) = (\mathbf{id}_D; a, s \mapsto \mathbf{refl}_{d(a, s)}) \end{aligned}$$

Now we have

$$\begin{aligned} P_{f, \epsilon, g, \gamma} & \equiv \\ (g \circ f; a, t \mapsto \mathbf{ap}_g(\epsilon(a, t)) \cdot \gamma(a, f \circ t)) & \simeq (\mathbf{id}_C; a, t \mapsto \mathbf{refl}_{c(a, t)}) \\ \Sigma_{\alpha: g \circ f = \mathbf{id}_C} (\lambda_a \lambda_t \mathbf{ap}_g(\epsilon(a, t)) \cdot \gamma(a, f \circ t)) & = \mathbf{tr}_{(i \mapsto \Pi_a \Pi_t i(c(a, t)) = c(a, i \circ t))}^{-1}(\alpha) (\lambda_a \lambda_t \mathbf{refl}_{c(a, t)}) \simeq \\ \Sigma_{\alpha: g \circ f = \mathbf{id}_C} (\lambda_a \lambda_t \mathbf{ap}_g(\epsilon(a, t)) \cdot \gamma(a, f \circ t)) & = \lambda_a \lambda_t \\ & = \mathbf{Eq}^\Pi(\alpha, c(a, t)) \cdot \mathbf{refl}_{c(a, t)} \cdot (\mathbf{ap}_{c(a)}(\Pi \mathbf{Eq}^\Pi(\lambda_b = \mathbf{Eq}^\Pi(\alpha, t b))))^{-1} \simeq \\ \Sigma_{\alpha: g \circ f = \mathbf{id}_C} \Pi_a \Pi_t (\mathbf{ap}_g(\epsilon(a, t)) \cdot \gamma(a, f \circ t)) & = \\ & = \mathbf{Eq}^\Pi(\alpha, c(a, t)) \cdot \mathbf{refl}_{c(a, t)} \cdot (\mathbf{ap}_{c(a)}(\Pi \mathbf{Eq}^\Pi(\lambda_b = \mathbf{Eq}^\Pi(\alpha, t b))))^{-1} \simeq \\ \Sigma_{\alpha: g \circ f \sim \mathbf{id}_C} \Pi_a \Pi_t (\mathbf{ap}_g(\epsilon(a, t)) \cdot \gamma(a, f \circ t)) & = \\ \alpha(c(a, t)) \cdot \mathbf{refl}_{c(a, t)} \cdot (\mathbf{ap}_{c(a)}(\Pi \mathbf{Eq}^\Pi(\lambda_b \alpha(t b))))^{-1} & \simeq \\ \Sigma_{\alpha: g \circ f \sim \mathbf{id}_C} \Pi_a \Pi_t (\alpha(c(a, t)) = \mathbf{ap}_g(\epsilon(a, t)) \cdot \gamma(a, f \circ t) \cdot \mathbf{ap}_{c(a)}(\Pi \mathbf{Eq}^\Pi(\lambda_b \alpha(t b)))) & \end{aligned}$$

and analogously

$$Q_{f, \epsilon, h, \delta} \simeq \Sigma_{\beta: f \circ h \sim \mathbf{id}_D} \Pi_a \Pi_s (\beta(d(a, s)) = \mathbf{ap}_f(\delta(a, s)) \cdot \epsilon(a, h \circ s) \cdot \mathbf{ap}_{d(a)}(\Pi \mathbf{Eq}^\Pi(\lambda_b \beta(s b))))$$

Thus we can express $\mathbf{W-Alg-Iso} (C, c) (D, d)$ equivalently as the type

$$\Sigma_{f: C \rightarrow D} \Sigma_{\epsilon: (\Pi_a \Pi_t f(c(a, t)) = d(a, f \circ t))} \Sigma_{g: D \rightarrow C} \Sigma_{\alpha: g \circ f \sim \mathbf{id}_C} \Sigma_{h: D \rightarrow C} \Sigma_{\beta: f \circ h \sim \mathbf{id}_D} R_{f, \epsilon, g, \alpha} \times S_{f, \epsilon, h, \beta}$$

where

$$\begin{aligned}
R_{f,\epsilon,g,\alpha} &:= \Sigma_{\gamma: (\Pi_a \Pi_s g(d(a,s))=c(a,g \circ s))} \Pi_a \Pi_t \\
\alpha(c(a,t)) &= \mathsf{ap}_g(\epsilon(a,t)) \cdot \gamma(a, f \circ t) \cdot \mathsf{ap}_{c(a)}(\Pi \mathsf{Eq}^=(\lambda_b \alpha(t \ b))) \\
S_{f,\epsilon,h,\beta} &:= \Sigma_{\delta: (\Pi_a \Pi_s h(d(a,s))=c(a,h \circ s))} \Pi_a \Pi_s \\
\beta(d(a,s)) &= \mathsf{ap}_f(\delta(a,s)) \cdot \epsilon(a, h \circ s) \cdot \mathsf{ap}_{d(a)}(\Pi \mathsf{Eq}^=(\lambda_b \beta(s \ b)))
\end{aligned}$$

Now we have

$$\begin{aligned}
&S_{f,\epsilon,h,\beta} && \equiv \\
&\Sigma_{\delta: (\Pi_a \Pi_s h(d(a,s))=c(a,h \circ s))} \Pi_a \Pi_s && \\
&\quad \beta(d(a,s)) = \mathsf{ap}_f(\delta(a,s)) \cdot \epsilon(a, h \circ s) \cdot \mathsf{ap}_{d(a)}(\Pi \mathsf{Eq}^=(\lambda_b \beta(s \ b))) && \simeq \\
&\Pi_a \Pi_s \Sigma_{\delta: h(d(a,s))=c(a,h \circ s)} && \\
&\quad \beta(d(a,s)) = \mathsf{ap}_f(\delta) \cdot \epsilon(a, h \circ s) \cdot \mathsf{ap}_{d(a)}(\Pi \mathsf{Eq}^=(\lambda_b \beta(s \ b))) && \simeq \\
&\Pi_a \Pi_s \Sigma_{\delta: h(d(a,s))=c(a,h \circ s)} && \\
&\quad \mathsf{ap}_f(\delta) = \beta(d(a,s)) \cdot \left(\mathsf{ap}_{d(a)}(\Pi \mathsf{Eq}^=(\lambda_b \beta(s \ b))) \right)^{-1} \cdot \epsilon(a, h \circ s)^{-1} && \simeq \\
&\Pi_a \Pi_s 1 && \simeq \\
&1 &&
\end{aligned}$$

by Lem. ??, ??, and the fact that g, α, h, β make f into an equivalence. This last fact also implies that the mapping $t \mapsto f \circ t$ is an equivalence between $B(a) \rightarrow C$ and $B(a) \rightarrow D$ by Lem. ??⁸. Thus the mapping $\gamma \mapsto \lambda_a \lambda_t \gamma(a, f \circ t)$ is an equivalence between the types $\Pi_{a:A} \Pi_{s:B(a) \rightarrow D} g(d(a,s)) = c(a, g \circ s)$ and $\Pi_{a:A} \Pi_{t:B(a) \rightarrow C} g(d(a, f \circ t)) = c(a, g \circ f \circ t)$. Thus:

$$\begin{aligned}
&R_{f,\epsilon,g,\alpha} && \equiv \\
&\Sigma_{\gamma: (\Pi_a \Pi_s g(d(a,s))=c(a,g \circ s))} \Pi_a \Pi_t && \\
&\quad \alpha(c(a,t)) = \mathsf{ap}_g(\epsilon(a,t)) \cdot \gamma(a, f \circ t) \cdot \mathsf{ap}_{c(a)}(\Pi \mathsf{Eq}^=(\lambda_b \alpha(t \ b))) && \simeq \\
&\Sigma_{\gamma: (\Pi_a \Pi_t g(d(a, f \circ t))=c(a, g \circ f \circ t))} \Pi_a \Pi_t && \\
&\quad \alpha(c(a,t)) = \mathsf{ap}_g(\epsilon(a,t)) \cdot \gamma(a, t) \cdot \mathsf{ap}_{c(a)}(\Pi \mathsf{Eq}^=(\lambda_b \alpha(t \ b))) && \simeq \\
&\Pi_a \Pi_t \Sigma_{\gamma: g(d(a, f \circ t))=c(a, g \circ f \circ t)} && \\
&\quad \alpha(c(a,t)) = \mathsf{ap}_g(\epsilon(a,t)) \cdot \gamma \cdot \mathsf{ap}_{c(a)}(\Pi \mathsf{Eq}^=(\lambda_b \alpha(t \ b))) && \simeq \\
&\Pi_a \Pi_t \Sigma_{\gamma: g(d(a, f \circ t))=c(a, g \circ f \circ t)} && \\
&\quad \gamma = \left(\mathsf{ap}_g(\epsilon(a,t)) \right)^{-1} \cdot \alpha(c(a,t)) \cdot \left(\mathsf{ap}_{c(a)}(\Pi \mathsf{Eq}^=(\lambda_b \alpha(t \ b))) \right)^{-1} && \simeq \\
&\Pi_a \Pi_t 1 && \simeq \\
&1 &&
\end{aligned}$$

⁸EdNOTE: Which says that if $f : B \rightarrow C$ is an equivalence, then so is the mapping $h \mapsto f \circ h$ between $A \rightarrow B$ and $A \rightarrow C$

by Lem. ?? . Thus, we have

$$\begin{aligned}
& \text{W-Alg-Iso } (C, c) \ (D, d) && \simeq \\
& \Sigma_{f:C \rightarrow D} \Sigma_{g:D \rightarrow C} \Sigma_{\alpha:g \circ f \sim \text{id}_C} \Sigma_{h:D \rightarrow C} \Sigma_{\beta:f \circ h \sim \text{id}_D} \Pi_a \Pi_t f(c(a, t)) = d(a, f \circ t) && \simeq \\
& \Sigma_{f:C \rightarrow D} \text{is-equiv}(f) \times \Pi_a \Pi_t f(c(a, t)) = d(a, f \circ t) && \simeq \\
& \Sigma_{p:C \simeq D} \Pi_a \Pi_t (\text{fst}(p) \ c(a, t)) = d(a, \text{fst}(p) \circ t) && \simeq \\
& \Sigma_{p:C=D} \Pi_a \Pi_t (\text{fst}(\text{Eq}^\sim(p)) \ c(a, t)) = d(a, \text{fst}(\text{Eq}^\sim(p)) \circ t) && \equiv \\
& \Sigma_{p:C=D} \Pi_a \Pi_t (\text{tr}_{X \mapsto X}(p) \ c(a, t) = d(a, \text{fst}(\text{Eq}^\sim(p)) \circ t)) && \simeq \\
& \Sigma_{p:C=D} \Pi_a \Pi_t (c(a, t) = \text{tr}_{X \mapsto X}^{-1}(p) \ d(a, \text{fst}(\text{Eq}^\sim(p)) \circ t)) && \simeq \\
& \Sigma_{p:C=D} (c = \lambda_a \lambda_t \text{tr}_{X \mapsto X}^{-1}(p) \ d(a, \text{fst}(\text{Eq}^\sim(p)) \circ t)) && \simeq \\
& \Sigma_{p:C=D} (c = \text{tr}_{(X \mapsto \Pi_{a:A} (B(a) \rightarrow X)) \rightarrow X}^{-1}(p) \ d) && \simeq \\
& (C, c) = (D, d)
\end{aligned}$$

□

As desired, the analogues of the lemmas from section ?? still hold in the setting of homotopy type theory:

LEMMA 4.28. *In \mathcal{H} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $\mathcal{X} : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ satisfies the induction principle on the universe \mathcal{U}_k , it also satisfies the induction uniqueness principle on \mathcal{U}_k . In other words, we have*

$$\text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X}) \rightarrow \text{has-W-ind-uniq}_{\mathcal{U}_k}(\mathcal{X})$$

PROOF. Let an algebra $(C, c) : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ be given. To prove the induction uniqueness principle, take any algebra $(E, e) : \text{W-Fib-Alg}_{\mathcal{U}_k}(A, B)$ (C, c) and homomorphisms $(f, \gamma), (g, \delta) : \text{W-Fib-Hom}(C, c) (E, e)$. By Lem. 4.25, to show $(f, \gamma) = (g, \delta)$ it suffices to exhibit a fibered 2-cell between (f, γ) and (g, δ) . For this we use the induction principle with the fibered algebra $(f \sim g; x, p, r \mapsto \gamma(x, p) \cdot \text{ap}_{e(x, p)}(\text{Eq}^\sim(r)) \cdot \delta(x, p)^{-1})$ and we are done. □

COROLLARY 4.29. *In \mathcal{H} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $\mathcal{X} : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ satisfies the induction principle on the universe \mathcal{U}_k , it is homotopy-initial on \mathcal{U}_k . In other words, we have*

$$\text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X}) \rightarrow \text{is-W-hinit}_{\mathcal{U}_k}(\mathcal{X})$$

LEMMA 4.30. *In \mathcal{H} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $\mathcal{X} : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_k and $k \geq j$, then it satisfies the induction principle on \mathcal{U}_k . In other words, we have*

$$\text{has-W-rec}_{\mathcal{U}_k}(\mathcal{X}) \times \text{has-W-rec-uniq}_{\mathcal{U}_k}(\mathcal{X}) \rightarrow \text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X})$$

provided $k \geq j$.

PROOF. Let algebras $(C, c) : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ and $(E, e) : \text{W-Fib-Alg}_{\mathcal{U}_k}(A, B)$ be given. We use the recursion principle with the algebra $(\Sigma_{x:C} E(x); a, s \mapsto d(a, s))$ where

$$d(a, s) := (c(a, \lambda_{b:B(a)} \text{fst}(s \ b)), e(a, \lambda_{b:B(a)} \text{fst}(s \ b)), \lambda_{b:B(a)} \text{snd}(s \ b))$$

We note that the carrier type belongs to \mathcal{U}_k as $j \leq k$. This gives us a homomorphism (u, θ) , where $u : C \rightarrow \Sigma_{x:C} E(x)$ and $\theta : \Pi_{a:A} \Pi_{t:B(a)} \rightarrow C u(c(a, t)) = d(a, \lambda_{b:B(a)} u(t b))$. We can now form two homomorphisms

$$\left(\text{fst} \circ u; a, t \mapsto \text{fst}(= \text{Eq}^\Sigma(\theta(a, t))) \right), \left(\text{id}_C; a, t \mapsto \text{refl}_{c(a, t)} \right) : \text{W-Hom } (C, c) (C, c)$$

The recursion uniqueness principle tells us that these homomorphisms are equal. By Cor. 4.26 this means there exists a 2-cell (α, η) between them, i.e., we have

$$\alpha : \text{fst} \circ u \sim \text{id}_C$$

$$\eta : \Pi_{a:A} \Pi_{t:B(a)} \rightarrow C \left(\alpha(c(a, t)) = \text{fst}(= \text{Eq}^\Sigma(\theta(a, t))) \cdot \text{ap}_{c(a)}(^\Pi \text{Eq}^=(\lambda_{b:B(a)} \alpha(t b))) \cdot \text{refl}_{c(a, t)} \right)$$

Now it is easy to see that for any $a : A$, path $p : t_1 =_{B(a)} t_2$, and $s : \Pi_{b:B(a)} E(t_1 b)$, we have a higher path

$$\epsilon(a, p, s) : \text{tr}_E(\text{ap}_{c(a)}(p)) e(a, t_1, s) = e(a, t_2, (\lambda_{b:B(a)} \text{tr}_E(= \text{Eq}^\Pi(p, b)) (s b)))$$

To show this, we simply use path induction on p .

We can thus define the desired fibered homomorphism as

$$(x \mapsto \text{tr}_E(\alpha(x)) \text{snd}(u(x)); a, t \mapsto \phi(a, t)) : \text{W-Fib-Hom } (C, c) (E, e)$$

where $\phi(a, t)$ is the path

$$\begin{aligned} & \text{tr}_E(\alpha(c(a, t))) \text{snd}(u(c(a, t))) \\ & \quad \Big| \text{via } \eta(a, t) \\ & \text{tr}_E \left(\text{fst}(= \text{Eq}^\Sigma(\theta(a, t))) \cdot \text{ap}_{c(a)}(^\Pi \text{Eq}^=(\lambda_b \alpha(t b))) \cdot \text{refl}_{c(a, t)} \right) \text{snd}(u(c(a, t))) \\ & \quad \Big| \\ & \text{tr}_E \left(\text{fst}(= \text{Eq}^\Sigma(\theta(a, t))) \cdot \text{ap}_{c(a)}(^\Pi \text{Eq}^=(\lambda_b \alpha(t b))) \right) \text{snd}(u(c(a, t))) \\ & \quad \Big| \\ & \text{tr}_E \left(\text{ap}_{c(a)}(^\Pi \text{Eq}^=(\lambda_b \alpha(t b))) \right) \left(\text{tr}_E(\text{fst}(= \text{Eq}^\Sigma(\theta(a, t))) \text{snd}(u(c(a, t)))) \right) \\ & \quad \Big| \text{via } \text{snd}(= \text{Eq}^\Sigma(\theta(a, t))) \\ & \text{tr}_E \left(\text{ap}_{c(a)}(^\Pi \text{Eq}^=(\lambda_b \alpha(t b))) \right) e(a, \lambda_b \text{fst}(u(t b)), \lambda_b \text{snd}(u(t b))) \\ & \quad \Big| \epsilon(a, ^\Pi \text{Eq}^=(\lambda_b \alpha(t b)), \lambda_b \text{snd}(u(t b))) \\ & e(a, t, \lambda_b \text{tr}_E(= \text{Eq}^\Pi(^\Pi \text{Eq}^=(\lambda_b \alpha(t b)), b)) \text{snd}(u(t b))) \\ & \quad \Big| \\ & e(a, t, \lambda_b \text{tr}_E(\alpha(t b)) \text{snd}(u(t b))) \end{aligned}$$

□

COROLLARY 4.31. *In \mathcal{H} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, the following conditions on an algebra $\mathcal{X} : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ are equivalent:*

- (1) \mathcal{X} satisfies the induction principle on the universe \mathcal{U}_k
- (2) \mathcal{X} satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_k
- (3) \mathcal{X} is homotopy-initial on the universe \mathcal{U}_k

for $k \geq j$. In other words, we have

$$\text{has-W-ind}_{\mathcal{U}_k}(\mathcal{X}) \simeq \text{has-W-rec}_{\mathcal{U}_k}(\mathcal{X}) \times \text{has-W-rec-uniq}_{\mathcal{U}_k}(\mathcal{X}) \simeq \text{is-W-hinit}_{\mathcal{U}_k}(\mathcal{X})$$

provided $j \geq i$. Furthermore, all 3 conditions are mere propositions.

PROOF. Conditions (1) and (3) are mere propositions by Lem. ?? (for the latter), Lem. ??, 4.28 (for the former), and the fact that a family of mere propositions is itself a mere proposition. \square

As in the case of the type 2, we have the following corollary:

COROLLARY 4.32. *In \mathcal{H} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, two algebras $\mathcal{X}, \mathcal{Y} : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ which are homotopy-initial on \mathcal{U}_j are equal:*

$$\text{is-W-hinit}_{\mathcal{U}_j}(\mathcal{X}) \rightarrow \text{is-W-hinit}_{\mathcal{U}_j}(\mathcal{Y}) \rightarrow \mathcal{X} = \mathcal{Y}$$

PROOF. By Lem. 4.27 it suffices to construct an isomorphism between \mathcal{X} and \mathcal{Y} . Since \mathcal{X} and \mathcal{Y} are both homotopy-initial on \mathcal{U}_j , there exist homomorphisms $\mu : \text{W-Hom } \mathcal{X} \mathcal{Y}$ and $\nu : \text{W-Hom } \mathcal{Y} \mathcal{X}$. Again by homotopy-initiality, we have $\nu \circ \mu = 1_{\mathcal{X}}$ and $\mu \circ \nu = 1_{\mathcal{Y}}$, which gives us the desired isomorphism. \square

We can thus characterize W-types using the universal property of initiality as follows.

COROLLARY 4.33. *In \mathcal{H} with W-types, for any $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, the algebra*

$$\left(\text{W}_{x:A}^{\mathcal{U}_i} B(x), \lambda_a \lambda_t \sup_{\mathcal{U}_i}^{A, x. B(x)}(a, t) \right) : \text{W-Alg}_{\mathcal{U}_i}(A, B)$$

is homotopy-initial on any universe \mathcal{U}_j .

COROLLARY 4.34. *In \mathcal{H} extended with an algebra $\mathcal{X}_{\mathcal{U}_i}(A, B) : \text{W-Alg}_{\mathcal{U}_i}(A, B)$ for any \mathcal{U}_i , $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, which is homotopy-initial on any universe \mathcal{U}_j , Martin-Löf's W-types are definable.*

PROOF. For any i , the algebra $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i \vdash \mathcal{X}_{\mathcal{U}_i}(A, B) : \text{W-Alg}_{\mathcal{U}_i}(A, B)$ is such that for any j , there exists a term $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i \vdash h_j^i : \text{is-W-hinit}_{\mathcal{U}_j}(\mathcal{X}_{\mathcal{U}_i}(A, B))$. By Cor. 4.31, for any $j \geq i$ there is a term $A : \mathcal{U}_i, B : A \rightarrow \mathcal{U}_i \vdash r_j^i : \text{has-W-ind}_{\mathcal{U}_j}(\mathcal{X}_{\mathcal{U}_i}(A, B))$. Since universes are cumulative, this implies that such a term r_j^i exists for any j . This in turn implies that W-types are definable. \square

We have the following analogue of Lambek's lemma for W-types in homotopy type theory:

LEMMA 4.35. *Over \mathcal{H} , for $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if an algebra $(C, c) : \text{W-Alg}_{\mathcal{U}_j}(A, B)$ is homotopy-initial on \mathcal{U}_j and $j \geq i$, then the map from $\Sigma_{x:A} B(x) \rightarrow C$ to C given by c is an equivalence.*

PROOF. By abuse of notation we refer to both the curried and uncurried versions of the structure map by c . Since (C, c) is homotopy-initial on \mathcal{U}_j , it satisfies the recursion principle on \mathcal{U}_j . We use it with the algebra

$$\left(\Sigma_{x:A} B(x) \rightarrow C; a, s \mapsto (a, \lambda_{b:B(a)} c(s \ b)) \right)$$

We note that the carrier type belongs to \mathcal{U}_j as $i \leq j$. This gives us a homomorphism (u, θ) where $u : C \rightarrow (\Sigma_{x:A} B(x) \rightarrow C)$ and $\theta : \Pi_a \Pi_t u(c(a, t)) = (a, \lambda_{b:B(a)} c(u(t\ b)))$. We can now form two homomorphisms

$$(c \circ u; a, t \mapsto \text{ap}_c(\theta(a, t))), (\text{id}_C; a, t \mapsto \text{refl}_{c(a, t)}) : \text{W-Hom } (C, c) \ (C, c)$$

Since (C, c) is initial on \mathcal{U}_j , it satisfies the recursion uniqueness principle on \mathcal{U}_j , thus the above homomorphisms are equal. Thus, we have $c \circ u = \text{id}_C$ and in particular there is a homotopy $\epsilon : c \circ u \sim \text{id}_C$. For any a, t , the path $\theta(a, t) \cdot \text{ap}_{(a, -)}(\Pi \text{Eq}^=(\lambda_{b:B(a)} \epsilon(t\ b)))$ gives us $u(c(a, t)) = (a, t)$. Thus we have a homotopy $\eta : u \circ c \sim \text{id}_{\Sigma_{x:A} B(x) \rightarrow C}$. \square

COROLLARY 4.36. *Over \mathcal{H} , given $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$ and $a_1, a_2 : A$, $t_1 : B(a_1) \rightarrow W$, $t_2 : B(a_2) \rightarrow W$ we have*

$$\text{sup}(a_1, t_1) = \text{sup}(a_2, t_2) \simeq (a_1, t_1) = (a_2, t_2)$$

PROOF. By Lem. 4.35 and Cor. 4.33, the structure map sup defines an equivalence between $\Sigma_{x:A} B(x) \rightarrow W$ and W . The rest follows from Lem. ???. \square

Finally, W-types with propositional computation rules still preserve homotopy levels, in the following sense:

LEMMA 4.37. *For $A : \mathcal{U}_i$, $B : A \rightarrow \mathcal{U}_i$, if A is an $(n+1)$ -type, then so is $W_{x:A}^{\mathcal{U}_i} B(x)$:*

$$\text{is-}(n+1)\text{-type}(A) \rightarrow \text{is-}(n+1)\text{-type}(W_{x:A}^{\mathcal{U}_i} B(x))$$

PROOF. We need to show that for any $u, w : W$ we have $\text{is-}n\text{-type}(u = w)$. By induction on u , it suffices to show that for any a, t we have $\Pi_{w:W} \text{is-}n\text{-type}(\text{sup}(a, t) = w)$ under the induction hypothesis $h : \Pi_{b:B(a)} \Pi_{w:W} \text{is-}n\text{-type}(t(b) = w)$.

By another induction, this time on w , it suffices to show that for any a', t' we have $\text{is-}n\text{-type}(\text{sup}(a, t) = \text{sup}(a', t'))$ under the hypothesis $\Pi_{b:B(a')} \text{is-}n\text{-type}(\text{sup}(a, t) = t'(b))$, which however is not necessary. Now we have

$$\begin{aligned} \text{sup}(a, t) &= \text{sup}(a', t') && \simeq \\ (a, t) &= (a', t') && \simeq \\ \Sigma_{p:a=a'} (t = \text{tr}_{x \mapsto B(x) \rightarrow W}(p)\ t') &&& \simeq \\ \Sigma_{p:a=a'} (t = \lambda_{b:B(a)} t'(\text{tr}_B(p)\ b)) &&& \simeq \\ \Sigma_{p:a=a'} \Pi_{b:B(a)} (t(b) = t'(\text{tr}_B(p)\ b)) \end{aligned}$$

where the first equality follows by Cor. 4.36. Since A is an $(n+1)$ -type by assumption, we have $\text{is-}n\text{-type}(a = a')$. For any p, b we have $\text{is-}n\text{-type}(t(b) = t'(\text{tr}_B(p)\ b))$ by the hypothesis $h(b, t'(\text{tr}_B(p)\ b))$. Since a family of n -types is an n -type and a dependent sum of a family of n -types over an n -type is again an n -type, the last type in the above chain of equalities is an n -type. This finishes the proof. \square

We note that there is no restriction on the homotopy level of the fibers of B since they only appear contravariantly. Furthermore, we note that the lemma is no longer true if $n+1$ is replaced by n : if $A := 1$ and $B(x) := 1$, then $W_{x:A}^{\mathcal{U}_0} B(x) \simeq 0$, which is of course not contractible.

5. DEFINABILITY

A development entirely analogous to the foregoing can be given for the type of natural numbers, lists, the second number class, and other inductive types. For those types which can be presented as a W-type, however - which includes the aforementioned examples - the characterization in terms of homotopy-initial algebras can be obtained

as a corollary to the main theorem. We illustrate this for the type \mathbb{N} of natural numbers, with the usual rules for zero and successor, the familiar induction principle, and the computation rules in *propositional* form. We refrain from giving these rules explicitly since they can be easily read off from the corresponding definitions of \mathbb{N} -algebras, \mathbb{N} -homomorphisms, etc.

Definition 5.1. Define the type of \mathbb{N} -algebras on a universe \mathcal{U}_i as

$$\mathbb{N}\text{-Alg}_{\mathcal{U}_i} := \Sigma_{C:\mathcal{U}_i} C \times (C \rightarrow C)$$

Definition 5.2. Define the type of *fibred* \mathbb{N} -algebras on a universe \mathcal{U}_j over $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ by

$$\mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j}(C, c_0, c_s) := \Sigma_{E:C \rightarrow \mathcal{U}_j} E(c_0) \times (\Pi_{x:C} E(x) \rightarrow E(c_s x))$$

Definition 5.3. Given algebras $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ and $\mathcal{Y} : \mathbb{N}\text{-Alg}_{\mathcal{U}_j}$, define the type of \mathbb{N} -homomorphisms from \mathcal{X} to \mathcal{Y} by

$$\mathbb{N}\text{-Hom}(C, c_0, c_s)(D, d_0, d_s) := \Sigma_{f:C \rightarrow D} (f(c_0) = d_0) \times (\Pi_{x:C} f(c_s x) = d_s(f(x)))$$

Definition 5.4. Given algebras $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ and $\mathcal{Y} : \mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j} \mathcal{X}$, define the type of *fibred* \mathbb{N} -homomorphisms from \mathcal{X} to \mathcal{Y} by

$$\mathbb{N}\text{-Fib-Hom}(C, c_0, c_s)(E, e_0, e_s) := \Sigma_{(f:\Pi_{x:C} E(x))} (f(c_0) = e_0) \times (\Pi_{x:C} f(c_s x) = e_s(x, f(x)))$$

Definition 5.5. An algebra $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ *satisfies the recursion principle* on a universe \mathcal{U}_j if for any algebra $\mathcal{Y} : \mathbb{N}\text{-Alg}_{\mathcal{U}_j}$ there exists a \mathbb{N} -homomorphism between \mathcal{X} and \mathcal{Y} :

$$\text{has-}\mathbb{N}\text{-rec}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbb{N}\text{-Alg}_{\mathcal{U}_j})} \mathbb{N}\text{-Hom } \mathcal{X} \mathcal{Y}$$

Definition 5.6. An algebra $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ *satisfies the induction principle* on a universe \mathcal{U}_j if for any fibred algebra $\mathcal{Y} : \mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j} \mathcal{X}$ there exists a fibred \mathbb{N} -homomorphism between \mathcal{X} and \mathcal{Y} :

$$\text{has-}\mathbb{N}\text{-ind}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j} \mathcal{X})} \mathbb{N}\text{-Fib-Hom } \mathcal{X} \mathcal{Y}$$

Definition 5.7. An algebra $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ *satisfies the recursion uniqueness principle* on a universe \mathcal{U}_j if for any algebra $\mathcal{Y} : \mathbb{N}\text{-Alg}_{\mathcal{U}_j}$ any two \mathbb{N} -homomorphisms between \mathcal{X} and \mathcal{Y} are equal:

$$\text{has-}\mathbb{N}\text{-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbb{N}\text{-Alg}_{\mathcal{U}_j})} \text{is-prop}(\mathbb{N}\text{-Hom } \mathcal{X} \mathcal{Y})$$

Definition 5.8. An algebra $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ *satisfies the induction uniqueness principle* on a universe \mathcal{U}_j if for any fibred algebra $\mathcal{Y} : \mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j} \mathcal{X}$ any two fibred \mathbb{N} -homomorphisms between \mathcal{X} and \mathcal{Y} are equal:

$$\text{has-}\mathbb{N}\text{-ind-uniq}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j} \mathcal{X})} \text{is-prop}(\mathbb{N}\text{-Fib-Hom } \mathcal{X} \mathcal{Y})$$

Definition 5.9. An algebra $\mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$ is *homotopy-initial* on a universe \mathcal{U}_j if for any algebra $\mathcal{Y} : \mathbb{N}\text{-Alg}_{\mathcal{U}_j}$, the type of \mathbb{N} -homomorphisms between \mathcal{X} and \mathcal{Y} is contractible:

$$\text{is-}\mathbb{N}\text{-hinit}_{\mathcal{U}_j}(\mathcal{X}) := \Pi_{(\mathcal{Y}:\mathbb{N}\text{-Alg}_{\mathcal{U}_j})} \text{is-contr}(\mathbb{N}\text{-Hom } \mathcal{X} \mathcal{Y})$$

We can encode the type of natural numbers as a W-type with $A := 2$ and B given by $0 \mapsto 0, 1 \mapsto 1$. By the propositional computation rules for 2 we have $B(0) = 0, B(1) = 1$. Thus in particular we have an equivalence $F : B(0) \rightarrow 0$ (and also $G : B(1) \rightarrow 1$ but this one is redundant).

LEMMA 5.10. *There is an equivalence*

$$\mathbf{W}\text{-to-}\mathbb{N}\text{-Alg}_{\mathcal{U}_i} : \mathbf{W}\text{-Alg}_{\mathcal{U}_i}(A, B) \rightarrow \mathbb{N}\text{-Alg}_{\mathcal{U}_i}$$

PROOF. Fix $C : \mathcal{U}_i$. We have an equivalence

$$\begin{array}{c} \Pi_{a:2}(B(a) \rightarrow C) \rightarrow C \\ \downarrow c \mapsto (c(0), c(1)) \\ \left((B(0) \rightarrow C) \rightarrow C \right) \times \left((B(1) \rightarrow C) \rightarrow C \right) \end{array}$$

Since $B(0) = 0$, the type $B(0) \rightarrow C$ is contractible, with center $\lambda_{b:B(0)} 0\text{rec}(C, F b)$. We thus have an equivalence

$$\begin{array}{c} (B(0) \rightarrow C) \rightarrow C \\ \downarrow u \mapsto u(\lambda_{b:B(0)} 0\text{rec}(C, F b)) \\ C \end{array}$$

Since $B(1) = 1$, the map $x \mapsto \lambda_- x$ is an equivalence from C to $B(1) \rightarrow C$. Thus, we have an equivalence

$$\begin{array}{c} (B(1) \rightarrow C) \rightarrow C \\ \downarrow u \mapsto \lambda_{x:C} u(\lambda_- x) \\ C \rightarrow C \end{array}$$

Putting this all together, we see that the map

$$(C, c) \mapsto \left(C, c(0, \lambda_b 0\text{rec}(C, F b)), \lambda_{x:C} c(1, \lambda_- x) \right)$$

is an equivalence from $\mathbf{W}\text{-Alg}_{\mathcal{U}_i}(A, B)$ to $\mathbb{N}\text{-Alg}_{\mathcal{U}_i}$. \square

LEMMA 5.11. *For any $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_i}(A, B)$ there is an equivalence*

$$\mathbf{W}\text{-to-}\mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j} : \mathbf{W}\text{-Fib-Alg}_{\mathcal{U}_j}(A, B) \mathcal{X} \rightarrow \mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j}(\mathbf{W}\text{-to-}\mathbb{N}\text{-Alg}_{\mathcal{U}_i}(\mathcal{X}))$$

PROOF. Let an algebra $(C, c) : \mathbf{W}\text{-Alg}_{\mathcal{U}_i}(A, B)$ be given and fix $E : C \rightarrow \mathcal{U}_j$. We have an equivalence

$$\begin{array}{c} \Pi_{a:2} \Pi_{t:B(a) \rightarrow C} (\Pi_{b:B(a)} E(t b)) \rightarrow E(c(a, t)) \\ \downarrow e \mapsto (e(0), e(1)) \\ \left(\Pi_{t:B(0) \rightarrow C} (\Pi_{b:B(0)} E(t b)) \rightarrow E(c(0, t)) \right) \times \left(\Pi_{t:B(1) \rightarrow C} (\Pi_{b:B(1)} E(t b)) \rightarrow E(c(1, t)) \right) \end{array}$$

Since $B(0) = 0$, the type $B(0) \rightarrow C$ is contractible, with center $\lambda_{b:B(0)} 0\text{rec}(C, F b)$. Likewise, $\Pi_{b:B(0)} E(0\text{rec}(C, F b))$ is contractible, with center $\lambda_{b:B(0)} 0\text{rec}(E(0\text{rec}(C, F b)), F b)$. We thus have equivalences

$$\begin{array}{c}
\Pi_{t:B(0) \rightarrow C} (\Pi_{b:B(0)} E(t \ b)) \rightarrow E(c(0, t)) \\
\downarrow u \mapsto u(\lambda_{b:B(0)} \mathbf{0rec}(C, F \ b)) \\
(\Pi_{b:B(0)} E(\mathbf{0rec}(C, F \ b))) \rightarrow E(c(0, \lambda_{b:B(0)} \mathbf{0rec}(C, F \ b))) \\
\downarrow u \mapsto u(\lambda_{b:B(0)} \mathbf{0rec}(E(\mathbf{0rec}(C, F \ b)), F \ b)) \\
E(c(0, \lambda_{b:B(0)} \mathbf{0rec}(C, F \ b)))
\end{array}$$

Since $B(1) = 1$, the map $x \mapsto \lambda_- x$ is an equivalence from C to $B(1) \rightarrow C$. Likewise, for any $x : C$ the map $y \mapsto \lambda_- y$ is an equivalence from $E(x)$ to $B(1) \rightarrow E(x)$. Thus, we have equivalences

$$\begin{array}{c}
\Pi_{t:B(1) \rightarrow C} (\Pi_{b:B(1)} E(t \ b)) \rightarrow E(c(1, t)) \\
\downarrow u \mapsto \lambda_{x:C} u(\lambda_- x) \\
\Pi_{x:C} (B(1) \rightarrow E(x)) \rightarrow E(c(1, \lambda_- x)) \\
\downarrow u \mapsto \lambda_{x:C} \lambda_{y:E(x)} u(x, \lambda_- y) \\
\Pi_{x:C} E(x) \rightarrow E(c(1, \lambda_- x))
\end{array}$$

Putting this all together, we see that the map

$$(E, e) \mapsto (E, e(0, \lambda_b \mathbf{0rec}(C, F \ b), \lambda_b \mathbf{0rec}(E(\mathbf{0rec}(C, F \ b)), F \ b)), \lambda_{x:C} \lambda_{y:E(x)} e(1, \lambda_- x, \lambda_- y))$$

is an equivalence from $\mathbf{W}\text{-Fib-Alg}_{\mathcal{U}_j}(A, B) \ (C, c)$ to $\mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j}(\mathbf{W}\text{-to-}\mathbb{N}\text{-Alg}_{\mathcal{U}_i}(C, c))$. \square

LEMMA 5.12. *For any $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_i}(A, B)$ and $\mathcal{Y} : \mathbf{W}\text{-Fib-Alg}_{\mathcal{U}_j}(A, B) \ \mathcal{X}$ we have*

$$\mathbf{W}\text{-Fib-Hom} \ \mathcal{X} \ \mathcal{Y} \ \simeq \ \mathbb{N}\text{-Fib-Hom} \ (\mathbf{W}\text{-to-}\mathbb{N}\text{-Alg}_{\mathcal{U}_i}(\mathcal{X})) \ (\mathbf{W}\text{-to-}\mathbb{N}\text{-Fib-Alg}_{\mathcal{U}_j}(\mathcal{Y}))$$

PROOF. Let algebras $(C, c) : \mathbf{W}\text{-Alg}_{\mathcal{U}_i}(A, B)$ and $(E, e) : \mathbf{W}\text{-Fib-Alg}_{\mathcal{U}_j}(A, B) \ (C, c)$ be given and fix $f : \Pi_{x:C} E(x)$. We have an equivalence

$$\begin{array}{c}
\Pi_{a:2} \Pi_{t:B(a) \rightarrow C} f(c(a, t)) = e(a, t, \lambda_{b:B(a)} f(t \ b)) \\
\downarrow \simeq \\
\left(\Pi_{t:B(0) \rightarrow C} f(c(0, t)) = e(0, t, \lambda_b f(t \ b)) \right) \times \left(\Pi_{t:B(1) \rightarrow C} f(c(1, t)) = e(1, t, \lambda_b f(t \ b)) \right)
\end{array}$$

Since $B(0) = 0$, the type $B(0) \rightarrow C$ is contractible, with center $\lambda_{b:B(0)} \mathbf{0rec}(C, F \ b)$. Furthermore, since all functions out of 0 are equal, we have

$$\lambda_b f(\mathbf{0rec}(C, F \ b)) = \lambda_b \mathbf{0rec}(E(\mathbf{0rec}(C, F \ b)), F \ b)$$

This implies the following equivalences:

$$\begin{aligned}
\Pi_{t:B(0) \rightarrow C} f(c(0, t)) &= e(0, t, \lambda_b f(t \ b)) \\
&\quad \Big| \simeq \\
f(c(0, \lambda_b 0\text{rec}(C, F \ b))) &= e(0, \lambda_b 0\text{rec}(C, F \ b), \lambda_b f(0\text{rec}(C, F \ b))) \\
&\quad \Big| \simeq \\
f(c(0, \lambda_b 0\text{rec}(C, F \ b))) &= e(0, \lambda_b 0\text{rec}(C, F \ b), \lambda_b 0\text{rec}(E(0\text{rec}(C, F \ b)), F \ b))
\end{aligned}$$

Since $B(1) = 1$, the map $x \mapsto \lambda_- x$ is an equivalence from C to $B(1) \rightarrow C$. Thus, we have an equivalence

$$\begin{aligned}
\Pi_{t:B(1) \rightarrow C} f(c(1, t)) &= e(1, t, \lambda_b f(t \ b)) \\
&\quad \Big| \simeq \\
\Pi_{x:C} f(c(1, \lambda_- x)) &= e(1, \lambda_- x, \lambda_- f(x))
\end{aligned}$$

This finishes the proof. \square

COROLLARY 5.13. *For any $\mathcal{X} : \mathbf{W}\text{-Alg}_{\mathcal{U}_i}(A, B)$ and $\mathcal{Y} : \mathbf{W}\text{-Alg}_{\mathcal{U}_j}(A, B)$ we have*

$$\mathbf{W}\text{-Hom } \mathcal{X} \ \mathcal{Y} \ \simeq \ \mathbf{N}\text{-Hom } (\mathbf{W}\text{-to-}\mathbf{N}\text{-Alg}_{\mathcal{U}_i}(\mathcal{X})) \ (\mathbf{W}\text{-to-}\mathbf{N}\text{-Alg}_{\mathcal{U}_j}(\mathcal{Y}))$$

COROLLARY 5.14. *For any $\mathcal{X} : \mathbf{N}\text{-Alg}_{\mathcal{U}_i}$ we have*

$$\begin{aligned}
\text{has-}\mathbf{N}\text{-rec}_{\mathcal{U}_j}(\mathcal{X}) &\simeq \text{has-}\mathbf{W}\text{-rec}_{\mathcal{U}_j}(\mathbf{W}\text{-to-}\mathbf{N}\text{-Alg}_{\mathcal{U}_i}^{-1}(\mathcal{X})) \\
\text{has-}\mathbf{N}\text{-ind}_{\mathcal{U}_j}(\mathcal{X}) &\simeq \text{has-}\mathbf{W}\text{-ind}_{\mathcal{U}_j}(\mathbf{W}\text{-to-}\mathbf{N}\text{-Alg}_{\mathcal{U}_i}^{-1}(\mathcal{X})) \\
\text{has-}\mathbf{N}\text{-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) &\simeq \text{has-}\mathbf{W}\text{-rec-uniq}_{\mathcal{U}_j}(\mathbf{W}\text{-to-}\mathbf{N}\text{-Alg}_{\mathcal{U}_i}^{-1}(\mathcal{X})) \\
\text{has-}\mathbf{N}\text{-ind-uniq}_{\mathcal{U}_j}(\mathcal{X}) &\simeq \text{has-}\mathbf{W}\text{-ind-uniq}_{\mathcal{U}_j}(\mathbf{W}\text{-to-}\mathbf{N}\text{-Alg}_{\mathcal{U}_i}^{-1}(\mathcal{X})) \\
\text{is-}\mathbf{N}\text{-hinit}_{\mathcal{U}_j}(\mathcal{X}) &\simeq \text{is-}\mathbf{W}\text{-hinit}_{\mathcal{U}_j}(\mathbf{W}\text{-to-}\mathbf{N}\text{-Alg}_{\mathcal{U}_i}^{-1}(\mathcal{X}))
\end{aligned}$$

COROLLARY 5.15. *In \mathcal{H} , the following conditions on an algebra $\mathcal{X} : \mathbf{N}\text{-Alg}_{\mathcal{U}_i}$ are equivalent:*

- (1) \mathcal{X} satisfies the induction principle on the universe \mathcal{U}_j
- (2) \mathcal{X} satisfies the recursion and recursion uniqueness principles on the universe \mathcal{U}_j
- (3) \mathcal{X} is homotopy-initial on the universe \mathcal{U}_j

for $j \geq i$. In other words, we have

$$\text{has-}\mathbf{N}\text{-ind}_{\mathcal{U}_j}(\mathcal{X}) \simeq \text{has-}\mathbf{N}\text{-rec}_{\mathcal{U}_j}(\mathcal{X}) \times \text{has-}\mathbf{N}\text{-rec-uniq}_{\mathcal{U}_j}(\mathcal{X}) \simeq \text{is-}\mathbf{N}\text{-hinit}_{\mathcal{U}_j}(\mathcal{X})$$

provided $j \geq i$. Furthermore, all 3 conditions are mere propositions.

We can thus characterize the type \mathbf{N} using the universal property of initiality as follows.

COROLLARY 5.16. *In \mathcal{H} with natural numbers, the algebra $(\mathbf{N}, z, \text{suc}(-)) : \mathbf{N}\text{-Alg}_{\mathcal{U}_0}$ is homotopy-initial on any universe \mathcal{U}_j .*

COROLLARY 5.17. *In \mathcal{H} extended with an algebra $\mathcal{X} : \mathbf{N}\text{-Alg}_{\mathcal{U}_0}$ which is homotopy-initial on any universe \mathcal{U}_j , the type \mathbf{N} with propositional computation rules is definable.*

PROOF. We have an algebra $\cdot \vdash \mathcal{X} : \mathbb{N}\text{-Alg}_{\mathcal{U}_0}$ such that for any j , there exists a term $\cdot \vdash h_j : \text{is-}\mathbb{N}\text{-hinit}_{\mathcal{U}_j}(\mathcal{X})$. Since the requirement $j \geq 0$ always holds, Cor. 5.15 implies that for any j , we have a term $\cdot \vdash r_j : \text{has-}\mathbb{N}\text{-ind}_{\mathcal{U}_j}(\mathcal{X})$. This implies that the type \mathbb{N} with propositional computation rules is definable. \square

6. FUTURE WORK

ACKNOWLEDGMENTS

We would like to thank Vladimir Voevodsky and Michael Warren for helpful discussions on the subject of this paper. In particular, Vladimir Voevodsky suggested a simplification of the proof that the rules for homotopical W-types imply h-initiality.

Steve Awodey gratefully acknowledges the support of the National Science Foundation, Grant DMS-1001191 and the Air Force OSR, Grant 11NL035. Nicola Gambino is grateful for the support of the Institute for Advanced Study, where he worked on this project. This work was supported by the National Science Foundation under agreement No. DMS-0635607. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Kristina Sojakova is grateful for the support of CyLab at Carnegie Mellon under grants DAAD19-02-1-0389 and W911NF-09-1-0273 from the Army Research Office.

REFERENCES

- M. Abbott, T. Altenkirch, and N. Ghani. 2005. Containers: Constructing strictly positive types. *Theoretical Computer Science* 342, 1 (2005), 3–27.
- T. Altenkirch, C. McBride, and W. Swierstra. 2007. Observational equality, now. In *Programming languages meets program verification (PLPV '07)*. ACM, 57–68.
- S. Awodey. 2010. Type theory and homotopy. (2010). Available from the author's web page.
- S. Awodey and A. Bauer. 2004. Propositions as [types]. *Journal of Logic and Computation* 14, 4 (2004), 447–471.
- S. Awodey, N. Gambino, and K. Sojakova. 2011. Inductive types in Homotopy Type Theory: Coq proofs. (2011). Available at: www.andrew.cmu.edu/~awodey/hott/ithottCoq.zip.
- S. Awodey and M. Warren. 2009. Homotopy-theoretic models of identity types. *Mathematical Proceedings of the Cambridge Philosophical Society* 146, 1 (2009), 45–55.
- M. Batanin. 1998. Monoidal globular categories as a natural environment for the theory of weak n -categories. *Advances in Mathematics* 136, 1 (1998), 39–103.
- Y. Bertot and P. Castéran. 2004. *Interactive Theorem Proving and Program Development. Coq'Art: the Calculus of Inductive Constructions*. Springer-Verlag.
- T. Coquand and C. Paulin-Mohring. 1990. Inductively defined types. In *International Conference on Computer Logic (COLOG '88) (LNCS)*, Vol. 417. Springer.
- P. Dybjer. 1997. Representing inductively defined sets by well-orderings in Martin-Löf's type theory. *Theoretical Computer Science* 176 (1997), 329–335.
- N. Gambino and M. Hyland. 2004. Well-founded trees and dependent polynomial functors. In *Types for Proofs and Programs (TYPES '03) (LNCS)*, S. Berardi, M. Coppo, and F. Damiani (Eds.), Vol. 3085. 210–225.
- R. Garner. 2009. On the strength of dependent products in the type theory of Martin-Löf. *Annals of Pure and Applied Logic* 160 (2009), 1–12.
- H. Goguen and Z. Luo. 1993. Inductive data types: well-ordering types revisited. In *Logical Environments*, G. Huet and G. Plotkin (Eds.). Cambridge University Press, 198–218.
- E. Griffor and M. Rathjen. 1994. The strength of some Martin-Löf type theories. *Archive for Mathematical Logic* 33, 5 (1994), 347–385.
- M. Hofmann. 1997. *Extensional constructs in intensional type theory*. Springer-Verlag.
- M. Hofmann and T. Streicher. 1998. The groupoid interpretation of type theory. In *Twenty-five years of constructive type theory 1995 (Oxford Logic Guides)*, Vol. 36. Oxford Univ. Press, 83–111.
- W. Howard. 1980. The formulae-as-types notion of construction. In *To H.B. Curry: Essays on Combinatory Logic, Lambda Calculus and Formalism*, J. Seldin and J. Hindley (Eds.). Academic Press, 479–490.
- T. Leinster. 2004. *Higher operads, higher categories*. Cambridge University Press.
- P. Lumsdaine. 2010a. *Higher categories from type theories*. Ph.D. Dissertation. Carnegie Mellon University.
- P. Lumsdaine. 2010b. Weak ω -categories from intensional type theory. *Logical Methods in Computer Science* 6 (2010), 1–19.

- P. Lumsdaine. 2011. Higher inductive types: a tour of the menagerie. (2011). Post on the Homotopy Type Theory blog.
- P. Martin-Löf. 1975. An Intuitionistic Theory of Types: Predicative Part. In *Logic Colloquium 1973*, H. Rose and J. Shepherdson (Eds.). North-Holland, 73–118.
- P. Martin-Löf. 1982. Constructive mathematics and computer programming. In *Logic, Methodology and Philosophy of Science*. North-Holland, 153–175.
- P. Martin-Löf. 1984. Intuitionistic Type Theory. Notes by G. Sambin of a series of lectures given in Padua, 1980. (1984). Bibliopolis.
- C. McBride. 2010. W-types: good news and bad news. (2010). Post on the Epigram blog.
- C. McBride and J. McKinna. 2004. The view from the left. *Journal of Functional Programming* 14, 1 (2004), 16–111.
- I. Moerdijk and E. Palmgren. 2000. Well-founded trees in categories. *Annals of Pure and Applied Logic* 104 (2000), 189–218.
- B. Nordstrom, K. Petersson, and J. Smith. 1990. *Programming in Martin-Löf type theory*. Oxford University Press.
- B. Nordstrom, K. Petersson, and J. Smith. 2000. Martin-Löf type theory. In *Handbook of Logic in Computer Science*, Vol. 5. Oxford University Press, 1–37.
- U. Norell. 2007. *Towards a Practical Programming Language Based on Dependent Type Theory*. Ph.D. Dissertation. Chalmers University of Technology.
- C. Paulin-Mohring. 1993. Inductive definitions in the system Coq - rules and properties. In *Typed Lambda Calculi and Applications (TLCA '93)*, Vol. 664. Springer.
- K. Petersson and D. Synek. 1989. A set constructor for inductive sets in Martin-Löf type theory. In *Category Theory and Computer Science (LNCS)*, Vol. 389. Springer-Verlag.
- M. Shulman. 2011. Homotopy Type Theory, VI. (2011). Post on the n-category cafe blog.
- T. Streicher. 1993. Investigations into intensional type theory. (1993). Habilitation Thesis. Available from the author's web page.
- B. van den Berg and R. Garner. 2011. Types are weak ω -groupoids. *London Mathematical Society* 102, 2 (2011), 370–394.
- B. van den Berg and R. Garner. 2012. Topological and Simplicial Models of Identity Types. *ACM Transactions on Computational Logic* 13, 1 (2012).
- V. Voevodsky. 2009. Notes on type systems. (2009). Available from the author's web page.
- V. Voevodsky. 2010a. Univalent foundations Coq files. (2010). Available from the author's web page.
- V. Voevodsky. 2010b. Univalent foundations project. (2010). Available from the author's web page.

Received ; revised ; accepted