

Volume I: Foundations

Introduction to Homotopy Type Theory

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Issue I: Type Theory

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Анотація

Background. The long road from pure type systems of AUTOMATH by de Bruijn to type checkers with homotopical core was made. This article touches only the formal Martin-Löf Type Theory core type system with Π and Σ types (that correspond to \forall and \exists quantifiers for mathematical reasoning) and identity type (MLTT-75). Expressing the MLTT embedding in a host type checker for a long time was inaccessible due to the non-derivability of the J eliminator in pure functions. This was recently made possible by cubical type theory and cubical type checker.

Objective. Select the type system as a part of conceptual model of theorem proving system that is able to derive the J eliminator and its theorems based on the latest research in cubical type systems. The goal of this article is to demonstrate the formal embedding of MLTT-75 into **Per** with constructive proofs of the complete set of inference rules including J eliminator.

Methods. As types are formulated using 5 types of rules (formation, intro, elimination, computation, uniqueness) according to MLTT we constructed aliases for the host language primitives and used the cubical type checker to prove that it has the realization of MLTT-75.

Results. This work leads to several results: 1) **Per** — a special embedded version of type theory with infinite number of universes and Path type suitable for HoTT purposes without uniqueness rule of equality type; 2) The actual embedding of MLTT with syntax implying universe polymorphism and cubical primitives in **Per**; 3) The different interpretations of types were given: set-theoretical, groupoid, homotopical; 4) Internalization could be seen as an ultimate test sample for type checker as intro-elimination fusion resides in beta-eta rules, so by proving them, we prove properties of the host type checker.

Conclusion. We should note that this is an entrance to the internalization technique, and after formal MLTT embedding, we could go through inductive types up to embedding of CW-complexes as the indexed gluing of the higher inductive types. This means the implementation of a wide spectrum of math theories inside HoTT up to algebraic topology.

Keywords: Martin-Löf Type Theory, Cubical Type Theory.

Introduction

Each language implementation needs to be checked. The one of possible test cases for type checkers is the direct embedding of type theory model into the language of type checker. As types in Martin-Löf Type Theory [3, 5] are formulated using 5 types of rules (formation, introduction, elimination, computation, uniqueness), we construct aliases for host language primitives and use type checker to prove that it is MLTT-75. This could be seen as ultimate test sample for type checker as intro-elimination fusion resides in beta-eta rules, so by proving them we prove properties of the host type checker.

Also this issue opens a series of articles dedicated to formalization in cubical type theory the foundations of mathematics. This issue is dedicated to MLTT modeling and its verification. Also as many may not be familiar with Π and Σ types, this issue presents different interpretation of MLTT types.

This test is fully made possible only after 2017 when new constructive HoTT [1] prover cubicaltt¹ prover was presented [17].

Problem Statement

The formal initial problem was to create a full self-contained MLTT internalization in the host typechecker, where all theorems are being checked constructively. This task involves a modern techniques in type theory, namely cubical type theories. By following most advaced theories apply this results for building minimal type checker that is able to derive J and the whole MLTT theorems constructively. This leads us to the compact MLTT core yet compatible with future possible homotopy extensions.

Per Language Syntax

The BNF notation of type checker language used in code samples consists of: i) telescopes (contexts or sigma chains) and definitions; ii) pure dependent type theory syntax; iii) inductive data definitions (sum chains) and split eliminator; iv) cubical face system; v) module system. It is slightly based on cubicaltt.

```
sys := [ sides ]
side := (id=0)→exp +(id=1)→exp
f1 := f1 /\ f2
f2 := -f2 + id + 0 + 1
form := form \/ f1 + f1 + f2
sides := #empty + cos + side
cos := side , side + side , cos
id := #list #nat
ids := #list id
mod := module id where imps dec
imps := #list imp
imp := import id
brs := #empty + cobrs
cobrs := | br brs
```

¹<http://github.com/mortberg/cubicaltt>

```

br := ids → exp +ids @ ids → exp
tel := #empty + cotel
dec := #empty + codec
cotel := (exp:exp) tel
codec := def dec
sum := #empty + id tel + id tel | sum
def := data id tel=sum +id tel:exp=exp
      + id tel : exp where def
app := exp exp
exp := cotel * exp + cotel → exp
      + exp → exp +(exp) +id
      + (exp,exp) + \cotele → exp
      + split cobrs +exp .1
      + exp .2 + ⟨ ids ⟩ exp
      + exp @ form + app + comp exp sys

```

Here `:=` (definition), `+` (disjoint sum), `#empty`, `#nat`, `#list` are parts of BNF language and `|`, `:`, `*`, `⟨ ⟩`, `(,)`, `=`, `\`, `/`, `-`, `→`, `0`, `1`, `@`, `[,]`, **module**, **import**, **data**, **split**, **where**, **comp**, **.1**, **.2**, and `,` are terminals of type checker language. This language includes inductive types, higher inductive types and gluening operations needed for both, the constructive homotopy type theory and univalence. All these concepts as a part of the languages will be described in the upcoming **Issues II — V**.

1 Interpretations

Martin-Löf Type Theory MLTT-80 contains Π , Σ , Id, W, 0, 1, 2 types.

Any new type in MLTT presented with set of 5 rules: i) formation rules, the signature of type; ii) the set of constructors which produce the elements of formation rule signature; iii) the dependent eliminator or induction principle for this type; iv) the beta-equality or computational rule; v) the eta-equality or uniqueness principle. Π , Σ , and Path types will be given shortly. This interpretation or rather way of modeling is MLTT specific.

The most interesting are Id types. Id types were added in MLTT-75 [5] while original MLTT-72 with only Π and Σ was introduced in [3]. Predicative Universe Hierarchy was added in [4]. While original MLTT-75 contains Id types that preserve uniqueness of identity proofs (UIP) or eta-rule of Id type, HoTT refutes UIP (eta rule doesn't hold) and introduces univalent heterogeneous Path equality [7].

Path types are essential to prove computation and uniqueness rules for all types (needed for building signature and terms), so we will be able to prove all the MLTT rules as a whole.

In contexts you can bind to variables (through de Bruijn indexes or string names): i) indexed universes; ii) built-in types; iii) user constructed types, and ask questions about type derivability, type checking and code extraction. This system defines the core type checker within its language.

By using this languages it is possible to encode different interpretations of type theory itself and its syntax by construction. Usually the issues will refer to

following interpretations: i) type-theoretical; ii) categorical; iii) set-theoretical; iv) homotopical; v) fibrational or geometrical.

Табл. 1: *

Table. Interpretations correspond to mathematical theories

Type Theory	Logic	Category Theory	Homotopy Theory
A type	class	object	space
isProp A	proposition	(-1)-truncated object	space
a:A program	proof	generalized element	point
$B(x)$	predicate	indexed object	fibration
$b(x) : B(x)$	conditional proof	indexed elements	section
\emptyset	\perp false	initial object	empty space
$\mathbf{1}$	\top true	terminal object	singleton
$A + B$	$A \vee B$ disjunction	coproduct	coproduct space
$A \times B$	$A \wedge B$ conjunction	product	product space
$A \rightarrow B$	$A \Rightarrow B$	internal hom	function space
$\sum x : A, B(x)$	$\exists_{x:A} B(x)$	dependent sum	total space
$\prod x : A, B(x)$	$\forall_{x:A} B(x)$	dependent product	space of sections
\mathbf{Path}_A	equivalence $=_A$	path space object	path space A^I
quotient	equivalence class	quotient	quotient
W-type	induction	colimit	complex
type of types	universe	object classifier	universe
quantum circuit	proof net	string diagram	

1.1 Logical Interpretation

According to type theoretical interpretation of MLTT for any type should be provided 5 formal inference rules: i) formation; ii) introduction; iii) dependent elimination principle; iv) beta rule or computational rule; v) eta rule or uniqueness rule. The last one could be exceptional for Path types. The formal representation of all rules of MLTT are given according to type-theoretical interpretation as a final result in this Issue I. It was proven that classical Logic could be embedded into intuitionistic propositional logic (IPL) which is directly embedded into MLTT.

Logical and type-theoretical interpretations could be distinguished. Also set-theoretical interpretation is not presented in the Table.

1.2 Categorical Interpretation

Categorical interpretation [11] is a modeling through categories and functors. First category is defined as objects, morphisms and their properties, then we define functors, etc. In particular, as an example, according to categorical interpretation Π and Σ types of MLTT are presented as adjoint functors, and forms itself a locally closed cartesian category, which will be given an intermediate result in future issues. In some sense we include here topos-theoretical interpretation.

tations, with presheaf model of type theory as example (in this case fibrations are constructed as functors, categorically).

1.3 Homotopical Interpretation

In classical MLTT uniqueness rule of Id type does not hold strictly. In Homotopical interpretation of MLTT we need to allow a path space as Path type where uniqueness rule doesn't hold. Groupoid interpretation of Path equality that doesn't hold UIP generally was given in 1996 by Martin Hofmann and Thomas Streicher [7].

When objects are defined as fibrations, or dependent products, or indexed-objects this leads to fibrational semantics and geometric sheaf interpretation. Several definition of fiber bundles and trivial fiber bundle as direct isomorphisms of Π types is given here as theorem. As fibrations study in homotopical interpretation, geometric interpretation could be treated as homotopical.

1.4 Set Interpretation

Set-theoretical interpretations could replace first-order logic, but could not allow higher equalities, as long as inductive types to be embedded directly. Set is modelled in type theory according to homotopical interpretation as n-type.

MLTT-80 could be reduced to Π , Σ , Path types (MLTT-75) omitting polynomial functors W modeled by F-algebras and their terminators: 0, 1, 2 types. In this issue Π , Σ , Path are given as a core of MLTT-75. The inductive types will be discussed in the upcoming **Issue II: Inductive Types**.

2 Internalized Type Theory

2.1 Dependent Product (Π)

Π is a dependent product type, the generalization of functions. As a function it can serve the wide range of mathematical constructions as its domain and codomain, which are in general: objects, types, or spaces; and could have as its instance: sets, functions, polynomial functors, infinitesimals, ∞ -groupoids, topological ∞ -groupoid, CW-complexes, categories, languages, etc.

At this light there could be many interpretation of Π types from different areas of mathematics. We give here three: i) logical interpretation of Π as \forall quantifier from higher order logic that forms a ground of type theory; ii) geometric interpretation of Π as fiber bundle; iii) categorical interpretation of functions as functors.

Type-theoretical interpretation

As a logical system dependent type theory could correspond to higher order logic. However here only type-theoretical model is given completely.

Definition 1. (Π -Formation).

$$(x : A) \rightarrow B(x) =_{def} \prod_{x:A} B(x) : U.$$

$$\text{Pi } (A : U) (B : A \rightarrow U) : U = (x : A) \rightarrow B \ x$$

Definition 2. (Π -Introduction).

$$\backslash (x : A) \rightarrow b =_{def} \prod_{A:U} \prod_{B:A \rightarrow U} \prod_{a:A} \prod_{b:B(a)} \lambda x.b : \prod_{y:A} B(y).$$

$$\begin{aligned} \text{lambda } (A B : U) (b : B) : A \rightarrow B &= \backslash (x : A) \rightarrow b \\ \text{lam } (A:U) (B : A \rightarrow U) (a:A) (b:B \ a) \\ : A \rightarrow B \ a &= \backslash (x : A) \rightarrow b \end{aligned}$$

Definition 3. (Π -Elimination).

$$f \ a =_{def} \prod_{A:U} \prod_{B:A \rightarrow U} \prod_{a:A} \prod_{f:\prod_{x:A} B(x)} f(a) : B(a).$$

$$\begin{aligned} \text{apply } (A B : U) (f : A \rightarrow B) (a : A) : B &= f \ a \\ \text{app } (A : U) (B : A \rightarrow U) (a : A) \\ (f : A \rightarrow B \ a) : B \ a &= f \ a \end{aligned}$$

Theorem 1. (Π -Computation).

$$f(a) =_{B(a)} (\lambda(x : A) \rightarrow f(a))(a).$$

$$\begin{aligned} \text{Beta } (A : U) (B : A \rightarrow U) (a : A) (f : A \rightarrow B \ a) \\ : \text{Path } (B \ a) (\text{app } A \ B \ a \ (\text{lam } A \ B \ a \ (f \ a))) \\ (f \ a) \end{aligned}$$

Theorem 2. (Π -Uniqueness).

$$f =_{(x:A) \rightarrow B(a)} (\lambda(y : A) \rightarrow f(y)).$$

$$\begin{aligned} \text{Eta } (A : U) (B : A \rightarrow U) (a : A) (f : A \rightarrow B \ a) \\ : \text{Path } (A \rightarrow B \ a) f (\backslash (x:A) \rightarrow f \ x) \end{aligned}$$

Categorical interpretation

The adjoints Π and Σ is not the only adjoints could be presented in type system. Axiomatic cohesions could contain a set of adjoint pairs as a core type checker operations.

Definition 4. (Dependent Product). The dependent product along morphism $g : B \rightarrow A$ in category C is the right adjoint $\Pi_g : C_{/B} \rightarrow C_{/A}$ of the base change functor.

Definition 5. (Space of Sections). Let \mathbf{H} be a $(\infty, 1)$ -topos, and let $E \rightarrow B : \mathbf{H}_{/B}$ a bundle in \mathbf{H} , object in the slice topos. Then the space of sections $\Gamma_\Sigma(E)$ of this bundle is the Dependent Product:

$$\Gamma_\Sigma(E) = \Pi_\Sigma(E) \in \mathbf{H}.$$

Theorem 3. (HomSet). If codomain is set then space of sections is a set.

```
setFun (A B : U) (⋅ : isSet B)
      : isSet (A → B)
```

Theorem 4. (Contractability). If domain and codomain is contractible then the space of sections is contractible.

```
piIsContr (A: U) (B: A → U) (u: isContr A)
          (q: (x: A) → isContr (B x))
          : isContr (Pi A B)
```

Definition 6. (Section). A section of morphism $f : A \rightarrow B$ in some category is the morphism $g : B \rightarrow A$ such that $f \circ g : B \xrightarrow{g} A \xrightarrow{f} B$ equals the identity morphism on B .

Homotopical interpretation

Geometrically, Π type is a space of sections, while the dependent codomain is a space of fibrations. Lambda functions are sections or points in these spaces, while the function result is a fibration. Π type also represents the cartesian family of sets, generalizing the cartesian product of sets.

Definition 7. (Fiber). The fiber of the map $p : E \rightarrow B$ in a point $y : B$ is all points $x : E$ such that $p(x) = y$.

Definition 8. (Fiber Bundle). The fiber bundle $F \rightarrow E \xrightarrow{p} B$ on a total space E with fiber layer F and base B is a structure (F, E, p, B) where $p : E \rightarrow B$ is a surjective map with following property: for any point $y : B$ exists a neighborhood U_b for which a homeomorphism $f : p^{-1}(U_b) \rightarrow U_b \times F$ making the following diagram commute.

$$\begin{array}{ccc} p^{-1}(U_b) & \xrightarrow{f} & U_b \times F \\ p \downarrow & \swarrow pr_1 & \\ U_b & & \end{array}$$

Definition 9. (Cartesian Product of Family over B). Is a set F of sections of the bundle with elimination map $app : F \times B \rightarrow E$ such that

$$F \times B \xrightarrow{app} E \xrightarrow{pr_1} B \quad (1)$$

pr_1 is a product projection, so pr_1, app are morphisms of slice category Set/B . The universal mapping property of F : for all A and morphism $A \times B \rightarrow E$ in Set/B exists unique map $A \rightarrow F$ such that everything commute. So a category with all dependent products is necessarily a category with all pullbacks.

Definition 10. (Trivial Fiber Bundle). When total space E is cartesian product $\Sigma(B, F)$ and $p = pr_1$ then such bundle is called trivial $(F, \Sigma(B, F), pr_1, B)$.

Theorem 5. (Functions Preserve Paths). For a function $f : (x : A) \rightarrow B(x)$ there is an $ap_f : x =_A y \rightarrow f(x) =_{B(x)} f(y)$. This is called application of f to path or congruence property (for non-dependent case — *cong* function). This property behaves functorially as if paths are groupoid morphisms and types are objects.

Theorem 6. (Trivial Fiber equals Family of Sets). Inverse image (fiber) of fiber bundle $(F, B * F, pr_1, B)$ in point $y : B$ equals $F(y)$.

FiberPi (B: U) (F: B \rightarrow U) (y: B)
 : Path U (fiber (Sigma B F) B (pi1 B F) y)
 (F y)

Theorem 7. (Homotopy Equivalence). If fiber space is set for all base, and there are two functions $f, g : (x : A) \rightarrow B(x)$ and two homotopies between them, then these homotopies are equal.

setPi (A: U) (B: A \rightarrow U)
 (h: (x: A) \rightarrow isSet (B x)) (f g: Pi A B)
 (p q: Path (Pi A B) f g)
 : Path (Path (Pi A B) f g) p q

Note that we will not be able to prove this theorem until **Issue III: Homotopy Type Theory** because bi-invertible iso type will be announced there.

2.2 Dependent Sum (Σ)

Σ is a dependent sum type, the generalization of products. Σ type is a total space of fibration. Element of total space is formed as a pair of basepoint and fibration.

Type-theoretical interpretation

Definition 11. (Σ -Formation).

Sigma (A : U) (B : A \rightarrow U)
 : U = (x : A) * B x

Definition 12. (Σ -Introduction).

$\text{dpair} \ (A: U) \ (B: A \rightarrow U) \ (a: A) \ (b: B \ a)$
 $\quad : \text{Sigma } A \ B = (a, b)$

Definition 13. (Σ -Elimination).

$\text{pr1} \ (A: U) \ (B: A \rightarrow U)$
 $\quad (x: \text{Sigma } A \ B): A = x.1$

$\text{pr2} \ (A: U) \ (B: A \rightarrow U)$
 $\quad (x: \text{Sigma } A \ B): B \ (\text{pr1 } A \ B \ x) = x.2$

$\text{sigInd} \ (A: U) \ (B: A \rightarrow U)$
 $\quad (C: \text{Sigma } A \ B \rightarrow U)$
 $\quad (g: (a: A) \ (b: B \ a) \rightarrow C \ (a, \ b))$
 $\quad (p: \text{Sigma } A \ B) : C \ p = g \ p.1 \ p.2$

Theorem 8. (Σ -Computation).

$\text{Beta1} \ (A: U) \ (B: A \rightarrow U)$
 $\quad (a: A) \ (b: B \ a)$
 $\quad : \text{Equ } A \ a \ (\text{pr1 } A \ B \ (a, b))$

$\text{Beta2} \ (A: U) \ (B: A \rightarrow U)$
 $\quad (a: A) \ (b: B \ a)$
 $\quad : \text{Equ } (B \ a) \ b \ (\text{pr2 } A \ B \ (a, b))$

Theorem 9. (Σ -Uniqueness).

$\text{Eta2} \ (A: U) \ (B: A \rightarrow U) \ (p: \text{Sigma } A \ B)$
 $\quad : \text{Equ } (\text{Sigma } A \ B) \ p \ (\text{pr1 } A \ B \ p, \text{pr2 } A \ B \ p)$

Categorical interpretation

Definition 14. (Dependent Sum). The dependent sum along the morphism $f: A \rightarrow B$ in category \mathcal{C} is the left adjoint $\Sigma_f: \mathcal{C}_{/A} \rightarrow \mathcal{C}_{/B}$ of the base change functor.

Set-theoretical interpretation

Theorem 10. (Axiom of Choice). If for all $x: A$ there is $y: B$ such that $R(x, y)$, then there is a function $f: A \rightarrow B$ such that for all $x: A$ there is a witness of $R(x, f(x))$.

$\text{ac} \ (A \ B: U) \ (R: A \rightarrow B \rightarrow U)$
 $\quad : (p: (x: A) \rightarrow (y: B) * (R \ x \ y))$
 $\rightarrow (f: A \rightarrow B) * ((x: A) \rightarrow R(x) (f \ x))$

Theorem 11. (Total). If fiber over base implies another fiber over the same base then we can construct total space of section over that base with another fiber.

```

total (A:U) (B C: A → U)
  (f: (x:A) → B x → C x) (w: Sigma A B)
  : Sigma A C = (w.1, f (w.1) (w.2))

```

Theorem 12. (Σ -Contractability). If the fiber is set then the Σ is set.

```

setSig (A:U) (B: A → U) (sA: isSet A)
  (sB : (x:A) → isSet (B x))
  : isSet (Sigma A B)

```

Theorem 13. (Path Between Sigmas). Path between two sigmas $t, u : \Sigma(A, B)$ could be decomposed to sigma of two paths $p : t_1 =_A u_1$ and $(t_2 =_{B(p@i)} u_2)$.

```

pathSig (A:U) (B : A → U) (t u : Sigma A B)
  : Path U (Path (Sigma A B) t u)
    ((p: Path A t.1 u.1)
     * PathP (<i>B(p@i)) t.2 u.2)

```

2.3 Path (Ξ)

The Path identity type or Ξ defines a Path space with elements and values. Elements of that space are functions from interval $[0, 1]$ to a values of that path space. This ctt file reflects ²CCHM cubicaltt model with connections. For ³ABCFHL yacctt model with variables please refer to ytt file. You may also want to read ⁴BCH, ⁵AFH. There is a ⁶PO paper about CCHM axiomatic in a topos.

Cubical interpretation

Cubical interpretation was first given by Simon Huber [18] and later was written first constructive type checker in the world by Anders Mörtberg [17].

Definition 15. (Path Formation).

```

Hetero (A B: U) (a: A) (b: B) (P: Path U A B)
  : U = PathP P a b
Path (A: U) (a b: A)
  : U = PathP (<i>A) a b

```

²Cyril Cohen, Thierry Coquand, Simon Huber, Anders Mörtberg. Cubical Type Theory: a constructive interpretation of the univalence axiom. 2015. <https://5ht.co/cubicaltt.pdf>

³Carlo Angiuli, Brunerie, Coquand, Kuen-Bang Hou (Favonia), Robert Harper, Dan Licata. Cartesian Cubical Type Theory. 2017. <https://5ht.co/ccctt.pdf>

⁴Marc Bezem, Thierry Coquand, Simon Huber. A model of type theory in cubical sets. 2014. <http://www.cse.chalmers.se/~coquand/mod1.pdf>

⁵Carlo Angiuli, Kuen-Bang Hou (Favonia), Robert Harper. Cartesian Cubical Computational Type Theory: Constructive Reasoning with Paths and Equalities. 2018. <https://www.cs.cmu.edu/~cangiuli/papers/ccctt.pdf>

⁶Andrew Pitts, Ian Orton. Axioms for Modelling Cubical Type Theory in a Topos. 2016. <https://arxiv.org/pdf/1712.04864.pdf>

Definition 16. (Path Reflexivity). Returns an element of reflexivity path space for a given value of the type. The inhabitant of that path space is the lambda on the homotopy interval $[0, 1]$ that returns a constant value a . Written in syntax as $|<i>a|$ which equals to $\lambda (i : I) \rightarrow a$.

`refl (A: U) (a: A) : Path A a a`

Definition 17. (Path Application). You can apply face to path.

`app1 (A: U) (a b:A) (p:Path A a b):A=p@0`
`app2 (A: U) (a b:A) (p:Path A a b):A=p@1`

Definition 18. (Path Composition). Composition operation allows to build a new path by given to paths in a connected point.

$$\begin{array}{ccc} & a & \xrightarrow{\text{comp}} c \\ \lambda(i : I) \rightarrow a \uparrow & & \uparrow q \\ a & \xrightarrow{p@i} & b \end{array}$$

`composition`
`(A: U) (a b c: A)`
`(p: Path A a b) (q: Path A b c)`
`: Path A a c`
`= comp (<i>Path A a (q@i)) p []`

Theorem 14. (Path Inversion).

`inv (A: U) (a b: A) (p: Path A a b)`
`: Path A b a = <i> p @ -i`

Definition 19. (Connections). Connections allows you to build square with given only one element of path: i) $\lambda (i, j : I) \rightarrow p @ \min(i, j)$; ii) $\lambda (i, j : I) \rightarrow p @ \max(i, j)$.

$$\begin{array}{ccc} & a & \xrightarrow{p} b \\ \lambda(i : I) \rightarrow a \uparrow & & \uparrow p \\ a & \xrightarrow{\lambda(i : I) \rightarrow a} & a \end{array} \quad \begin{array}{ccc} & b & \xrightarrow{\lambda(i : I) \rightarrow b} b \\ p \uparrow & & \uparrow \lambda(i : I) \rightarrow b \\ a & \xrightarrow{p} & b \end{array}$$

`meet (A: U) (a b: A) (p: Path A a b)`
`: PathP (<x> Path A a (p@x)) (<i>a) p`
`= <x y> p @ (x /\ y)`
`join (A: U) (a b: A) (p: Path A a b)`
`: PathP (<x> Path A (p@x) b) p (<i>b)`
`= <y x> p @ (x \/ y)`

Theorem 15. (Congruence). Is a map between values of one type to path space of another type by an encode function between types. Implemented as lambda defined on $[0, 1]$ that returns application of encode function to path application of the given path to lamda argument $|\lambda (i:I) \rightarrow f (p @ i)|$ for both cases.

```

ap  (A B: U) (f: A → B)
    (a b: A) (p: Path A a b)
    : Path B (f a) (f b)

apd (A: U) (a x:A) (B: A → U) (f: A → B a)
    (b: B a) (p: Path A a x)
    : Path (B a) (f a) (f x)

```

Theorem 16. (Transport). Transports a value of the domain type to the value of the codomain type by a given path element of the path space between domain and codomain types. Defined as path composition with $|||$ of a over a path p — $|comp\ p\ a\ |||$.

```

trans (A B: U) (p: Path U A B) (a: A) : B

```

Type-theoretical interpretation

Definition 20. (Singleton).

```

singl (A: U) (a: A): U = (x: A) * Path A a x

```

Theorem 17. (Singleton Instance).

```

eta (A: U) (a: A): singl A a = (a, refl A a)

```

Theorem 18. (Singleton Contractability).

```

contr (A: U) (a b: A) (p: Path A a b)
    : Path (singl A a) (eta A a) (b, p)
    = <i> (p @ i, <j> p @ i /\ j)

```

Theorem 19. (Path Elimination, Paulin-Mohring). J is formulated in a form of Paulin-Mohring and implemented using two facts that singleton are contractible and dependent function transport.

```

J (A: U) (a b: A)
    (P: singl A a → U)
    (u: P (a, refl A a))
    (p: Path A a b) : P (b, p)

```

Theorem 20. (Path Elimination, HoTT). J from HoTT book.

```

J (A: U) (a b: A)
    (C: (x: A) → Path A a x → U)
    (d: C a (refl A a))
    (p: Path A a b) : C b p

```

Theorem 21. (Path Computation).

```

trans_comp (A: U) (a: A)
  : Path A a (trans A A (<_> A) a)
  = fill (<i> A) a []
subst_comp (A: U) (P: A → U) (a: A) (e: P a)
  : Path (P a) e (subst A P a a (refl A a) e)
  = trans_comp (P a) e
J_comp (A: U) (a: A) (C: (x: A)
  → Path A a x → U) (d: C a (refl A a))
  : Path (C a (refl A a)) d
  (J A a C d a (refl A a))
  = subst_comp (singl A a) T (eta A a) d
  where T (z: singl A a)
    : U = C a (z.1) (z.2)

```

Note that Path type has no Eta rule due to groupoid interpretation.

Groupoid interpretation

The groupoid interpretation of type theory is well known article by Martin Hofmann and Thomas Streicher, more specific interpretation of identity type as infinity groupoid.

2.4 Contexts

Speaking of type checker execution, we introduce context or dictionary with types and terms, from which we can derive typed variables. This chain could be implemented as nested sigma types (due to R.A.G.Seely) or list types (due to Voevodsky). Categorically dependent type theory is built upon categories of contexts.

Definition 21. (Empty Context).

$$\gamma_0 : \Gamma =_{def} \star.$$

Definition 22. (Context Comprehension).

$$\Gamma ; A =_{def} \sum_{\gamma : \Gamma} A(\gamma).$$

Definition 23. (Context Derivability).

$$\Gamma \vdash A =_{def} \prod_{\gamma : \Gamma} A(\gamma).$$

2.5 Universes

Definition 24. (Terms). Point in initial object of language AST inductive definition is called a term. If type theory or language is defined as an inductive type (AST) then the term is defined as its instance.

Definition 25. (Sorts). N -indexed set of universes $U_{n \in N}$. Could have any number of elements which defines different type systems. All built-in types as long as user defined types are landed usually by default in U_0 universe. Sorts represented in type checker as a separate constructor.

Definition 26. (Axioms). The inclusion rules $U_i : U_j, i, j \in N$, that define which universe is element of another given universe. You may attach any rules that joins i, j in some way. Axioms with sorts define universe hierarchy.

Definition 27. (Rules). The set of landings $U_i \rightarrow U_j : U_{\lambda(i,j), i,j \in N}$, where $\lambda : N \times N \rightarrow N$. These rules define term dependence or how we land (in which universe) formation rules in definitions.

Definition 28. (Predicative hierarchy). If λ in Rules is an uncurried function $\max : N \times N \rightarrow N$ then such universe hierarchy is called predicative.

Definition 29. (Impredicative hierarchy). If λ in Rules is a second projection of a tuple $\text{snd} : N \times N \rightarrow N$ then such universe hierarchy is called impredicative.

Definition 30. (Definitional Equality). For any $U_i, i \in N$ there is defined an equality between its members and between its instances. For all $x, y \in A$, there is defined a $x=y$. Definitional equality compares normalized term instances.

Definition 31. (SAR). The universum space is configured with a triple of: i) sorts, a set of universes $U_{n \in N}$ indexed over set N ; ii) axioms, a set of inclusions $U_i : U_j, i, j \in N$; iii) rules of term dependence universe landing, a set of landings $U_i \rightarrow U_j : U_{\lambda(i,j), i,j \in N}$, where λ could be function \max (predicative) or snd (impredicative).

Example 1. (CoC). $\text{SAR} = \{\{\star, \square\}, \{\star : \square\}, \{i \rightarrow j : j; i, j \in \{\star, \square\}\}$. Terms live in universe \star , and types live in universe \square . In CoC $\lambda = \text{snd}$.

Example 2. ($\text{PTS}^\infty, \text{MLTT}^\infty$).

$\text{SAR} = \{U_{i \in N}, U_i : U_{j; i < j; i, j \in N}, U_i \rightarrow U_j : U_{\lambda(i,j); i, j \in N}\}$. Where U_i is a universe of i -level or i -category in categorical interpretation. The working prototype of PTS^∞ is given in **Issue XVI: Pure Type System** [19].

2.6 MLTT-75

Here is given formal model of type-theoretical interpretation of Martin-Löf Type Theory. It combines 4 Path rules (no eta), 5 Π rules, and 6 Σ rules (two elims). The proof is provided by direct embedding (internalizing) the model into the model of type checker which is even more powerful.

Definition 32. (MLTT-75). The MLTT as a Type is defined by taking all rules for Π , Σ and Path types into one Σ telescope or context.

```

MLTT (A: U): U
= (Pi_Former: (A → U) → U)
* (Pi_Intro: (B: A → U) (a: A) → B a → (A → B a))
* (Pi_Elim: (B: A → U) (a: A) → (A → B a) → B a)
* (Pi_Comp1: (B: A → U) (a: A)
  (f: A → B a) → Path (B a)
  (Pi_Elim B a (Pi_Intro B a (f a))) (f a))
* (Pi_Comp2: (B: A → U) (a: A)
  (f: A → B a) → Path (A → B a) f (\(x:A) → f x))
* (Sigma_Former: (A → U) → U)
* (Sigma_Intro: (B: A → U) (a: A) (b: B a) → Sigma A B)
* (Sigma_Elim1: (B: A → U)
  (_: Sigma A B) → A)
* (Sigma_Elim2: (B: A → U)
  (x: Sigma A B) → B (pr1 A B x))
* (Sigma_Comp1: (B: A → U) (a: A) (b: B a)
  → Path A a (Sigma_Elim1 B (Sigma_Intro B a b)))
* (Sigma_Comp2: (B: A → U) (a: A)
  (b: B a) → Path (B a) b
  (Sigma_Elim2 B (a, b)))
* (Sigma_Comp3: (B: A → U) (p: Sigma A B)
  → Path (Sigma A B) p (pr1 A B p, pr2 A B p))
* (Id_Former: A → A → U)
* (Id_Intro: (a: A) → Path A a a)
* (Id_Elim: (x: A) (C: D A)
  (d: C x x (Id_Intro x))
  (y: A) (p: Path A x y) → C x y p)
* (Id_Comp: (a:A) (C: D A)
  (d: C a a (Id_Intro a)) →
  Path (C a a (Id_Intro a))
  d (Id_Elim a C d a (Id_Intro a))) * U

```

Theorem 22. (Model Check). There is an instance of MLTT.

```
instance (A: U): MLTT A
= (Pi A,      lam A, app A,
   Beta A, Eta A,
   Sigma A, dpair A, pr1 A, pr2 A,
   Beta1 A, Beta2 A, Eta2 A,
   Path A, refl A, J A,
   J_comp A, A)
```

Cubical Model Check

The result of the work is a `|mltt.ctt|` file which can be runned using `|cubicaltt|`. Note that computation rules take a seconds to type check.

```
cubicaltt — 6 second.
Arend — 1 second.
Agda (cubical) — & 2 second.
```

Conclusions

In this issue the type-theoretical model (interpretation) of MLTT was presented in cubical syntax and type checked in it. This is the first constructive proof of internalization of MLTT.

From the theoretical point of view the landspace of possible interpretation was shown corresponding different mathematical theories for those who are new to type theory. The brief description of the previous attempts to internalize MLTT could be found as canonical example in MLTT works, but none of them give the constructive J eliminator or its equality rule.

Type theoretical cubical constructions was given for the Path types along the article for other interpretations, all of them were taken from our Groupoid Infinity ⁷ base library.

The objective of complete derivability of all eliminators, computational and uniqueness rules is a basic objective for constructive mathematics as mathematical reasoning implies verification and mechanization. Yes cubical type system represent most compact system that make possible derivability of all theorems for core types which make this system as a first candidate for the metacircular type checker.

Also for programming purposes we may also want to investigate Fixpoint as a useful type in coinductive and modal type theories and harmful type in theoretical foundation of type systems. Elimination the possibility of uncontrolled Fixpoint is a main objective of the correct type system for reasoning without paradoxes. By this creatiria we could filter all the fixpoint implementations being condidered harmful.

Without a doubt the core type that makes type theory more like programming is the inductive type system that allows to define type families. In the

⁷<https://groupoid.space/>

Табл. 2: *

Table. Core Features							
Lang	Π	Σ	\equiv	Path	U^∞	Co/Fix	Lazy
PTS	x						
Cedile, MLTT	x	x	x				
Henk	x				x		
Per	x	x		x	x		
Lean, Agda	x		x	x	x		
NuPRL	x	x	x			x	
System-D	x	x				x	x
cubicaltt	x	x	x	x		x	

following Issue II will be shown the semantics and embedding of inductive types with several types of Inductive-Recursive encodings.

Табл. 3: *

Table. Inductive Type Systems			
Lang	Co/Inductive	Quot/Trunc	HITs
System-D	x		
Lean	x	x	
NuPRL	x	x	
Arend	x	x	x
Agda, Coq	x		x
cubicaltt, yacctl, RedPRL	x		x

Further research of the most pure type theory on a weak fibrations and pure Kan oprations without interval lattice structure (connections, de Morgan algebra, connection algebras) and diagonal coersions could be made on the way of building a minimal homotopy core [2].

The next language after **Henk** and **Per** will be **Anders** with homotopy type system and infinite number of universes. Along with **Joe** cartesian interpreter this evaluators form a set of languages as a part of conceptual model of theorem proving system with formalized virtual machine as extraction target.

Табл. 4: *

Table. Cubical Type Systems

Lang	Interval	Diagonal	Kan/Coe
BCH, cubical			$0 \rightarrow r, 1 \rightarrow r$
CCHM, cubicaltt, Agda	\vee, \wedge		$0 \rightarrow 1$
Dedekind	\vee, \wedge		$0 \rightarrow 1, 1 \rightarrow 0$
AFH/ABCFHL, yacett		x	$r \rightarrow s$
HTS/CMS			$r \rightarrow s, \text{weak}$

Further Research

This article opens the door to a series that will unveil the different topics of homotopy type theory with practical emphasis to cubical type checkers. The Foundations volume of articles define formal programming language with geometric foundations and show how to prove properties of such constructions. The second volume of article is dedicated to cover the programming and modeling of Mathematics.

Issue I: Type Theory. The first volume of definitions gathered into one article dedicated to various \prod , \sum and \equiv properties and internalization of MLTT in the host language typechecker.

Issue II: Inductive Types. This episode tales a story of inductive types, their encodings, induction principle and its models.

Issue III: Homotopy Type Theory. This issue is try to present the Homotopy Type Theory without higher inductive types to neglect the core and principles of homotopical proofs.

Issue IV: Higher Inductive Types. The metamodel of HIT is a theory of CW-complexes. The category of HIT is a homotopy category. This volume finalizes the building of the computational theory.

Issue V: Modalities. The constructive extensions with additional context and adjoint transports between toposes (cohesive toposes). This approach serves the needs of modal logics, differential geometry, cohomology.

The main intention of Foundation volume is to show the internal language of working topos of CW-complexes, the construction of fibrational sheaf type theory.

Issue XVI: Pure Type System. Pure Type System named after **Henk Barendregt**.

Issue XVII: Inductive Type System. Inductive Type System named after **Per Martin-Löf**.

Issue XIX: Modal Homotopy Type System. Modal Homotopy Type System named after **Anders Mörtberg**.

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Issue II: Inductive Types

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Анотація

Impredicative Encoding of Inductive Types in HoTT.

Keywords: Formal Methods, Type Theory, Programming Languages, Theoretical Computer Science, Applied Mathematics, Cubical Type Theory, Martin-Löf Type Theory

3 Inductive Encodings

3.1 Church Encoding

You know Church encoding which also has its dependent analogue in CoC, however in Coq it is impossible to derive Inductive Principle as type system lacks fixpoint and functional extensionality. The example of working compiler of PTS languages are Om and Morte. Assume we have Church encoded NAT:

$\text{nat} = (X:U) \rightarrow (X \rightarrow X) \rightarrow X \rightarrow X$

where first parameter $(X \rightarrow X)$ is a *succ*, the second parameter X is *zero*, and the result of encoding is landed in X . Even if we encode the parameter

$\text{list } (A: U) = (X:U) \rightarrow X \rightarrow (A \rightarrow X) \rightarrow X$

and parameter A let's say live in 42 universe and X live in 2 universe, then by the signature of encoding the term will be landed in X , thus 2 universe. In other words such dependency is called impredicative displaying that landed term is not a predicate over parameters. This means that Church encoding is incompatible with predicative type checkers with predicative of predicative-cumulative hierarchies.

3.2 Scott Encoding

3.3 Parigot Encoding

3.4 CPS Encoding

3.5 Interaction Networks Encoding

3.6 Impredicative Encoding

In HoTT n -types is encoded as n -groupoids, thus we need to add a predicate in which n -type we would like to land the encoding:

$\text{NAT } (A: U) = (X:U) \rightarrow \text{isSet } X \rightarrow X \rightarrow (A \rightarrow X) \rightarrow X$

Here we added *isSet* predicate. With this motto we can implement propositional truncation by landing term in *isProp* or even HIT by landing in *isGroupoid*:

$\text{TRUN } (A:U) \text{ type} = (X: U) \rightarrow \text{isProp } X \rightarrow (A \rightarrow X) \rightarrow X$
 $\text{S1} = (X:U) \rightarrow \text{isGroupoid } X \rightarrow ((x:X) \rightarrow \text{Path } X \ x \ x) \rightarrow X$
 $\text{MONOPL} (A:U) = (X:U) \rightarrow \text{isSet } X \rightarrow (A \rightarrow X) \rightarrow X$
 $\text{NAT} = (X:U) \rightarrow \text{isSet } X \rightarrow X \rightarrow (A \rightarrow X) \rightarrow X$

The main publication on this topic could be found at [11] and [10].

The Unit Example

Here we have the implementation of Unit impredicative encoding in HoTT.

```

upPath      (X Y:U) (f:X→Y) (a:X→X): X → Y = o X X Y f a
downPath    (X Y:U) (f:X→Y) (b:Y→Y): X → Y = o X Y Y b f
naturality  (X Y:U) (f:X→Y) (a:X→X) (b:Y→Y): U
  = Path (X→Y) (upPath X Y f a) (downPath X Y f b)

unitEnc': U = (X: U) → isSet X → X → X
isUnitEnc (one: unitEnc'): U
  = (X Y:U) (x: isSet X) (y: isSet Y) (f:X→Y) →
    naturality X Y f (one X x) (one Y y)

unitEnc: U = (x: unitEnc') * isUnitEnc x
unitEncStar: unitEnc = (\(X:U) (\_ : isSet X) →
  idfun X, \ (X Y: U) (\_ : isSet X) (\_ : isSet Y) → refl (X→Y))
unitEncRec  (C: U) (s: isSet C) (c: C): unitEnc → C
  = \ (z: unitEnc) → z.1 C s c
unitEncBeta (C: U) (s: isSet C) (c: C)
  : Path C (unitEncRec C s c unitEncStar) c = refl C c
unitEncEta  (z: unitEnc): Path unitEnc unitEncStar z = undefined
unitEncInd  (P: unitEnc → U) (a: unitEnc): P unitEncStar → P a
  = subst unitEnc P unitEncStar a (unitEncEta a)
unitEncCondition (n: unitEnc'): isProp (isUnitEnc n)
  = \ (f g: isUnitEnc n) →
    <h> \ (x y: U) → \ (X: isSet x) → \ (Y: isSet y)
    → \ (F: x → y) → <i> \ (R: x → Y (F (n x X R))) (n y Y (F R))
    (<j> f x y X Y F @ j R) (<j> g x y X Y F @ j R) @ h @ i

```

3.7 Lambek Encoding: Homotopy Initial Algebras

4 Inductive Types

4.1 W

Well-founded trees without mutual recursion represented as W-types.

Definition 33. (W-Formation). For $A : \mathcal{U}$ and $B : A \rightarrow \mathcal{U}$, type W is defined as $W(A, B) : \mathcal{U}$ or

$$W_{(x:A)}B(x) : \mathcal{U}.$$

def $W \ (A : \mathcal{U}) \ (B : A \rightarrow \mathcal{U}) : \mathcal{U} := W \ (x : A), B \ x$

Definition 34. (W-Introduction). Elements of $W_{(x:A)}B(x)$ are called well-founded trees and created with single sup constructor:

$$\text{sup} : W_{(x:A)}B(x).$$

def $\text{sup}\$'\$ \ (A : \mathcal{U}) \ (B : A \rightarrow \mathcal{U}) \ (x : A) \ (f : B \ x \rightarrow W^* \ A \ B)$
 $: W^* \ A \ B$
 $:= \text{sup} \ A \ B \ x \ f$

Theorem 23. (Induction Principle ind_W). The induction principle states that for any types $A : \mathcal{U}$ and $B : A \rightarrow \mathcal{U}$ and type family C over $W(A, B)$ and the function $g : G$, where

$$G = \prod_{x:A} \prod_{f:B(x) \rightarrow W(A,B)} \prod_{b:B(x)} C(f(b)) \rightarrow C(\text{sup}(x, f))$$

there is a dependent function:

$$\text{ind}_W : \prod_{C:W(A,B) \rightarrow \mathcal{U}} \prod_{g:A \rightarrow C} \prod_{a:A} \prod_{f:B(a) \rightarrow W(A,B)} \prod_{b:B(a)} C(f(b)).$$

def $W\text{-ind} \ (A : \mathcal{U}) \ (B : A \rightarrow \mathcal{U})$
 $(C : (W \ (x : A), B \ x) \rightarrow \mathcal{U})$
 $(g : \prod (x : A) (f : B \ x \rightarrow (W \ (x : A), B \ x)) ,$
 $(\prod (b : B \ x), C \ (f \ b)) \rightarrow C \ (\text{sup} \ A \ B \ x \ f))$
 $(a : A) (f : B \ a \rightarrow (W \ (x : A), B \ x)) (b : B \ a)$
 $: C \ (f \ b) := \text{ind}^W \ A \ B \ C \ g \ (f \ b)$

Theorem 24. (ind_W Computes). The induction principle ind^W satisfies the equation:

$$\begin{aligned} \text{ind}_W\text{-}\beta &: g(a, f, \lambda b. \text{ind}^W(g, f(b))) \\ &=_{\text{def}} \text{ind}_W(g, \text{sup}(a, f)). \end{aligned}$$

def $\text{ind}^W\text{-}\beta \ (A : \mathcal{U}) \ (B : A \rightarrow \mathcal{U})$
 $(C : (W \ (x : A), B \ x) \rightarrow \mathcal{U}) \ (g : \prod (x : A)$
 $(f : B \ x \rightarrow (W \ (x : A), B \ x)) , (\prod (b : B \ x), C \ (f \ b)) \rightarrow C \ (\text{sup} \ A \ B \ x \ f))$
 $(a : A) (f : B \ a \rightarrow (W \ (x : A), B \ x))$
 $: \text{PathP} \ (<_> \ C \ (\text{sup} \ A \ B \ a \ f))$
 $(\text{ind}^W \ A \ B \ C \ g \ (\text{sup} \ A \ B \ a \ f))$
 $(g \ a \ f \ (\lambda (b : B \ a), \text{ind}^W \ A \ B \ C \ g \ (f \ b)))$
 $:= <_> \ g \ a \ f \ (\lambda (b : B \ a), \text{ind}^W \ A \ B \ C \ g \ (f \ b))$

4.2 M

4.3 Empty

The Empty type represents False-type logical $\mathbf{0}$, type without inhabitants, void or \perp (Bottom). As it has not inhabitants it lacks both constructors and eliminators, however, it has induction.

Definition 35. (Formation). Empty-type is defined as built-in $\mathbf{0}$ -type:

$$\mathbf{0} : \mathcal{U}.$$

Theorem 25. (Induction Principle ind_0). $\mathbf{0}$ -type is satisfying the induction principle:

$$\text{ind}_0 : \prod_{C : \mathbf{0} \rightarrow \mathcal{U}} \prod_{z : \mathbf{0}} C(z).$$

`def Empty-ind (C: $\mathbf{0} \rightarrow \mathcal{U}$) (z: $\mathbf{0}$) : C z := ind0 (C z) z`

Definition 36. (Negation or isEmpty). For any type A negation of A is defined as arrow from A to $\mathbf{0}$:

$$\neg A := A \rightarrow \mathbf{0}.$$

`def isEmpty (A: \mathcal{U}): \mathcal{U} := A $\rightarrow \mathbf{0}$`

The witness of $\neg A$ is obtained by assuming A and deriving a contradiction. This techniques is called proof of negation and is applicable to any types in constrast to proof by contradiction which implies $\neg\neg A \rightarrow A$ (double negation elimination) and is applicable only to decidable types with $\neg A + A$ property.

4.4 Unit

Unit type is the simplest type equipped with full set of MLTT inference rules. It contains single inhabitant \star (star).

- 4.5 Bool
- 4.6 Maybe
- 4.7 Either
- 4.8 Nat
- 4.9 List
- 4.10 Vector
- 4.11 Stream
- 4.12 Interpreter

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Issue III: Homotopy Type Theory

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Анотація

Here is presented distinctive points of Homotopy Type Theory as an extension of Martin-Löf Type Theory but without higher inductive types which will be given in the next issue. The study of identity system is given. Groupoid (categorical) interpretation is presented as categories of spaces and paths between them as invertible morphisms. At last constructive proof $\Omega(S^1) = \mathbb{Z}$ is given through helix.

Keywords: Homotopy Theory, Type Theory

5 Groupoid Interpretation

5.1 Introduction: Type Theory

Type theory is a universal programming language for pure mathematics, designed for theorem proving. It supports an arbitrary number of consistent axioms, structured as pseudo-isomorphisms consisting of *encode* functions (methods for constructing type elements), *decode* functions (dependent eliminators of the universal induction principle), and their equations—beta and eta rules governing computability and uniqueness.

As a programming language, type theory includes basic primitives (axioms as built-in types) and accompanying documentation, such as lecture notes or textbooks, explaining their applications, including:

- Function (**Π**)
- Context (**Σ**)
- Identification (=)
- Polynomial (**W**)
- Path (**Ξ**)
- Gluing (**Glue**)
- Infinitesimal (**ℑ**)
- Complex (**HIT**)

Students (10) are tasked with applying type theory to prove an initial but non-trivial result addressing an open problem in one of the following areas offered by the Department of Pure Mathematics (KM-111):

$$\text{Mathematics} := \left\{ \begin{array}{l} \text{Homotopy Theory} \\ \text{Homological Algebra} \\ \text{Category Theory} \\ \text{Functional Analysis} \\ \text{Differential Geometry} \end{array} \right. .$$

5.2 Motivation: Homotopy Type Theory

The primary motivation of homotopy type theory is to provide computational semantics for homotopic types and CW-complexes. The central idea, as described in, is to combine function spaces (Π), context spaces (Σ), and path spaces (Ξ) to form a fiber bundle, proven within HoTT to coincide with the Π type itself.

Key definitions include:

```
def contr (A: U) : U :=  $\Sigma$  (x: A),  $\Pi$  (y: A),  $\Xi$  A x y
def fiber (A B: U) (f: A  $\rightarrow$  B) (y: B): U :=  $\Sigma$  (x: A), Path B y (f x)
def isEquiv (A B: U) (f: A  $\rightarrow$  B): U :=  $\Pi$  (y: B), contr (fiber A B f y)
def equiv (X Y: U): U :=  $\Sigma$  (f: X  $\rightarrow$  Y), isEquiv X Y f
def ua (A B: U) (p :  $\Xi$  U A B) : equiv A B
:= transp (<i>equiv A (p @ i)</i>) 0 (idEquiv A)
```

The absence of an eta-rule for equality implies that not all proofs of the same path space are equal, resulting in a multidimensional ∞ -groupoid structure for path spaces. Further definitions include:

```
def isProp (A : U) : U
:=  $\Pi$  (a b : A),  $\Xi$  A a b

def isSet (A : U) : U
:=  $\Pi$  (a b : A) (x y :  $\Xi$  A a b),  $\Xi$  ( $\Xi$  A a b) x y

def isGroupoid (A : U) : U
:=  $\Pi$  (a b : A) (x y :  $\Xi$  A a b) (i j :  $\Xi$  ( $\Xi$  A a b) x y),
 $\Xi$  ( $\Xi$  ( $\Xi$  A a b) x y) i j
```

The groupoid interpretation raises questions about the existence of a language for mechanically proving all properties of the categorical definition of a groupoid:

```
def CatGroupoid (X : U) (G : isGroupoid X)
: isCatGroupoid (PathCat X)
:= ( idp X,
    comp-Path X,
    G,
    sym X,
    comp-inv-Path-1 X,
    comp-inv-Path X,
    comp-Path-left X,
    comp-Path-right X,
    comp-Path-assoc X,
    *
  )
```

5.3 Metatheory: Adjunction Triples

The course is divided into four parts, each exploring type-axioms and their meta-theoretical adjunctions.

5.3.1 Fibrational Proofs

$$\Sigma \dashv f_{\star} \dashv \Pi$$

Fibrational proofs are modeled by primitive axioms, which are type-theoretic representations of categorical meta-theoretical models of adjunctions of three Cockett-Reit functors, giving rise to function spaces (Π) and pair spaces (Σ). These proof methods enable direct analysis of fibrations.

5.3.2 Equality Proofs

$$Q \dashv \Xi \dashv C$$

In intensional type theory, the equality type is embedded as type-theoretic primitives of categorical meta-theoretical models of adjunctions of three Jacobs-Lambek functors: quotient space (Q), identification system (Ξ), and contractible space (C). These methods allow direct manipulation of identification systems, strict for set theory and homotopic for homotopy theory.

5.3.3 Inductive Proofs

$$W \dashv \odot \dashv M$$

Inductive types in type theory can be embedded as polynomial functors (W , M) or general inductive type schemes (Calculus of Inductive Constructions), with properties including: 1) Verification of program finiteness; 2) Verification of strict positivity of parameters; 3) Verification of mutual recursion.

In this course, induction and coinduction are introduced as type-theoretic primitives of categorical meta-theoretical models of adjunctions of polynomial functors (Lambek-Bohm), enabling manipulation of initial and terminal algebras, algebraic recursive data types, and infinite processes. Higher inductive proofs, where constructors include path spaces, are modeled by polynomial functors using monad-algebras and comonad-coalgebras (Lumsdaine-Shulman).

Historical Notes

Homotopy Type Theory takes its origins in 1996 from groupoid interpretation by Hofmann and Streicher's, and later (in 10 years) was formalized by Awodey, Warren and Voevodsky. Voevodsky constructed Kan simplicial sets interpretation of type theory and discovered the property of this model, that was named univalence. This property allows to identify isomorphic structures in terms of type theory.

Homotopy type theory to classical homotopy theory is like Euclidian syntethic geometry (points, lines, axioms and deduction rules) to analytical geometry with cartesian coordinates on \mathbb{R}^n (geometric and algebraic)¹.

In the same way as inductive types extends MLTT for inductive programming, the higher inductive types (HIT) extend homotopy type theory for geometry programming. You can directly encode CW-complexes by using HIT. The definition of HIT syntax will be given in the next **Issue IV: Higher Inductive Types**.

Cubical with HITs has very lightweight core and syntax, and is an internal language of $(\infty, 1)$ -topos. Cubical with $[0, 1]$ Path types but without HITs is an internal language of $(\infty, 1)$ -categories, while MLTT is an internal language of locally cartesian closed categories.

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This article is dedicated to Ihor Horobets and written on his request for clarification and direct introduction to HoTT.

¹We will denote geometric, type theoretical and homotopy constants bold font **R** while analitical will be denoted with double lined letters \mathbb{R} .

6 Homotopy Type Theory

6.1 Identity Systems

Definition 37. (Identity System). An identity system over type A in universe X_i is a family $R : A \rightarrow A \rightarrow X_i$ with a function $r_0 : \prod_{a:A} R(a, a)$ such that any type family $D : \prod_{a,b:A} R(a, b) \rightarrow X_i$ and $d : \prod_{a:A} D(a, a, r_0(a))$, there exists a function $f : \prod_{a,b:A} \prod_{r:R(a,b)} D(a, b, r)$ such that $f(a, a, r_0(a)) = d(a)$ for all $a : A$.

```
def IdentitySystem (A : U) : U
:=  $\Sigma$  ( $\text{=form} : A \rightarrow A \rightarrow U$ )
    ( $\text{=ctor} : \prod (a : A), \text{=form } a \ a$ )
    ( $\text{=elim} : \prod (a : A) (C : \prod (x \ y : A)
        (p : \text{=form } x \ y), U)
        (d : C \ a \ a (\text{=ctor } a)) (y : A)
        (p : \text{=form } a \ y), C \ a \ y \ p)$ )
    ( $\text{=comp} : \prod (a : A) (C : \prod (x \ y : A)
        (p : \text{=form } x \ y), U)
        (d : C \ a \ a (\text{=ctor } a)),
        \exists (C \ a \ a (\text{=ctor } a)) \ d
        (\text{=elim } a \ C \ d \ a (\text{=ctor } a))) , 1$ 
```

Example 3. There are number of equality signs used in this tutorial, all of them listed in the following table of identity systems:

Sign	Meaning
=_{def}	Definition
$=$	Id
\equiv	Path
\simeq	Equivalence
\cong	Isomorphism
\sim	Homotopy
\approx	Bisimulation

Theorem 26. (Fundamental Theorem of Identity System).

Definition 38. (Strict Identity System). An identity system over type A and universe of pretypes V_i is called strict identity system ($=$), which respects UIP.

Definition 39. (Homotopy Identity System). An identity system over type A and universe of homotopy types U_i is called homotopy identity system (\equiv), which models discrete infinity groupoid.

6.2 Path (Ξ)

The homotopy identity system defines a **Path** space indexed over type A with elements as functions from interval $[0, 1]$ to values of that path space $[0, 1] \rightarrow A$. HoTT book defines two induction principles for identity types: path induction and based path induction.

Definition 40. (Path Formation).

$$\equiv : U =_{def} \prod_{A:U} \prod_{x,y:A} \mathbf{Path}_A(x, y).$$

```
def  $\Xi$  (A : U) (x y : A) : U
:= PathP (<_> A) x y
```

```
def  $\Xi'$  (A : U) (x y : A)
:=  $\Pi$  (i : I),
    A [  $\partial$  i ] -> [ (i = 0)  $\rightarrow$  x ,
                  (i = 1)  $\rightarrow$  y ]]
```

Definition 41. (Path Introduction). Returns a reflexivity path space for a given value of the type. The inhabitant of that path space is the lambda on the homotopy interval $[0, 1]$ that returns a constant value x . Written in syntax as $[i]x$.

$$\text{id}_{\equiv} : x \equiv_A x =_{def} \prod_{A:U} \prod_{x:A} [i]x$$

```
def idp (A: U) (x: A)
:  $\Xi$  A x x := <_> x
```

Definition 42. (Path Application).

```
def at0 (A: U) (a b: A)
(p: Path A a b) : A := p @ 0
```

```
def at1 (A: U) (a b: A)
(p: Path A a b): A := p @ 1
```

Definition 43. (Path Connections). Connections allow you to build a square with only one element of path: i) $[i, j]p @ \min(i, j)$; ii) $[i, j]p @ \max(i, j)$.

$$\begin{array}{ccc} b & \xrightarrow{[i]b} & b \\ p \uparrow & & \uparrow [i]b \\ a & \xrightarrow{p} & b \end{array} \quad \begin{array}{ccc} a & \xrightarrow{p} & b \\ [i]a \uparrow & & \uparrow p \\ a & \xrightarrow{[i]a} & a \end{array}$$

```
def join (A: U) (a b: A) (p: Path A a b)
  : PathP (<x> Path A (p@x) b) p (<i> b)
:= <y x> p @ (x /\ y)
```

```
def meet (A: U) (a b: A) (p: Path A a b)
  : PathP (<x> Path A a (p@x)) (<i> a) p
:= <x y> p @ (x /\ y)
```

Definition 44. (Path Inversion).

Theorem 27. (Congruence).

$$ap : f(a) \equiv f(b) =_{def}$$

$$\prod_{A:U} \prod_{a,x:A} \prod_{B:A \rightarrow U} \prod_{f:\Pi(A,B)} \prod_{p:a \equiv_A x} [i]f(p@i).$$

```
def ap (A B: U) (f: A -> B)
  (a b: A) (p: Path A a b)
  : Path B (f a) (f b)
```

```
def apd (A: U) (a x: A) (B: A -> U)
  (f: A -> B a) (b: B a) (p: Path A a x)
  : Path (B a) (f a) (f x)
```

Maps a given path space between values of one type to path space of another type using an encode function between types. Implemented as a lambda defined on $[0, 1]$ that returns application of encode function to path application of the given path to lamda argument $[i]f(p@i)$ in both cases.

Definition 45. (Generalized Transport Kan Operation). Transports a value of the left type to the value of the right type by a given path element of the path space between left and right types.

$$\text{transport} : A(0) \rightarrow A(1) =_{def}$$

$$\prod_{A:I \rightarrow U} \prod_{r:I} \lambda x, \mathbf{transp}([i]A(i), 0, x).$$

```
def transp' (A: U) (x y: A) (p : PathP (<_>A) x y) (i: I)
:= transp (<_> (\(_:A), A) (p @ i)) i x
```

```
def transpU (A B: U) (p : PathP (<_>U) A B) (i: I)
:= transp (<_> (\(_:U), U) (p @ i)) i A
```

Definition 46. (Partial Elements).

$$\text{Partial} : V =_{def} \prod_{A:U} \prod_{i:I} \mathbf{Partial}(A, i).$$

```
def Partial' (A : U) (i : I)
: V := Partial A i
```

Definition 47. (Cubical Subtypes).

$$\text{Subtype} : V =_{def}$$

$$\prod_{A:U} \prod_{i:I} \prod_{u:\mathbf{Partial}(A,i)} A[i \mapsto u].$$

```
def sub (A : U) (i : I) (u : Partial A i)
: V := A [i ↦ u]
```

Definition 48. (Cubical Elements).

$$\text{inS} : A [(i = 1) \mapsto a] =_{def}$$

$$\prod_{A:U} \prod_{i:I} \prod_{a:A} \mathbf{inc}(A, i, a).$$

$$\text{outS} : A [i \mapsto u] \rightarrow A =_{def}$$

$$\prod_{A:U} \prod_{i:I} \prod_{u:\mathbf{Partial}(A,i)} \mathbf{ouc}(a).$$

```
def inS (A : U) (i : I) (a : A)
: sub A i [(i = 1) → a] := inc A i a
```

```
def outS (A : U) (i : I) (u : Partial A i)
: A [i ↦ u] → A := λ (a: A[i ↦ u]), ouc a
```

Theorem 28. (Heterogeneous Composition Kan Operation).

$$\text{comp}_{\text{CCHM}} : A(0) [r \mapsto u(0)] \rightarrow A(1) =_{\text{def}}$$

$$\prod_{A:U} \prod_{r:I} \prod_{u:\Pi_{i:I} \mathbf{Partial}(A(i),r)} \prod_{\lambda u_0, \mathbf{hcomp}(A(1), r, \lambda i. [(r=1) \rightarrow \mathbf{transp}([j]A(i/j), i, u(i, 1=1))], \mathbf{transp}([i]A(i), 0, \mathbf{ouc}(u_0)))}.$$

```
def compCCHM (A : I → U) (r : I)
  (u : Π (i : I), Partial (A i) r)
  (u₀ : (A 0)[r ↦ u 0]) : A 1
:= hcomp (A 1) r (λ (i : I),
  [(r = 1) → transp (<j> A (i ∨ j)) i (u i 1=1)])
  (transp (<i> A i) 0 (ouc u₀))
```

Theorem 29. (Homogeneous Composition Kan Operation).

$$\text{comp}_{\text{CHM}} : A [r \mapsto u(0)] \rightarrow A =_{\text{def}}$$

$$\prod_{A:U} \prod_{r:I} \prod_{u:I \rightarrow \mathbf{Partial}(A,r)} \prod_{\lambda u_0, \mathbf{hcomp}(A, r, u, \mathbf{ouc}(u_0))}.$$

```
def compCHM (A : U) (r : I)
  (u : I → Partial A r) (u₀ : A[r ↦ u 0]) : A
:= hcomp A r u (ouc u₀)
```

Theorem 30. (Substitution).

$$\text{subst} : P(x) \rightarrow P(y) =_{\text{def}}$$

$$\prod_{A:U} \prod_{P:A \rightarrow U} \prod_{x,y:A} \prod_{p:x=y} \prod_{\lambda e. \mathbf{transp}([i]P(p@i), 0, e)}.$$

```
def subst (A: U) (P: A → U) (x y: A) (p: Path A x y)
  : P x → P y
:= λ (e: P x), transp (<i> P (p @ i)) 0 e
```

Other synonyms are `mapOnPath` and `cong`.

Theorem 31. (Path Composition).

$$\begin{array}{ccc} a & \xrightarrow{pcomp} & c \\ [i]a \uparrow & & \uparrow q \\ a & \xrightarrow{p @ i} & b \end{array}$$

```
def pcomp (A: U) (a b c: A)
  (p: Path A a b) (q: Path A b c)
  : Path A a c := subst A (Path A a) b c q p
```

Composition operation allows building a new path from two given paths in a connected point. The proof term is **comp**($[i]\mathbf{Path}_A(a, q@i), p, []$).

Theorem 32. (J by Paulin-Mohring).

```
def J (A: U) (a b: A)
  (P: singl A a -> U)
  (u: P (a, refl A a))
  : Π (p: Path A a b), P (b, p)
```

J is formulated in a form of Paulin-Mohring and implemented using two facts that singletons are contractible and dependent function transport.

Theorem 33. (Contractability of Singleton).

```
def singl (A: U) (a: A) : U
  := Σ (x: A), Path A a x

def contr (A: U) (a b: A) (p: Path A a b)
  : Path (singl A a) (a, <_>a) (b, p)
```

Proof that singleton is contractible space. Implemented as $[i](p@i, [j]p@(i \wedge j))$.

Theorem 34. (HoTT Dependent Eliminator).

```
def J (A: U) (a: A)
  (C: (x: A) -> Path A a x -> U)
  (d: C a (refl A a)) (x: A)
  : Π (p: Path A a x) : C x p
```

Theorem 35. (Diagonal Path Induction).

```
def D (A: U) : U
  := Π (x y: A), Path A x y -> U

def J (A: U) (x: A) (C: D A)
  (d: C x x (refl A x))
  (y: A)
  : Π (p: Path A x y), C x y p
```

Theorem 36. (Path Computation).

```

def trans_comp (A: U) (a: A)
  : Path A a (trans A A (<_>) a)

def subst_comp (A: U) (P: A → U) (a: A) (e: P a)
  : Path (P a) e (subst A P a a (refl A a) e)

def J_comp (A: U) (a: A)
  (C: (x: A) → Path A a x → U)
  (d: C a (refl A a))
  : Path (C a (refl A a)) d
    (J A a C d a (refl A a))

```

Note that in HoTT there is no Eta rule, otherwise Path between element would requested to be unique applying UIP at any Path level which is prohibited. UIP in HoTT is defined only as instance of n-groupoid, see the PROP type.

6.3 Glue

Glue types defines composition structure for fibrant universes that allows partial elements to be extended to fibrant types. In other words it turns equivalences in the multidimensional cubes to path spaces. Unlike ABCHFL, CCHM needn't another universe for that purpose.

Definition 49. (Glue Formation). The Glue types take a partial family of types A that are equivalent to the base type B . These types are then “glued” onto B and the equivalence data gets packaged up into a new type.

$$\mathbf{Glue}(A, \varphi, e) : U.$$

```
def Glue' (A : U) (φ : I)
  (e : Partial (Σ (T : U), equiv T A) φ) : U
:= Glue A φ e
```

Definition 50. (Glue Introduction).

$$\mathbf{glue} \ \varphi \ u \ (\mathbf{ouc} \ a) : \mathbf{Glue} \ A \ [\varphi=1 \mapsto (T, f)].$$

```
def glue' (A : U) (φ : I)
  (u : Partial (Σ (T : U), equiv T A × T) φ)
  (a : A [φ ↦ [(φ = 1) → (u 1=1).2.1.1 (u 1=1).2.2]])
:= glue φ u (ouc a)
```

Definition 51. (Glue Elimination).

$$\mathbf{unglue}(b) : A \ [\varphi \mapsto f(b)].$$

```
def unglue' (A : U) (φ : I)
  (e : Partial (Σ (T : U), equiv T A) φ)
  (a : Glue A φ e) : A
:= unglue φ e a
```

Theorem 37. (Glue Computation).

$$b = \mathbf{glue} \ [\varphi \mapsto b] \ (\mathbf{unglue} \ b).$$

Theorem 38. (Glue Uniqueness).

$$\mathbf{unglue} \ (\mathbf{glue} \ [\varphi \mapsto t] \ a) = a : A.$$

6.4 Fibration

Definition 52 (Fiber). The fiber of the map $p : E \rightarrow B$ at a point $y : B$ is the set of all points $x : E$ such that $p(x) = y$.

```

fiber (E B: U) (p: E -> B) (y: B): U
  = (x: E) *  $\Xi$  B y (p x)

```

Definition 53 (Fiber Bundle). The fiber bundle $F \rightarrow E \xrightarrow{p} B$ on a total space E with fiber layer F and base B is a structure (F, E, p, B) , where $p : E \rightarrow B$ is a surjective map with the following property: for any point $y : B$ there exists a neighborhood U_b for which there is a homeomorphism

$$f : p^{-1}(U_b) \rightarrow U_b \times F$$

making the following diagram commute:

$$\begin{array}{ccc}
 p^{-1}(U_b) & \xrightarrow{f} & U_b \times F \\
 p \downarrow & \swarrow pr_1 & \\
 U_b & &
 \end{array}$$

Definition 54 (Trivial Fiber Bundle). When the total space E is the cartesian product $\Sigma(B, F)$ and $p = pr_1$, then such a bundle is called trivial: $(F, \Sigma(B, F), pr_1, B)$.

```

Family (B: U): U = B -> U

```

```

total (B: U) (F: Family B): U = Sigma B F
trivial (B: U) (F: Family B): total B F -> B = \ (x: total B F) -> x.1
homeo (B E: U) (F: Family B) (p: E -> B) (y: B):
  fiber E B p y -> total B F

```


Theorem 39 (Fiber Bundle $\equiv \Pi$). The inverse image (fiber) of the trivial bundle $(F, B \times F, pr_1, B)$ at a point $y : B$ equals $F(y)$. Proof sketch:

```
F y = ( _ : isContr B ) * ( F y )
      = ( x y : B ) * ( _ :  $\Xi$  B x y ) * ( F y )
      = ( z : B ) * ( k : F z ) *  $\Xi$  B z y
      = ( z : E ) *  $\Xi$  B z.1 y
      = fiber (total B F) B (trivial B F) y
```

The equality is shown using the *isoPath* lemma and *encode/decode* functions.

```
def Family (B : U) : U1 := B → U
def Fibration (B : U) : U1 :=  $\Sigma$  (X : U), X → B

def encode-Pi (B : U) (F : B → U) (y : B)
  : fiber (Sigma B F) B (pr1 B F) y → F y
:= \ (x : fiber (Sigma B F) B (pr1 B F) y),
    subst B F x.1.1 y (<i> x.2 @ -i) x.1.2

def decode-Pi (B : U) (F : B → U) (y : B)
  : F y → fiber (Sigma B F) B (pr1 B F) y
:= \ (x : F y), ((y, x), idp B y)

def decode-encode-Pi (B : U) (F : B → U) (y : B) (x : F y)
  :  $\Xi$  (F y) (transp (<i> F (idp B y @ i)) 0 x) x
:= <j> transp (<i> F y) j x

def encode-decode-Pi (B : U) (F : B → U) (y : B)
  (x : fiber (Sigma B F) B (pr1 B F) y)
  :  $\Xi$  (fiber (Sigma B F) B (pr1 B F) y)
    ((y, encode-Pi B F y x), idp B y) x
:= <i> ( (x.2 @ i, transp (<j> F (x.2 @ i  $\vee$  -j)) i x.1.2),
      <j> x.2 @ i  $\wedge$  j )

def Bundle=Pi (B : U) (F : B → U) (y : B)
  : PathP (<> U) (fiber (Sigma B F) B (pr1 B F) y) (F y)
:= iso→Path (fiber (Sigma B F) B (pr1 B F) y) (F y)
  (encode-Pi B F y) (decode-Pi B F y)
  (decode-encode-Pi B F y) (encode-decode-Pi B F y)
```

Definition 55. (Fibration-1) Dependent fiber bundle derived from Ξ contractability.

```
def isFBundle1 (B: U) (p: B → U) (F: U): U1
:= Σ ( _ : Π (b: B), isContr (PathP (<_>U) (p b) F)), (Π (x: Sigma B p), B)
```

Definition 56. (Fibration-2). Dependent fiber bundle derived from surjective function.

```
def isFBundle2 (B: U) (p: B → U) (F: U): U
:= Σ (v: U) (w: surjective v B), (Π (x: v), PathP (<_>U) (p (w.1 x)) F)
```

Definition 57. (Fibration-3). Non-dependent fiber bundle derived from fiber truncation.

```
def im1 (A B: U) (f: A → B): U
:= Σ (b: B), ||_||-1 (Π (a : A), Path B (f a) b)

def BAut (F: U): U := im1 1 U (λ (x: 1), F)

def 1-Im1 (A B: U) (f: A → B): im1 A B f → B
:= λ (x : im1 A B f), x.1

def 1-BAut (F: U): BAut F → U := 1-Im1 1 U (λ (x: 1), F)

def classify (E: U) (A' A: U) (E': A' → U) (E: A → U)
(f: A' → A): U := Π(x: A'), Ξ U (E'(x)) (E(f(x)))

def isFBundle3 (E B: U) (p: E → B) (F: U): U1
:= Σ (X: B → BAut F),
    classify E B (BAut F) (λ (b: B), fiber E B p b)
    (1-BAut F) X
```

Definition 58. (Fibration-4). Non-dependen fiber bundle derived as pullback square.

```
def isFBundle4 (E B: U) (p: E → B) (F: U): U1
:= Σ (X: U) (v: surjective X B)
    (v': prod X F → E),
    pullbackSq (prod X F) E X B p v.1 v' (λ (x: prod X F), x.1)
```

6.5 Equivalence

Definition 59. (Fiberwise Equivalence). Fiberwise equivalence \simeq or **Equiv** of function $f : A \rightarrow B$ represents internal equality of types A and B in the universe U as contractible fibers of f over base B .

$$A \simeq B : U =_{def} \mathbf{Equiv}(A, B) : U =_{def} \sum_{f:A \rightarrow B} \prod_{y:B} \sum_{x:\Sigma_{x:A} y=f(x)} \sum_{w:\Sigma_{x:A} y=f(x)} x =_{\Sigma_{x:A} y=f(x)} w.$$

```
def isContr (A: U) : U
:= Σ (x: A), Π (y: A), ∃ A x y

def fiber (A B : U) (f: A → B) (y : B): U
:= Σ (x : A), ∃ B y (f x)

def isEquiv (A B : U) (f : A → B) : U
:= Π (y : B), isContr (fiber A B f y)

def equiv (A B : U) : U
:= Σ (f : A → B), isEquiv A B f
```

Definition 60. (Fiberwise Reflection). There is a fiberwise instance id_{\simeq} of $A \simeq A$ that is derived as $(\text{id}(A), \text{isContrSingl}(A))$:

$$\text{id}_{\simeq} : \mathbf{Equiv}(A, A).$$

```
def singl (A: U) (a: A): U
:= Σ (x: A), ∃ A a x

def contr (A : U) (a b : A) (p : ∃ A a b)
: ∃ (singl A a) (eta A a) (b, p)
:= <i> (p @ i, <j> p @ i /\ j)

def isContrSingl (A : U) (a : A) : isContr (singl A a)
:= ((a, idp A a), (\(z: singl A a), contr A a z.1 z.2))

def idEquiv (A : U) : equiv A A
:= (\(a:A) -> a, isContrSingl A)
```

Theorem 40. (Fiberwise Induction Principle). For any $P : A \rightarrow B \rightarrow A \simeq B \rightarrow U$ and it's evidence d at $(B, B, \text{id}_{\simeq}(B))$ there is a function \mathbf{Ind}_{\simeq} . HoTT 5.8.5

$$\mathbf{Ind}_{\simeq}(P, d) : (p : A \simeq B) \rightarrow P(A, B, p).$$

```
def J-equiv (A B: U)
(P: Π (A B: U), equiv A B → U)
(d: P B B (idEquiv B))
: Π (e: equiv A B), P A B e
:= λ (e: equiv A B),
  subst (single B) (\ (z: single B), P z.1 B z.2)
  (B, idEquiv B) (A, e)
  (contrSinglEquiv A B e) d
```

Theorem 41. (Fiberwise Computation of Induction Principle).

```
def compute-Equiv (A : U)
  (C :  $\Pi$  (A B: U), equiv A B  $\rightarrow$  U)
  (d: C A A (idEquiv A))
  :  $\Xi$  (C A A (idEquiv A)) d
    (ind-Equiv A A C d (idEquiv A))
```

Definition 61. (Surjective).

```
isSurjective (A B: U) (f: A  $\rightarrow$  B): U
  = (b: B) * pTrunc (fiber A B f b)

surjective (A B: U): U
  = (f: A  $\rightarrow$  B)
    * isSurjective A B f
```

Definition 62. (Injective).

```
isInjective' (A B: U) (f: A  $\rightarrow$  B): U
  = (b: B)  $\rightarrow$  isProp (fiber A B f b)

injective (A B: U): U
  = (f: A  $\rightarrow$  B)
    * isInjective A B f
```

Definition 63. (Embedding).

```
isEmbedding (A B: U) (f: A  $\rightarrow$  B) : U
  = (x y: A)  $\rightarrow$  isEquiv ( $\Xi$  A x y) ( $\Xi$  B (f x) (f y)) (cong A B f x y)

embedding (A B: U): U
  = (f: A  $\rightarrow$  B)
    * isEmbedding A B f
```

Definition 64. (Half-adjoint Equivalence).

```
isHae (A B: U) (f: A  $\rightarrow$  B): U
  = (g: B  $\rightarrow$  A)
    * ( $\eta$ _:  $\Xi$  (id A) (o A B A g f) (idfun A))
    * ( $\epsilon$ _:  $\Xi$  (id B) (o B A B f g) (idfun B))
    * ((x: A)  $\rightarrow$   $\Xi$  B (f (( $\eta$ _ @ 0) x)) (( $\epsilon$ _ @ 0) (f x)))

hae (A B: U): U
  = (f: A  $\rightarrow$  B)
    * isHae A B f
```

6.6 Homotopy

The first higher equality we meet in homotopy theory is a notion of homotopy, where we compare two functions or two path spaces (which is sort of dependent families). The homotopy interval $I = [0, 1]$ is the perfect foundation for definition of homotopy.

Definition 65. (Interval). Compact interval.

```
def I : U := inductive { i0 | i1 | seg : i0 ≡ i1 }
```

You can think of \mathbf{I} as isomorphism of equality type, disregarding carriers on the edges. By mapping $i0, i1 : \mathbf{I}$ to $x, y : A$ one can obtain identity or equality type from classic type theory.

Definition 66. (Interval Split). The conversion function from \mathbf{I} to a type of comparison is a direct eliminator of interval. The interval is also known as one of primitive higher inductive types which will be given in the next **Issue IV: Higher Inductive Types**.

```
def pathToHtpy (A: U) (x y: A) (p: ≡ A x y) : I → A
:= split { i0 → x | i1 → y | seg @ i → p @ i }
```

Definition 67. (Homotopy). The homotopy between two function $f, g : X \rightarrow Y$ is a continuous map of cylinder $H : X \times \mathbf{I} \rightarrow Y$ such that

$$\begin{cases} H(x, 0) = f(x), \\ H(x, 1) = g(x). \end{cases}$$

```
homotopy (X Y: U) (f g: X → Y)
(p: (x: X) → ≡ Y (f x) (g x))
(x: X): I → Y = pathToHtpy Y (f x) (g x) (p x)
```

Definition 68. (funExt-Formation)
$$\text{funext_form } (A B: U) (f g: A \rightarrow B): U \\ = \Xi (A \rightarrow B) f g$$
Definition 69. (funExt-Introduction)
$$\text{funext } (A B: U) (f g: A \rightarrow B) (p: (x:A) \rightarrow \Xi B (f x) (g x)) \\ : \text{funext_form } A B f g \\ = \text{<i> } \backslash (a: A) \rightarrow p a @ i$$
Definition 70. (funExt-Elimination)
$$\text{happly } (A B: U) (f g: A \rightarrow B) (p: \text{funext_form } A B f g) (x: A) \\ : \Xi B (f x) (g x) \\ = \text{cong } (A \rightarrow B) B (\backslash (h: A \rightarrow B) \rightarrow \text{apply } A B h x) f g p$$
Definition 71. (funExt-Computation)
$$\text{funext_Beta } (A B: U) (f g: A \rightarrow B) (p: (x:A) \rightarrow \Xi B (f x) (g x)) \\ : (x:A) \rightarrow \Xi B (f x) (g x) \\ = \backslash (x:A) \rightarrow \text{happly } A B f g (\text{funext } A B f g p) x$$
Definition 72. (funExt-Uniqueness)
$$\text{funext_Eta } (A B: U) (f g: A \rightarrow B) (p: \Xi (A \rightarrow B) f g) \\ : \Xi (\Xi (A \rightarrow B) f g) (\text{funext } A B f g (\text{happly } A B f g p)) p \\ = \text{refl } (\Xi (A \rightarrow B) f g) p$$

6.7 Isomorphism

Definition 73. (iso-Formation)

$\text{iso_Form } (A\ B : U) : U = \text{isIso } A\ B \rightarrow \exists U\ A\ B$

Definition 74. (iso-Introduction)

$\text{iso_Intro } (A\ B : U) : \text{iso_Form } A\ B$

Definition 75. (iso-Elimination)

$\text{iso_Elim } (A\ B : U) : \exists U\ A\ B \rightarrow \text{isIso } A\ B$

Definition 76. (iso-Computation)

$\text{iso_Comp } (A\ B : U) \ (p : \exists U\ A\ B)$
 $: \exists (\exists U\ A\ B) \ (\text{iso_Intro } A\ B \ (\text{iso_Elim } A\ B\ p)) \ p$

Definition 77. (iso-Uniqueness)

$\text{iso_Uniq } (A\ B : U) \ (p : \text{isIso } A\ B)$
 $: \exists (\text{isIso } A\ B) \ (\text{iso_Elim } A\ B \ (\text{iso_Intro } A\ B\ p)) \ p$

6.8 Univalence

Definition 78. (uni-Formation)

$\text{univ_Formation } (A B : U) : U = \text{equiv } A B \rightarrow \Xi U A B$

Definition 79. (uni-Introduction)

$\text{equivTo}\Xi (A B : U) : \text{univ_Formation } A B$
 $= \backslash (p : \text{equiv } A B) \rightarrow \langle i \rangle \text{ Glue } B \text{ [(i=0) } \rightarrow (A, p),$
 $(i=1) \rightarrow (B, \text{subst } U (\text{equiv } B) B B (\langle _ \rangle B) (\text{idEquiv } B))]$

Definition 80. (uni-Elimination)

$\text{pathToEquiv } (A B : U) (p : \Xi U A B) : \text{equiv } A B$
 $= \text{subst } U (\text{equiv } A) A B p (\text{idEquiv } A)$

Definition 81. (uni-Computation)

$\text{eqToEq } (A B : U) (p : \Xi U A B)$
 $: \Xi (\Xi U A B) (\text{equivToPath } A B (\text{pathToEquiv } A B p)) p$
 $= \langle j \ i \rangle \text{ let } Ai : U = p@i \text{ in Glue } B$
 $\text{ [(i=0) } \rightarrow (A, \text{pathToEquiv } A B p),$
 $(i=1) \rightarrow (B, \text{pathToEquiv } B B (\langle k \rangle B)),$
 $(j=1) \rightarrow (p@i, \text{pathToEquiv } Ai B (\langle k \rangle p @ (i \setminus / k)))]$

Definition 82. (uni-Uniqueness)

$\text{transPathFun } (A B : U) (w : \text{equiv } A B)$
 $: \Xi (A \rightarrow B) w.1 (\text{pathToEquiv } A B (\text{equivToPath } A B w)).1$

6.9 Loop

Definition 83. (Pointed Space). A pointed type (A, a) is a type $A : U$ together with a point $a : A$, called its basepoint.

```
pointed : U = (A : U) * A
point   (A : pointed) : A.1 = A.2
space   (A : pointed) : U = A.1
```

Definition 84. (Loop Space).

$$\Omega(A, a) =_{def} ((a =_A a), refl_A(a)).$$

```
omega1 (A : pointed) : pointed
      = (Ξ (space A) (point A) (point A), refl A.1 (point A))
```

Definition 85. (n-Loop Space).

$$\begin{cases} \Omega^0(A, a) =_{def} (A, a) \\ \Omega^{n+1}(A, a) =_{def} \Omega^n(\Omega(A, a)) \end{cases}$$

```
omega : nat -> pointed -> pointed = split
      zero -> idfun pointed
      succ n -> \ (A : pointed) -> omega n (omega1 A)
```

6.10 Groupoid

The first text about groupoid interpretation of type theory can be found in Francois Lamarche: A proposal about Foundations². Then Martin Hofmann and Thomas Streicher wrote the initial document on groupoid interpretation of type theory³.

Equality	Homotopy	∞ -Groupoid
reflexivity	constant path	identity morphism
symmetry	inversion of path	inverse morphism
transitivity	concatenation of paths	composition of morphisms

There is a deep connection between higher-dimensional groupoids in category theory and spaces in homotopy theory, equipped with some topology. The category or groupoid could be built where the objects are particular spaces or types, and morphisms are path types between these types, composition operation is a path concatenation. We can write this groupoid here recalling that it should be category with inverted morphisms.

```

cat : U = (A : U) * (A → A → U)
groupoid : U = (X : cat) * isCatGroupoid X
PathCat (X : U) : cat = (X, \ (x y : X) → Path X x y)

def isCatGroupoid (C : cat) : U := Σ
  (id :      Π (x : C.ob), C.hom x x)
  (c :      Π (x y z : C.ob), C.hom x y → C.hom y z → C.hom x z)
  (HomSet : Π (x y : C.ob), isSet (C.hom x y))
  (inv :    Π (x y : C.ob), C.hom x y → C.hom y x)
  (inv-left : Π (x y : C.ob) (p : C.hom x y),
    ≡ (C.hom x x) (c x y x p (inv x y p)) (id x))
  (inv-right : Π (x y : C.ob) (p : C.hom x y),
    ≡ (C.hom y y) (c y x y (inv x y p) p) (id y))
  (left :     Π (x y : C.ob) (f : C.hom x y),
    ≡ (C.hom x y) f (c x x y (id x) f))
  (right :    Π (x y : C.ob) (f : C.hom x y),
    ≡ (C.hom x y) f (c x y y f (id y)))
  (assoc :    Π (x y z w : C.ob) (f : C.hom x y)
    (g : C.hom y z) (h : C.hom z w),
    ≡ (C.hom x w) (c x z w (c x y z f g) h)
    (c x y w f (c y z w g h))), *

```

²<http://www.cse.chalmers.se/~coquand/Proposal.pdf>

³Martin Hofmann and Thomas Streicher. The Groupoid Interpretation of Type Theory. 1996.

```

def isProp (A : U) : U
:=  $\Pi$  (a b : A),  $\Xi$  A a b

def isSet (A : U) : U
:=  $\Pi$  (a b : A) (x y :  $\Xi$  A a b),
 $\Xi$  ( $\Xi$  A a b) x y

def isGroupoid (A : U) : U
:=  $\Pi$  (a b : A) (x y :  $\Xi$  A a b)
(i j :  $\Xi$  ( $\Xi$  A a b) x y),
 $\Xi$  ( $\Xi$  ( $\Xi$  A a b) x y) i j

def CatGroupoid (X : U) (G : isGroupoid X)
: isCatGroupoid (PathCat X)
:= ( idp X,
comp-Path X,
G,
sym X,
comp-inv-Path-1 X,
comp-inv-Path X,
comp-Path-left X,
comp-Path-right X,
comp-Path-assoc X,
 $\star$ 
)

def comp- $\Xi$  (A : U) (a b c : A) (p :  $\Xi$  A a b) (q :  $\Xi$  A b c) :  $\Xi$  A a c
:= <i> hcomp A ( $\partial$  i)
( $\lambda$  (j : I), [(i = 0)  $\rightarrow$  a,
(i = 1)  $\rightarrow$  q @ j]) (p @ i)

def comp-inv- $\Xi$ -1 (A : U) (a b : A) (p :  $\Xi$  A a b)
:  $\Xi$  ( $\Xi$  A a a) (comp- $\Xi$  A a b a p (<i> p @ -i)) (<_> a)
:= <k j> hcomp A ( $\partial$  j  $\vee$  k)
( $\lambda$  (i : I), [(j = 0)  $\rightarrow$  a,
(j = 1)  $\rightarrow$  p @ -i  $\wedge$  -k,
(k = 1)  $\rightarrow$  a]) (p @ j  $\wedge$  -k)

def comp-inv- $\Xi$  (A : U) (a b : A) (p :  $\Xi$  A a b)
:  $\Xi$  ( $\Xi$  A b b) (comp- $\Xi$  A b a b (<i> p @ -i) p) (<_> b)
:= <j i> hcomp A ( $\partial$  i  $\vee$  j)
( $\lambda$  (k : I), [(i = 0)  $\rightarrow$  b,
(j = 1)  $\rightarrow$  b,
(i = 1)  $\rightarrow$  p @ j  $\wedge$  k]) (p @ -i  $\vee$  j)

def comp- $\Xi$ -left (A : U) (a b : A) (p :  $\Xi$  A a b)
:  $\Xi$  ( $\Xi$  A a b) p (comp- $\Xi$  A a a b (<_> a) p)
:= <j i> hcomp A ( $\partial$  i  $\vee$  -j)
( $\lambda$  (k : I), [(i = 0)  $\rightarrow$  a,
(i = 1)  $\rightarrow$  p @ k,
(j = 0)  $\rightarrow$  p @ i  $\wedge$  k]) a

def comp- $\Xi$ -right (A : U) (a b : A) (p :  $\Xi$  A a b)
:  $\Xi$  ( $\Xi$  A a b) p (comp- $\Xi$  A a b b p (<_> b))
:= <j i> hcomp A ( $\partial$  i  $\vee$  -j)
( $\lambda$  (k : I), [(i = 0)  $\rightarrow$  a,
(i = 1)  $\rightarrow$  b,
(j = 0)  $\rightarrow$  p @ i]) (p @ i)

```

```

def comp-≡-assoc (A : U) (a b c d : A)
  (f : ≡ A a b) (g : ≡ A b c) (h : ≡ A c d)
  : ≡ (≡ A a d) (comp-≡ A a c d (comp-≡ A a b c f g) h)
    (comp-≡ A a b d f (comp-≡ A b c d g h))
:= J A a (λ (a : A) (b : A) (f : ≡ A a b),
  Π (c d : A) (g : ≡ A b c) (h : ≡ A c d),
  ≡ (≡ A a d) (comp-≡ A a c d (comp-≡ A a b c f g) h)
    (comp-≡ A a b d f (comp-≡ A b c d g h))))
  (λ (c d : A) (g : ≡ A a c) (h : ≡ A c d),
  comp-≡ (≡ A a d)
    (comp-≡ A a c d (comp-≡ A a a c (<_> a) g) h)
    (comp-≡ A a c d g h)
    (comp-≡ A a a d (<_> a) (comp-≡ A a c d g h))
    (<i> comp-≡ A a c d (comp-≡-left A a c g @ -i) h)
    (comp-≡-left A a d (comp-≡ A a c d g h))) b f c d g h

```

6.11 Homotopy Groups

Definition 86. (n-th Homotopy Group of m-Sphere).

$$\pi_n S^m = ||\Omega^n(S^m)||_0.$$

```
piS (n: nat): (m: nat) -> U = split
  zero  -> sTrunc (space (omega n (bool, false)))
  succ x -> sTrunc (space (omega n (Sn (succ x), north)))
```

Theorem 42. $(\Omega(S^1) = \mathbb{Z})$.

```
data S1 = base
  | loop <i> [ (i=0) -> base ,
              (i=1) -> base ]

loopS1 : U =  $\Xi$  S1 base base

encode (x:S1) (p: $\Xi$  S1 base x)
  : helix x
  = subst S1 helix base x p zeroZ

decode : (x:S1) -> helix x ->  $\Xi$  S1 base x = split
  base -> loopIt
  loop @ i -> rem @ i where
    p :  $\Xi$  U (Z -> loopS1) (Z -> loopS1)
    = <j> helix (loop1@j) ->  $\Xi$  S1 base (loop1@j)
  rem : PathP p loopIt loopIt
    = corFib1 S1 helix (\(x:S1)-> $\Xi$  S1 base x) base
      loopIt loopIt loop1 (\(n:Z) ->
        comp (<i>  $\Xi$  loopS1 (oneTurn (loopIt n))
          (loopIt (testIsoPath Z Z sucZ predZ
            sucpredZ predsucZ n @ i)))
          (<i>(lem1It n)@-i) [])
```

```
loopS1eqZ :  $\Xi$  U Z loopS1
  = isoPath Z loopS1 (decode base) (encode base)
  sectionZ retractZ
```

6.12 Hopf Fibrations

Example 4. ($S^1 \mathbb{R}$ Hopf Fiber).

```

data bool = false | true

negBool : bool -> bool
  = split { false -> true ; true -> false }

negBoolK : (b : bool) ->  $\Xi$  bool (negBool (negBool b)) b
  = split { false -> false ; true -> true }

negBoolEquiv : equiv bool bool
  = (negBool, gradLemma bool bool negBool negBool negBoolK negBoolK)

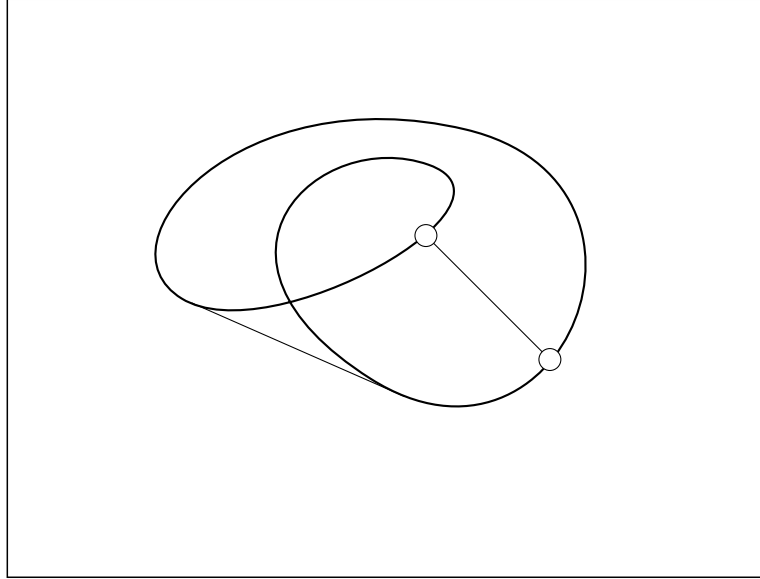
S2 : U = susp S1
S3 : U = susp S2

ua (A B : U) (e : equiv A B) :  $\Xi$  U A B =
  <i> Glue B [ (i = 0) -> (A,e),
              (i = 1) -> (B,idEquiv B) ]

moebius : S1 -> U = split
  base -> bool
  loop @ i -> ua bool bool negBoolEquiv @ i

TH0 : U = (c : S1) * moebius c

```



Example 5. ($S^3 \mathbb{C}$ Hopf Fiber). S^3 Fibration was peconeered by Guillaume Brunerie.

```

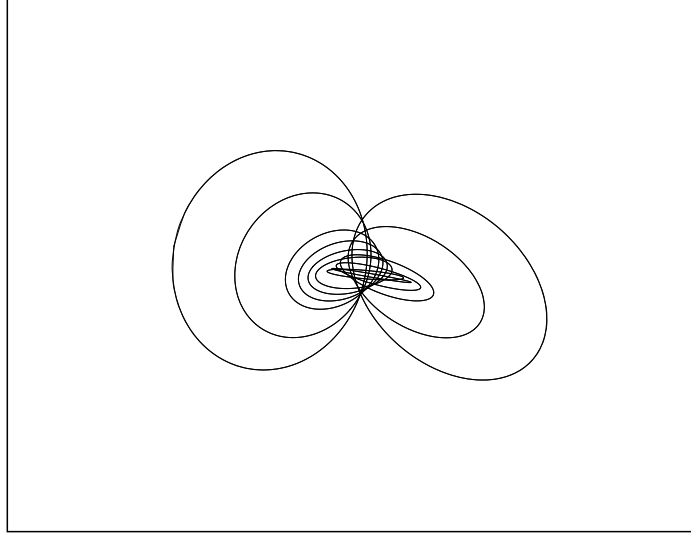
rot : (x : S1) → ∃ S1 x x = split
      base → loop1
      loop @ i → constSquare S1 base loop1 @ i

mu : S1 → equiv S1 S1 = split
      base → idEquiv S1
      loop @ i → equivPath S1 S1 (idEquiv S1)
                  (idEquiv S1) (<j> \ (x : S1) → rot x @ j) @ i

H : S2 → U = split
      north → S1
      south → S1
      merid x @ i → ua S1 S1 (mu x) @ i

total : U = (c : S2) * H c

```



Definition 87. (H-space). H-space over a carrier A is a tuple

$$H_A = \begin{cases} A : U \\ e : A \\ \mu : A \rightarrow A \rightarrow A \\ \beta : \Pi(a : A), \mu(e, a) = a \times \mu(a, e) = a \end{cases}$$

.

Theorem 43. (Hopf Invariant). Let $\phi : S^{2n-1} \rightarrow S^n$ a continuous map. Then homotopy pushout (cofiber) of ϕ is $\text{cofib}(\phi) = S^n \bigcup_{\phi} \mathbb{D}^{2n}$ has ordinary cohomology

$$H^k(\text{cofib}(\phi), \mathbb{Z}) = \begin{cases} \mathbb{Z} & \text{for } k = n, 2n \\ 0 & \text{otherwise} \end{cases}$$

Theorem 44. (Four). There are fiber bundles: (S^0, S^1, p, S^1) , (S^1, S^3, p, S^2) , (S^3, S^7, p, S^4) , (S^7, S^{15}, p, S^8) .

Hence for α, β generators of the cohomology groups in degree n and $2n$, respectively, there exists an integer $h(\phi)$ that expresses the **cup product** square of α as a multiple of $\beta - \alpha \sqcup \alpha = h(\phi) \cdot \beta$. This integer $h(\phi)$ is called Hopf invariant of ϕ .

Theorem 45. (Adams, Atiyah). Hopf Fibrations are only maps that have Hopf invariant 1.

Issue IV: Higher Inductive Types

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Анотація

CW-complexes are central to both homotopy theory and homotopy type theory (HoTT) and are encoded in cubical theorem-proving systems as higher inductive types (HIT), similar to recursive trees for (co)inductive types. We explore the basic primitives of homotopy theory, which are considered as a foundational basis in theorem-proving systems.

Keywords: Homotopy Theory, Type Theory

7 CW-Complexes

CW-complexes are spaces constructed by attaching cells of various dimensions. In HoTT, they are encoded as higher inductive types (HIT), where cells are constructors for points and paths.

Definition 88. (Cell Attachment). The attachment of an n -cell to a space X along $f : S^{n-1} \rightarrow X$ is a pushout:

$$\begin{array}{ccc} S^{n-1} & \xrightarrow{f} & X \\ \downarrow \iota & & \downarrow j \\ D^n & \xrightarrow{g} & X \cup_f D^n \end{array}$$

Here, $\iota : S^{n-1} \hookrightarrow D^n$ is the boundary inclusion, and $X \cup_f D^n$ is the pushout that attaches an n -cell to X via f . The result depends on the homotopy class of f .

Definition 89. (CW-Complex). A CW-complex is a space X , constructed inductively by attaching cells, with a skeletal filtration:

- (-1) -skeleton: $X_{-1} = \emptyset$.

- For $n \geq 0$, the n -skeleton X_n is obtained by attaching n -cells to X_{n-1} . For indices J_n and maps $\{f_j : S^{n-1} \rightarrow X_{n-1}\}_{j \in J_n}$, X_n is the pushout:

$$\begin{array}{ccc} \coprod_{j \in J_n} S^{n-1} & \xrightarrow{\coprod f_j} & X_{n-1} \\ \downarrow \coprod \iota_j & & \downarrow i_n \\ \coprod_{j \in J_n} D^n & \xrightarrow{\coprod g_j} & X_n \end{array}$$

where $\coprod_{j \in J_n} S^{n-1}$, $\coprod_{j \in J_n} D^n$ are disjoint unions, and $i_n : X_{n-1} \hookrightarrow X_n$ is the inclusion.

- X is the colimit:

$$\emptyset = X_{-1} \hookrightarrow X_0 \hookrightarrow X_1 \hookrightarrow \dots \hookrightarrow X,$$

where X_n is the n -skeleton, and $X = \operatorname{colim}_{n \rightarrow \infty} X_n$. The sequence is the skeletal filtration.

In HoTT, CW-complexes are higher inductive types (HIT) with constructors for cells and paths for attachment.

7.1 Introduction: Countable Constructors

Some HITs require an infinite number of constructors for spaces, such as Eilenberg-MacLane spaces or the infinite sphere S^∞ .

```
def S∞ : U
:= inductive { base
              | loop (n: ℕ) : base ≡ base
              }
```

Challenges include type checking, computation, and expressiveness.

Agda Cubical uses cubical primitives to handle HITs, supporting infinite constructors via HITs indexed by natural numbers, as colimits.

7.2 Motivation: Higher Inductive Types

HITs in HoTT enable direct encoding of topological spaces, such as CW-complexes. In homotopy theory, spaces are constructed by attaching cells via attaching maps. HoTT views types as spaces, elements as points, and equalities as paths, making HITs a natural choice. Standard inductive types cannot capture higher homotopies, but HITs allow constructors for points and paths. For example, the circle S^1 (Definition 2) has a base point and a loop, encoding its fundamental group \mathbb{Z} . HITs avoid the use of multiple quotient spaces, preserving the synthetic nature of HoTT. In cubical type theory, paths are intervals (e.g., $\langle i \rangle$) with computational content, unlike propositional equalities, enabling efficient type checking in tools such as Agda Cubical.

7.3 Metatheory: Cohesive Topoi

7.3.1 Geometric Proofs

$$\mathfrak{R} \dashv \mathfrak{S} \dashv \&$$

For differential geometry, type theory incorporates primitive axioms of categorical meta-theoretical models of three Schreiber-Shulman functors: infinitesimal neighborhood (\mathfrak{S}), reduced modality (\mathfrak{R}), and infinitesimal discrete neighborhood ($\&$).

7.3.2 Flat Proofs

7.3.3 Sharp Proofs

7.3.4 Bose Proofs

7.3.5 Fermi Proofs

7.3.6 Linear Proofs

$$\otimes \dashv x \dashv \multimap$$

For engineering applications (e.g., Milner’s π -calculus, quantum computing) and linear type theory, type theory embeds linear proofs based on the adjunction

of the tensor and linear function spaces: $(A \otimes B) \multimap A \simeq A \multimap (B \multimap C)$, represented in a symmetric monoidal category \mathbf{D} for a functor $[A, B]$ as: $\mathbf{D}(A \otimes B, C) \simeq \mathbf{D}(A, [B, C])$.

8 Higher Inductive Types

CW-complexes are central to HoTT and appear in cubical type checkers as HITs. Unlike inductive types (recursive trees), HITs encode CW-complexes, capturing points (0-cells) and higher paths (n-cells). The definition of an HIT specifies a CW-complex through cubical composition, an initial algebra in the cubical model.

8.1 Suspension

The suspension ΣA of a type A is a higher inductive type that constructs a new type by adding two points, called poles, and paths connecting each point of A to these poles. It is a fundamental construction in homotopy theory, often used to shift homotopy groups, e.g., obtaining S^{n+1} from S^n .

Definition 90. (Formation). For any type $A : \mathcal{U}$, there exists a suspension type $\Sigma A : \mathcal{U}$.

Definition 91. (Constructors). For a type $A : \mathcal{U}$, the suspension $\Sigma A : \mathcal{U}$ is generated by the following higher inductive compositional structure:

$$\Sigma := \begin{cases} \text{north} \\ \text{south} \\ \text{merid} : (a : A) \rightarrow \text{north} \equiv \text{south} \end{cases}$$

```
def Σ (A: U) : U
:= inductive {
  | north
  | south
  | merid (a: A) : north ≡ south
}
```

Theorem 46. (Elimination). For a family of types $B : \Sigma A \rightarrow \mathcal{U}$, points $n : B(\text{north})$, $s : B(\text{south})$, and a family of dependent paths

$$m : \Pi(a : A), \text{PathOver}(B, \text{merid}(a), n, s),$$

there exists a dependent map $\text{Ind}_{\Sigma A} : (x : \Sigma A) \rightarrow B(x)$, such that:

$$\begin{cases} \text{Ind}_{\Sigma A}(\text{north}) = n \\ \text{Ind}_{\Sigma A}(\text{south}) = s \\ \text{Ind}_{\Sigma A}(\text{merid}(a, i)) = m(a, i) \end{cases}$$

```
def PathOver (B: Σ A → U) (a: A) (n: B north) (s: B south) : U
:= PathP (λ i , B (merid a @ i)) n s
```

```
def Ind_ΣA (A: U) (B: Σ A → U) (n: B north) (s: B south)
(m: (a: A) → PathOver B (merid a) n s) : (x: Σ A) → B x
:= split { north → n | south → s | merid a @ i → m a @ i }
```

Theorem 47. (Computation).

$$\text{Ind}_{\Sigma A}(\text{north}) = n \text{Ind}_{\Sigma A}(\text{south}) = s \text{Ind}_{\Sigma A}(\text{merid}(a, i)) = m(a, i)$$

```
def Σ-β (A: U) (B: Σ A → U) (n: B north) (s: B south)
(m: (a: A) → PathOver B (merid a) n s) (x: Σ A)
: Path (B x) (Σ-I A B n s m x)
split { north → n | south → s | merid a @ i → m a @ i }
```

Theorem 48. (Uniqueness). Any two maps $h_1, h_2 : (x : \Sigma A) \rightarrow B(x)$ are homotopic if they agree on north, south, and merid, i.e., if $h_1(\text{north}) = h_2(\text{north})$, $h_1(\text{south}) = h_2(\text{south})$, and $h_1(\text{merid } a) = h_2(\text{merid } a)$ for all $a : A$.

8.2 Pushout

The pushout (amalgamation) is a higher inductive type that constructs a type by gluing two types A and B along a common type C via maps $f : C \rightarrow A$ and $g : C \rightarrow B$. It is a fundamental construction in homotopy theory, used to model cell attachment and cofibrant objects, generalizing the topological notion of a pushout.

Definition 92. (Formation). For types $A, B, C : \mathcal{U}$ and maps $f : C \rightarrow A$, $g : C \rightarrow B$, there exists a pushout $\sqcup(A, B, C, f, g) : \mathcal{U}$.

Definition 93. (Constructors). The pushout is generated by the following higher inductive compositional structure:

$$\sqcup := \begin{cases} \text{po}_1 : A \rightarrow \sqcup(A, B, C, f, g) \\ \text{po}_2 : B \rightarrow \sqcup(A, B, C, f, g) \\ \text{po}_3 : (c : C) \rightarrow \text{po}_1(f(c)) \equiv \text{po}_2(g(c)) \end{cases}$$

```
def  $\sqcup$  (A B C : U) (f : C  $\rightarrow$  A) (g : C  $\rightarrow$  B) : U
:= inductive {
  | po1 (a : A)
  | po2 (b : B)
  | po3 (c : C) : po1(f(c))  $\equiv$  po2(g(c))
}
```

Theorem 49. (Elimination). For a type $D : \mathcal{U}$, maps $u : A \rightarrow D$, $v : B \rightarrow D$, and a family of paths $p : (c : C) \rightarrow u(f(c)) \equiv v(g(c))$, there exists a map $\text{Ind}_{\sqcup} : \sqcup(A, B, C, f, g) \rightarrow D$, such that:

$$\begin{cases} \text{Ind}_{\sqcup}(\text{po}_1(a)) = u(a) \\ \text{Ind}_{\sqcup}(\text{po}_2(b)) = v(b) \\ \text{Ind}_{\sqcup}(\text{po}_3(c, i)) = p(c, i) \end{cases}$$

```
def PathOver (A B C : U) (f : C  $\rightarrow$  A) (g : C  $\rightarrow$  B)
  (D :  $\sqcup$  A B C f g  $\rightarrow$  U)
  (c : C) (u : D (po1 (f c))) (v : D (po2 (g c))) : U
:= PathP ( $\lambda$  i, D (po3 c i)) u v

def Ind $\sqcup$  : (A B C : U) (f : C  $\rightarrow$  A) (g : C  $\rightarrow$  B)
  (D :  $\sqcup$  A B C f g  $\rightarrow$  U)
  (u : (a : A)  $\rightarrow$  D (po1 a))
  (v : (b : B)  $\rightarrow$  D (po2 b))
  (p : (c : C)  $\rightarrow$  PathOver D c (u (f c)) (v (g c)))
  : (x :  $\sqcup$  A B C f g)  $\rightarrow$  D x
:= split { po1 a  $\rightarrow$  u a | po2 b  $\rightarrow$  v b | po3 c @ i  $\rightarrow$  p c @ i }
```

Theorem 50. (Computation). For $x : \sqcup(A, B, C, f, g)$,

$$\begin{cases} \text{Ind}_{\sqcup}(\text{po}_1(a)) \equiv u(a) \\ \text{Ind}_{\sqcup}(\text{po}_2(b)) \equiv v(b) \\ \text{Ind}_{\sqcup}(\text{po}_3(c, i)) \equiv p(c, i) \end{cases}$$

Theorem 51. (Uniqueness). Any two maps $u, v : \sqcup(A, B, C, f, g) \rightarrow D$ are homotopic if they agree on po_1 , po_2 , and po_3 , i.e., if $u(\text{po}_1(a)) = v(\text{po}_1(a))$ for all $a : A$, $u(\text{po}_2(b)) = v(\text{po}_2(b))$ for all $b : B$, and $u(\text{po}_3(c)) = v(\text{po}_3(c))$ for all $c : C$.

Example 6. (Cell Attachment) The pushout models the attachment of an n -cell to a space X . Given $f : S^{n-1} \rightarrow X$ and inclusion $g : S^{n-1} \rightarrow D^n$, the pushout $\sqcup(X, D^n, S^{n-1}, f, g)$ is the space $X \cup_f D^n$, attaching an n -disk to X along f .

$$\begin{array}{ccc} S^{n-1} & \xrightarrow{f} & X \\ \downarrow g & & \downarrow \\ D^n & \longrightarrow & X \cup_f D^n \end{array}$$

8.3 Spheres

Spheres are higher inductive types with higher-dimensional paths, representing fundamental topological spaces.

Definition 94. (Pointed n-Spheres) The n -sphere S^n is defined recursively as a type in the universe \mathcal{U} using general recursion over dimensions:

$$S^n := \begin{cases} \text{point} : \mathbb{S}^n, \\ \text{surface} : \langle i_1, \dots, i_n \rangle [(i_1 = 0) \rightarrow \text{point}, (i_1 = 1) \rightarrow \text{point}, \dots \\ (i_n = 0) \rightarrow \text{point}, (i_n = 1) \rightarrow \text{point}] \end{cases}$$

Definition 95. (n-Spheres via Suspension) The n -sphere S^n is defined recursively as a type in the universe \mathcal{U} using general recursion over natural numbers \mathbb{N} . For each $n \in \mathbb{N}$, the type $S^n : \mathcal{U}$ is defined as:

$$\mathbb{S}^n := \begin{cases} S^0 = \mathbf{2}, \\ S^{n+1} = \Sigma(S^n). \end{cases}$$

`def sphere : $\mathbb{N} \rightarrow \mathcal{U} := \text{N-iter } \mathbf{U} \ \mathbf{2} \ \Sigma$`

This iterative definition applies the suspension functor Σ to the base type $\mathbf{2}$ (0-sphere) n times to obtain S^n .

Example 7. (Sphere as CW-Complex) The n -sphere S^n can be constructed as a CW-complex with one 0-cell and one n -cell:

$$\begin{cases} X_0 = \{\text{base}\}, \text{ one point} \\ X_k = X_0 \text{ for } 0 < k < n, \text{ no additional cells} \\ X_n : \text{Attachment of an } n\text{-cell to } X_{n-1} = \{\text{base}\} \text{ along } f : S^{n-1} \rightarrow \{\text{base}\} \end{cases}$$

The constructor `cell` attaches the boundary of the n -cell to the base point, yielding the type S^n .

8.4 Hub and Spokes

The hub and spokes construction \odot defines an n -truncation, ensuring that the type has no non-trivial homotopy groups above dimension n . It models the type as a CW-complex with a hub (central point) and spokes (paths to points).

Definition 96. (Formation). For types $S, A : \mathcal{U}$, there exists a hub and spokes type $\odot (S, A) : \mathcal{U}$.

Definition 97. (Constructors). The hub and spokes type is freely generated by the following higher inductive compositional structure:

$$\odot := \begin{cases} \text{base} : A \rightarrow \odot (S, A) \\ \text{hub} : (S \rightarrow \odot (S, A)) \rightarrow \odot (S, A) \\ \text{spoke} : (f : S \rightarrow \odot (S, A)) \rightarrow (s : S) \rightarrow \text{hub}(f) \equiv f(s) \end{cases}$$

```
def  $\odot$  (S A: U) : U
:= inductive { base (x: A)
              | hub (f: S  $\rightarrow$   $\odot$  S A)
              | spoke (f: S  $\rightarrow$   $\odot$  S A) (s:S) : hub f  $\equiv$  f s
            }
```

Theorem 52. (Elimination). For a family of types $P : \text{HubSpokes } S \ A \rightarrow \mathcal{U}$, maps $\text{pbase} : (x : A) \rightarrow P(\text{base } x)$, $\text{phub} : (f : S \rightarrow \text{HubSpokes } S \ A) \rightarrow P(\text{hub } f)$, and a family of paths $\text{pspoke} : (f : S \rightarrow \text{HubSpokes } S \ A) \rightarrow (s : S) \rightarrow \text{PathP}(< i > P(\text{spoke } f \ s \ @ \ i)) (\text{phub } f) (P(f \ s))$, there exists a map $\text{hubSpokesInd} : (z : \text{HubSpokes } S \ A) \rightarrow P(z)$, such that:

$$\begin{cases} \text{Ind}_{\odot} (\text{base } x) = \text{pbase } x \\ \text{Ind}_{\odot} (\text{hub } f) = \text{phub } f \\ \text{Ind}_{\odot} (\text{spoke } f \ s \ @ \ i) = \text{pspoke } f \ s \ @ \ i \end{cases}$$

8.5 Truncation

Set Truncation

Definition 98. (Formation). Set truncation (0-truncation), denoted $\|A\|_0$, ensures that the type is a set, with homotopy groups vanishing above dimension 0.

Definition 99. (Constructors). For $A : \mathcal{U}$, $\|A\|_0 : \mathcal{U}$ is defined by the following higher inductive compositional structure:

$$\|_-\|_0 := \begin{cases} \text{inc} : A \rightarrow \|A\|_0 \\ \text{squash} : (a, b : \|A\|_0) \rightarrow (p, q : a \equiv b) \rightarrow p \equiv q \end{cases}$$

```
def \|_-\|_0 (A: U) : U
:= inductive { inc (a: A)
              | squash (a b: \|A\|_0) (p q: Path (\|A\|_0) a b)
                <i j> [ (i = 0) -> p @ j, (i = 1) -> q @ j,
                      (j = 0) -> a,      (j = 1) -> b ]
              }
```

Theorem 53. (Elimination $\|A\|_0$) For a set $B : \mathcal{U}$ (i.e., $\text{isSet}(B)$), and a map $f : A \rightarrow B$, there exists $\text{setTruncRec} : \|A\|_0 \rightarrow B$, such that $\text{Ind}_{\|A\|_0}(\text{inc}(a)) = f(a)$.

Groupoid Truncation

Definition 100. (Formation). Groupoid truncation (1-truncation), denoted $\|A\|_1$, ensures that the type is a 1-groupoid, with homotopy groups vanishing above dimension 1.

Definition 101. (Constructors). For $A : \mathcal{U}$, $\|A\|_1 : \mathcal{U}$ is defined by the following higher inductive compositional structure:

$$\|_-\|_1 := \begin{cases} \text{inc} : A \rightarrow \|A\|_1 \\ \text{squash} : (a, b : \|A\|_1) \rightarrow (p, q : a \equiv b) \rightarrow (r, s : p \equiv q) \rightarrow r \equiv s \end{cases}$$

```
def \|_-\|_1 (A: U) : U
:= inductive { inc (a: A)
              | squash (a b: \|A\|_1) (p q: Path (\|A\|_1) a b)
                (r s: Path (Path (\|A\|_1) a b) p q) <i j k>
                [ (i = 0) -> r @ j @ k, (i = 1) -> s @ j @ k,
                  (j = 0) -> p @ k,      (j = 1) -> q @ k,
                  (k = 0) -> a,          (k = 1) -> b ]
              }
```

Theorem 54. (Elimination $\|A\|_1$) For a 1-groupoid $B : \mathcal{U}$ (i.e., $\text{isGroupoid}(B)$), and a map $f : A \rightarrow B$, there exists $\text{Ind}_{\|A\|_1} : \|A\|_1 \rightarrow B$, such that $\text{Ind}_{\|A\|_1}(\text{inc}(a)) = f(a)$.

8.6 Quotients

Set Quotient Spaces

Quotient spaces are a powerful computational tool in type theory, embedded in the core of Lean.

Definition 102. (Formation). Set quotient spaces construct a type A , quotiented by a relation $R : A \rightarrow A \rightarrow \mathcal{U}$, ensuring that the result is a set.

Definition 103. (Constructors). For a type $A : \mathcal{U}$ and a relation $R : A \rightarrow A \rightarrow \mathcal{U}$, the set quotient space $A/R : \mathcal{U}$ is freely generated by the following higher inductive compositional structure:

$$A/R := \begin{cases} \text{quot} : A \rightarrow A/R \\ \text{ident} : (a, b : A) \rightarrow R(a, b) \rightarrow \text{quot}(a) \equiv \text{quot}(b) \\ \text{trunc} : (a, b : A/R) \rightarrow (p, q : a \equiv b) \rightarrow p \equiv q \end{cases}$$

```
def / (A : U) (R : A → A → U) : U
:= inductive { quot (a : A)
| ident (a b : A) (r : R a b) : quot(a) ≡ quot(b)
| trunc (a b : / A R) (p q : Path (/ A R) a b)
  <i j> [ (i = 0) → p @ j , (i = 1) → q @ j ,
        (j = 0) → a , (j = 1) → b ]
}
```

Theorem 55. (Elimination). For a family of types $B : A/R \rightarrow \mathcal{U}$ with $\text{isSet}(Bx)$, and maps $f : (x : A) \rightarrow B(\text{quot}(x))$, $g : (a, b : A) \rightarrow (r : R(a, b)) \rightarrow \text{PathP}(< i > B(\text{ident}(a, b, r) @ i))(f(a))(f(b))$, there exists $\text{Ind}_{A/R} : \Pi(x : A/R), B(x)$, such that $\text{Ind}_{A/R}(\text{quot}(a)) = f(a)$.

Groupoid Quotient Spaces

Definition 104. (Formation). Groupoid quotient spaces extend set quotient spaces to produce a 1-groupoid, including constructors for higher paths. Groupoid quotient spaces construct a type A , quotiented by a relation $R : A \rightarrow A \rightarrow \mathcal{U}$, ensuring that the result is a groupoid.

Definition 105. (Constructors). For a type $A : \mathcal{U}$ and a relation $R : A \rightarrow A \rightarrow \mathcal{U}$, the groupoid quotient space $A//R : \mathcal{U}$ includes constructors for points, paths, and higher paths, ensuring a 1-groupoid structure.

8.7 Wedge

The wedge of two pointed types A and B , denoted $A \vee B$, is a higher inductive type representing the union of A and B with identified base points. Topologically, it corresponds to $A \times \{y_0\} \cup \{x_0\} \times B$, where x_0 and y_0 are the base points of A and B , respectively.

Definition 106. (Formation). For pointed types $A, B : \text{pointed}$, the wedge $A \vee B : \mathcal{U}$.

Definition 107. (Constructors). The wedge is generated by the following higher inductive compositional structure:

$$\vee := \begin{cases} \text{winl} : A.1 \rightarrow A \vee B \\ \text{winr} : B.1 \rightarrow A \vee B \\ \text{wglue} : \text{winl}(A.2) \equiv \text{winr}(B.2) \end{cases}$$

```
def ∨ (A : pointed) (B : pointed) : U
:= inductive { winl (a : A.1)
              | winr (b : B.1)
              | wglue : winl(A.2) ≡ winr(B.2)
              }
```

Theorem 56. (Elimination). For a type $P : A \vee B \rightarrow \mathcal{U}$, maps $f : A.1 \rightarrow C$, $g : B.1 \rightarrow C$, and a path $p : \text{PathOverlue}(P, f(A.2), g(B.2))$, there exists a map $\text{Ind}_\vee : A \vee B \rightarrow C$, such that:

$$\begin{cases} \text{Ind}(\text{winl}(a)) = f(a) \\ \text{Ind}(\text{winr}(b)) = g(b) \\ \text{Ind}(\text{wglue}(x)) = p(x) \end{cases}$$

```
def PathOverGlue : (P : A ∨ B → U)
  (p : P (inl (A.2))) (q : P (inr (B.2))) : U
:= PathP (λ i → P (wglue i)) p q

def Ind_∨ (A B : pointed) (C : U) (f : A.1 → C) (g : B.1 → C)
  (p : Path C (f A.2) (g B.2))
  : A ∨ B → C
:= split { winl a → f a | winr b → g b | wglue @ x → p @ x }
```

Theorem 57. (Computation). For $z : \text{Wedge } AB$,

$$\begin{cases} \text{Ind}_\vee(\text{winl } a) \equiv f(a) \\ \text{Ind}_\vee(\text{winr } b) \equiv g(b) \\ \text{Ind}_\vee(\text{wglue } @ x) \equiv p @ x \end{cases}$$

Theorem 58. (Uniqueness). Any two maps $h_1, h_2 : \text{Wedge } AB \rightarrow C$ are homotopic if they agree on winl , winr , and wglue , i.e., if $h_1(\text{winl } a) = h_2(\text{winl } a)$ for all $a : A.1$, $h_1(\text{winr } b) = h_2(\text{winr } b)$ for all $b : B.1$, and $h_1(\text{wglue}) = h_2(\text{wglue})$.

8.8 Smash Product

The smash product of two pointed types A and B , denoted $A \wedge B$, is a higher inductive type that quotients the product $A \times B$ by the pushout $A \sqcup B$. It represents the space $A \times B / (A \times \{y_0\} \cup \{x_0\} \times B)$, collapsing the wedge to a single point.

Definition 108. (Formation). For pointed types $A, B : \text{pointed}$, the smash product $A \wedge B : \mathcal{U}$.

Definition 109. (Constructors). The smash product is generated by the following higher inductive compositional structure:

$$A \wedge B := \begin{cases} \text{basel} : A \wedge B \\ \text{baser} : A \wedge B \\ \text{proj}(x : A.1)(y : B.1) : A \wedge B \\ \text{gluel}(a : A.2) : \text{proj}(a, B.2) \equiv \text{basel} \\ \text{gluer}(b : B.2) : \text{proj}(A.2, b) \equiv \text{baser} \end{cases}$$

```
def ^ (A : pointed) (B : pointed) : U
:= inductive {
  | basel
  | baser
  | proj (a : A.1) (b : B.1)
  | gluel (a : A.2) : proj(a, B.2) ≡ basel
  | gluer (a : B.2) : proj(A.2, a) ≡ baser
}
```

Theorem 59. (Elimination). For a family of types $P : \text{Smash } A B \rightarrow \mathcal{U}$, points $\text{pbasel} : P(\text{basel})$, $\text{pbaser} : P(\text{baser})$, maps $\text{pproj} : (x : A.1) \rightarrow (y : B.1) \rightarrow P(\text{proj } x y)$, and a family of paths $\text{pgluel} : (a : A.1) \rightarrow \text{pproj}(a, B.2) \equiv \text{pbasel}$, $\text{pgluer} : (b : B.1) \rightarrow \text{pproj}(A.2, b) \equiv \text{pbaser}$, there exists a map $\text{Ind}_\wedge : (z : A \wedge B) \rightarrow P(z)$, such that:

$$\begin{cases} \text{Ind}_\wedge(\text{basel}) = \text{pbasel} \\ \text{Ind}_\wedge(\text{baser}) = \text{pbaser} \\ \text{Ind}_\wedge(\text{proj } x y) = \text{pproj } x y \\ \text{Ind}_\wedge(\text{gluel } a @ i) = \text{pgluel } a @ i \\ \text{Ind}_\wedge(\text{gluer } b @ i) = \text{pgluer } b @ i \end{cases}$$

```
def Ind_ (A B : pointed) (P : A ^ B -> U)
  (pbasel : P basel) (pbaser : P baser)
  (pproj : (x : A.1) -> (y : B.1) -> P (proj x y))
  (pgluel : (a : A.1) -> PathP (<i> P (gluel a @ i)) (pproj a B.2) pbasel)
  (pgluer : (b : B.1) -> PathP (<i> P (gluer b @ i)) (pproj A.2 b) pbaser)
  : (z : A ^ B) -> P z
:= split {
  | basel -> pbasel
  | baser -> pbaser
  | proj x y -> pproj x y
  | gluel a @ i -> pgluel a @ i
  | gluer b @ i -> pgluer b @ i
}
```

Theorem 60. (Computation). For a family of types $P : A \wedge B \rightarrow \mathcal{U}$, points $\text{pbasel} : P(\text{basel})$, $\text{pbaser} : P(\text{baser})$, map $\text{pproj} : (x : A.1) \rightarrow (y : B.1) \rightarrow P(\text{proj } x y)$, and families of paths $\text{pgluel} : (a : A.1) \rightarrow \text{PathP } (< i > P(\text{gluel } a @ i)) (\text{pproj } a B.2) \text{pbasel}$, $\text{pgluer} : (b : B.1) \rightarrow \text{PathP } (< i > P(\text{gluer } b @ i)) (\text{pproj } A.2 b) \text{pbaser}$, the map $\text{Ind}_\wedge : (z : A \wedge B) \rightarrow P(z)$ satisfies all equations for all variants of the predicate P :

$$\left\{ \begin{array}{l} \text{Ind}_\wedge (\text{basel}) \equiv \text{pbasel} \\ \text{Ind}_\wedge (\text{baser}) \equiv \text{pbaser} \\ \text{Ind}_\wedge (\text{proj } x y) \equiv \text{pproj } x y \\ \text{Ind}_\wedge (\text{gluel } a @ i) \equiv \text{pgluel } a @ i \\ \text{Ind}_\wedge (\text{gluer } b @ i) \equiv \text{pgluer } b @ i \end{array} \right.$$

Theorem 61. (Uniqueness). For a family of types $P : A \wedge B \rightarrow \mathcal{U}$, and maps $h_1, h_2 : (z : A \wedge B) \rightarrow P(z)$, if there exist paths $e_{\text{basel}} : h_1(\text{basel}) \equiv h_2(\text{basel})$, $e_{\text{baser}} : h_1(\text{baser}) \equiv h_2(\text{baser})$, $e_{\text{proj}} : (x : A.1) \rightarrow (y : B.1) \rightarrow h_1(\text{proj } x y) \equiv h_2(\text{proj } x y)$, $e_{\text{gluel}} : (a : A.1) \rightarrow \text{PathP } (< i > h_1(\text{gluel } a @ i) \equiv h_2(\text{gluel } a @ i)) (e_{\text{proj } a B.2}) e_{\text{basel}}$, $e_{\text{gluer}} : (b : B.1) \rightarrow \text{PathP } (< i > h_1(\text{gluer } b @ i) \equiv h_2(\text{gluer } b @ i)) (e_{\text{proj } A.2 b}) e_{\text{baser}}$, then $h_1 \equiv h_2$, i.e., there exists a path $(z : A \wedge B) \rightarrow h_1(z) \equiv h_2(z)$.

8.9 Join

The join of two types A and B , denoted $A \vee B$, is a higher inductive type that constructs a type by joining each point of A to each point of B via a path. Topologically, it corresponds to the join of spaces, forming a space that interpolates between A and B .

Definition 110. (Formation). For types $A, B : \mathcal{U}$, the join $A * B : \mathcal{U}$.

Definition 111. (Constructors). The join is generated by the following higher inductive compositional structure:

$$A \vee B := \begin{cases} \text{joinl} : A \rightarrow A \vee B \\ \text{joinr} : B \rightarrow A \vee B \\ \text{join}(a : A)(b : B) : \text{joinl}(a) \equiv \text{joinr}(b) \end{cases}$$

```
def ∨ (A : U) (B : U) : U
:= inductive { joinl (a : A)
              | joinr (b : B)
              | join (a : A) (b : B) : joinl(a) ≡ joinr(b)
            }
```

Theorem 62. (Elimination). For a type $C : \mathcal{U}$, maps $f : A \rightarrow C$, $g : B \rightarrow C$, and a family of paths $h : (a : A) \rightarrow (b : B) \rightarrow f(a) \equiv g(b)$, there exists a map $\text{Ind}_\vee : A \vee B \rightarrow C$, such that:

$$\begin{cases} \text{Ind}_\vee(\text{joinl}(a)) = f(a) \\ \text{Ind}_\vee(\text{joinr}(b)) = g(b) \\ \text{Ind}_\vee(\text{join}(a, b, i)) = h(a, b, i) \end{cases}$$

```
def Ind_∨ (A B C : U) (f : A → C) (g : B → C)
  (h : (a : A) → (b : B) → Path C (f a) (g b))
  : A ∨ B → C
:= split { joinl a → f a
          | joinr b → g b
          | join a b @ i → h a b @ i
        }
```

Theorem 63. (Computation). For all $z : A \vee B$, and predicate P , the rules of Ind_\vee hold for all parameters of the predicate P .

Theorem 64. (Uniqueness). Any two maps $h_1, h_2 : A \vee B \rightarrow C$ are homotopic if they agree on joinl , joinr , and join .

8.10 Colimit

Colimits construct the limit of a sequence of types, connected by maps, e.g., propositional truncations.

Definition 112. (Colimit) For a sequence of types $A : \mathbb{N} \rightarrow \mathcal{U}$ and maps $f : (n : \mathbb{N}) \rightarrow A n \rightarrow A(\text{succ}(n))$, the colimit type $\text{colimit}(A, f) : \mathcal{U}$.

$$\text{colim} := \begin{cases} \text{ix} : (n : \mathbb{N}) \rightarrow A n \rightarrow \text{colimit}(A, f) \\ \text{gx} : (n : \mathbb{N}) \rightarrow (a : A(n)) \rightarrow \text{ix}(\text{succ}(n), f(n, a)) \equiv \text{ix}(n, a) \end{cases}$$

```
def colimit (A : nat -> U) (f : (n : nat) -> A n -> A (succ n)) : U
:= inductive {
  | ix (n : nat) (x : A n)
  | gx (n : nat) (a : A n)
  <i> [ (i=0) -> ix (succ n) (f n a),
      (i=1) -> ix n a ]
}
```

Theorem 65. (Elimination colimit) For a type $P : \text{colimit } A f \rightarrow \mathcal{U}$, with $p : (n : \mathbb{N}) \rightarrow (x : A n) \rightarrow P(\text{ix}(n, x))$ and $q : (n : \mathbb{N}) \rightarrow (a : A n) \rightarrow \text{PathP}(\langle i \rangle P(\text{gx}(n, a) @ i))(p(\text{succ } n)(f n a))(p n a)$, there exists $i : \prod_{x : \text{colimit } A f} P(x)$, such that $i(\text{ix}(n, x)) = p n x$.

8.11 Coequalizers

Coequalizer

The coequalizer of two maps $f, g : A \rightarrow B$ is a higher inductive type (HIT) that constructs a type consisting of elements in B , where f and g agree, along with paths ensuring this equality. It is a fundamental construction in homotopy theory, capturing the subspace of B where $f(a) = g(a)$ for $a : A$.

Definition 113. (Formation). For types $A, B : \mathcal{U}$ and maps $f, g : A \rightarrow B$, the coequalizer $\text{coeq } ABfg : \mathcal{U}$.

Definition 114. (Constructors). The coequalizer is generated by the following higher inductive compositional structure:

$$\text{Coeq} := \begin{cases} \text{inC} : B \rightarrow \text{Coeq}(A, B, f, g) \\ \text{glueC} : (a : A) \rightarrow \text{inC}(f(a)) \equiv \text{inC}(g(a)) \end{cases}$$

```
def Coeq (A B: U) (f g: A → B) : U
:= inductive { inC (b: B)
              | glueC (a: A) : inC (f a) ≡ inC (g a)
              }
```

Theorem 66. (Elimination). For a type $C : \mathcal{U}$, map $h : B \rightarrow C$, and a family of paths $y : (x : A) \rightarrow \text{Path}_C(h(fx), h(gx))$, there exists a map $\text{coequRec} : \text{coeq } ABfg \rightarrow C$, such that:

$$\begin{cases} \text{coequRec}(\text{inC}(x)) = h(x) \\ \text{coequRec}(\text{glueC}(x, i)) = y(x, i) \end{cases}$$

```
def coequRec (A B C : U) (f g : A → B) (h : B → C)
  (y : (x : A) → Path C (h (f x)) (h (g x)))
  : (z : coeq A B f g) → C
:= split { inC x → h x | glueC x @ i → y x @ i }
```

Theorem 67. (Computation). For $z : \text{coeq } ABfg$,

$$\begin{cases} \text{coequRec}(\text{inC } x) \equiv h(x) \\ \text{coequRec}(\text{glueC } x @ i) \equiv y(x) @ i \end{cases}$$

Theorem 68. (Uniqueness). Any two maps $h_1, h_2 : \text{coeq } ABfg \rightarrow C$ are homotopic if they agree on inC and glueC , i.e., if $h_1(\text{inC } x) = h_2(\text{inC } x)$ for all $x : B$ and $h_1(\text{glueC } a) = h_2(\text{glueC } a)$ for all $a : A$.

Example 8. (Coequalizer as Subspace) The coequalizer $\text{coeq } ABfg$ represents the subspace of B , where $f(a) = g(a)$. For example, if $A = B = \mathbb{R}$ and $f(x) = x^2$, $g(x) = x$, the coequalizer captures the points where $x^2 = x$, i.e., $\{0, 1\}$.

Path Coequalizer

The path coequalizer is a higher inductive type that generalizes the coequalizer to handle pairs of paths in B . Given a map $p : A \rightarrow (b_1, b_2 : B) \times (\text{Path}_B(b_1, b_2)) \times (\text{Path}_B(b_1, b_2))$, it constructs a type where elements of A generate pairs of paths between points in B , with paths connecting the endpoints of these paths.

Definition 115. (Formation). For types $A, B : \mathcal{U}$ and a map $p : A \rightarrow (b_1, b_2 : B) \times (b_1 \equiv b_2) \times (b_1 \equiv b_2)$, there exists a path coequalizer $\text{Coeq}_{\equiv}(A, B, p) : \mathcal{U}$.

Definition 116. (Constructors). The path coequalizer is generated by the following higher inductive compositional structure:

$$\text{Coeq}_{\equiv} := \begin{cases} \text{inP} : B \rightarrow \text{Coeq}_{\equiv}(A, B, p) \\ \text{glueP} : (a : A) \rightarrow \text{inP}(p(a).2.2.1 @ 0) \equiv \text{inP}(p(a).2.2.2 @ 1) \end{cases}$$

```
data Coeq≡ (A B : U) (p : A → Σ (b1 b2 : B), b1 ≡ b2 × b1 ≡ b2)
  = inP (b : B)
  | glueP (a : A) <i> [(i=0) → inP ((p a).2.2.1 @ 0),
                     (i=1) → inP ((p a).2.2.2 @ 1)]
```

Theorem 69. (Elimination). For a type $C : \mathcal{U}$, map $h : B \rightarrow C$, and a family of paths $y : (a : A) \rightarrow h(p(a).2.2.1 @ 0) \equiv h(p(a).2.2.2 @ 1)$, there exists a map $\text{Ind-Coeq}_{\equiv} : \text{Coeq}_{\equiv}(A, B, p) \rightarrow C$, such that:

$$\begin{cases} \text{coeqPRec}(\text{inP}(b)) = h(b) \\ \text{coeqPRec}(\text{glueP}(a, i)) = y(a, i) \end{cases}$$

```
def Ind-Coeq≡ (A B C : U)
  (p : A → Σ (b1 b2 : B) (x : Path B b1 b2), Path B b1 b2)
  (h : B → C) (y : (a : A) → Path C (h ((p a).2.2.1 @ 0)) (h ((p a).2.2.2 @ 1)))
  : (z : coeqP A B p) → C
:= split { inP b → h b | glueP a @ i → y a @ i }
```

Theorem 70. (Computation). For $z : \text{coeqP } ABp$,

$$\begin{cases} \text{coeqPRec}(\text{inP } b) \equiv h(b) \\ \text{coeqPRec}(\text{glueP } a @ i) \equiv y(a) @ i \end{cases}$$

Theorem 71. (Uniqueness). Any two maps $h_1, h_2 : \text{coeqP } ABp \rightarrow C$ are homotopic if they agree on inP and glueP , i.e., if $h_1(\text{inP } b) = h_2(\text{inP } b)$ for all $b : B$ and $h_1(\text{glueP } a) = h_2(\text{glueP } a)$ for all $a : A$.

8.12 K(G,n)

Eilenberg-MacLane spaces $K(G, n)$ have a single non-trivial homotopy group $\pi_n(K(G, n)) = G$. They are defined using truncations and suspensions.

Definition 117. ($K(G, n)$) For an abelian group $G : \text{abgroup}$, the type $KGn(G) : \text{nat} \rightarrow \mathcal{U}$.

$$K(G, n) := \begin{cases} n = 0 \rightsquigarrow \text{discreteTopology}(G) \\ n \geq 1 \rightsquigarrow \|\Sigma^{n-1}(K1'(G.1, G.2.1))\|_n \end{cases}$$

```
def KGn (G: abgroup) : N -> U
:= split { zero -> discreteTopology G
          | succ n -> nTrunc (Σ (K1' (G.1, G.2.1)) n) (succ n)
          }
```

Theorem 72. (Elimination KGn) For $n \geq 1$, a type $B : \mathcal{U}$ with $\text{isNGroupoid}(B, \text{succ } n)$, and a map $f : \text{suspension}(K1'G) \rightarrow B$, there exists $\text{rec}_{KGn} : KGnG(\text{succ } n) \rightarrow B$, defined via nTruncRec .

8.13 Localization

Localization constructs an F -local type from a type X , with respect to a family of maps $F_A : S(a) \rightarrow T(a)$.

Definition 118. (Localization Modality) For a family of maps $F_A : S(a) \rightarrow T(a)$, the F -localization $L_F^{AST}(X) : \mathcal{U}$.

$$L_F^A(X) := \begin{cases} \text{center} : X \rightarrow L_{F_A}(X) \\ \text{ext}(a : A) \rightarrow (S(a) \rightarrow L_{F_A}(X)) : T(a) \rightarrow L_{F_A}(X) \\ \text{isExt}(a : A)(f : S(a) \rightarrow L_{F_A}(X)) \rightarrow (s : S(a)) : \text{ext}(a, f, F(a, s)) \equiv f(s) \\ \text{extEq}(a : A)(g, h : T(a) \rightarrow L_{F_A}(X)) \\ \quad (p : (s : S(a)) \rightarrow g(F(a, s)) \equiv h(F(a, s))) \\ \quad (t : T(a)) : g(t) \equiv h(t) \\ \text{isExtEq} : (a : A)(g, h : T(a) \rightarrow L_{F_A}(X)) \\ \quad (p : (s : S(a)) \rightarrow g(F(a, s)) \equiv h(F(a, s))) \\ \quad (s : S(a)) : \text{extEq}(a, g, h, p, F(a, s)) \equiv p(s) \end{cases}$$

```
data Localize (A X: U) (S T: A → U) (F : (x:A) → S x → T x)
= center (x: X)
| ext (a: A) (f: S a → Localize A X S T F) (t: T a)
| isExt (a: A) (f: S a → Localize A X S T F) (s: S a) <i>
  [ (i=0) → ext a f (F a s) , (i=1) → f s ]
| extEq (a: A) (g h: T a → Localize A X S T F)
  (p: (s : S a) → Path (Localize A X S T F) (g (F a s)) (h (F a s)))
  (t : T a) <i> [ (i=0) → g t , (i=1) → h t ]
| isExtEq (a: A) (g h : T a → Localize A X S T F)
  (p: (s : S a) → Path (T a → Localize A X S T F) (g (F a s)) (h (F a s)))
  (s : S a) <i> [ (i=0) → extEq a g h p (F a s) , (i=1) → p s ]
```

Theorem 73. (Localization Induction) For any $P : \Pi_{X:U} L_{F_A}(X) \rightarrow U$ with $\{n, r, s\}$, satisfying coherence conditions, there exists $i : \Pi_{x:L_{F_A}(X)} P(x)$, such that $i \cdot \text{center}_X = n$.

Conclusion

HITs directly encode CW-complexes in HoTT, bridging topology and type theory. They enable the analysis and manipulation of homotopical types.

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