

Intetics f(cafe) 25 July 2018 Freud House, Kyiv, Ukraine

Namdak Tonpa

HoTT: The Language of Space

Groupoid Infinity

The HoTT Lineage

- Nicolaas Govert de Bruijn [AUTOMATH]
- Henk Barendregt [λ -Cube]
- Robin Milner [ML, LCF, π -Calculus]
- Gérard Pierre Huet [CAML]
- Christine Paulin-Mohring [CiC]
- Peter Dybjer, Martin Hofmann, R.A.G. Seely [CwF, CwA, LCCC]
- Thierry Coquand [CoC, Coq, CCHM]
- Robert William "Bob" Harper, Jr. [HoTT, RedPRL, ML, Twelf]
- Steve Awodey, Vladimir Voevodsky [HoTT, C-Systems]
- Cyril Cohen, Simon Huber, Anders Mörtberg [CCHM, cubicaltt, yacctt]

Abstract

Cubical Base Library

Homotopy Type Theory (HoTT) is the most advanced programming language in the domain of intersection of several theories: algebraic topology, homological algebra, higher category theory, mathematical logic, and theoretical computer science. That is why it can be considered as a language of space, as it can encode any existent mathematics.

During this lecture on HoTT, we are trying to encode as much mathematics in the programming language as possible.

Talk Structure

Slightly based on HoTT Chapters

I. Foundations

- MLTT
- Inductive Types, Induction
- IPL and Elements of Set Theory
- Control, Recursive Schemes
- Equiv, Iso, Univalence
- Higher Inductive Types
- Modalities

II. Mathematics

- Category Theory, Topos Theory
- Basic Algebra
- Ordinals, Mahlo Universe
- Differential Topology
- Fiber Bundles and Hopf Fibrations
- K-Theory
- Sequences, Chain Complexes

I. Foundations

λ -Calculuses

in Extended Lambda Cube

CoC:	$* \rightsquigarrow *$	$\square \rightsquigarrow *$	$* \rightsquigarrow \square$	$\square \rightsquigarrow \square$
F ω :	$* \rightsquigarrow *$	$\square \rightsquigarrow *$		$\square \rightsquigarrow \square$
P2:	$* \rightsquigarrow *$	$\square \rightsquigarrow *$	$* \rightsquigarrow \square$	
AUT:	$* \rightsquigarrow *$		$* \rightsquigarrow \square$	
F:	$* \rightsquigarrow *$	$\square \rightsquigarrow *$		

System F ω :
Haskell, Scala, 1ML
Almost CoC
No Types
On Values

System F:
ML, Miranda,
OCaml

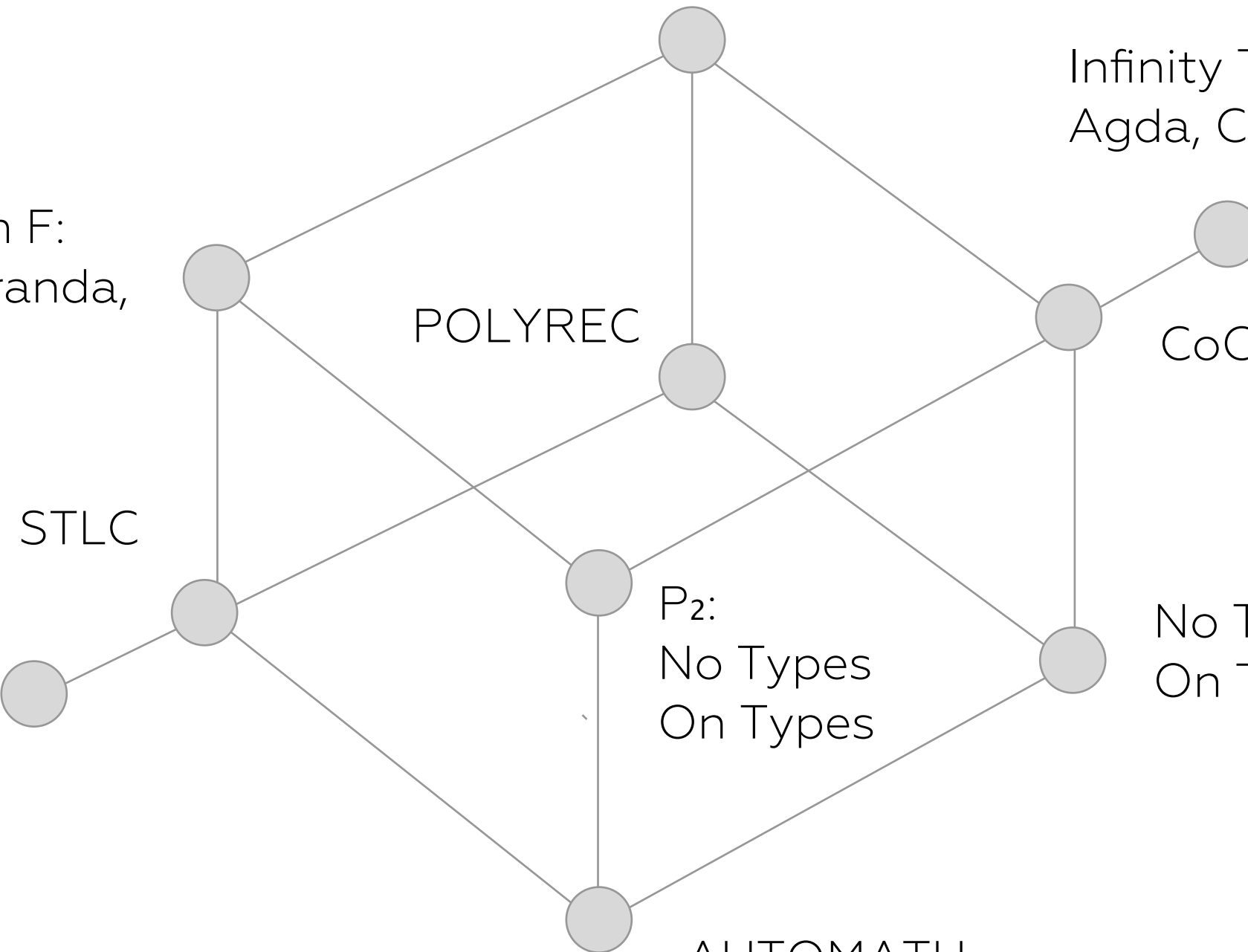
Infinity Topoi
Agda, Coq, Lean, Om

CoC: Morte, Henk

No Terms
On Types

P₂:
No Types
On Types

AUTOMATH



Untyped SLC:
Erlang, LISP,
JavaScript

MLTT 1972

Type Theory as new Foundations of Mathematics

$U : U$ — Single Universe Model — MLTT 1972, CoC 1988.

$x : A$ — x is a point (Star) in space A (Box)

$y = [x : A]$ — x and y are definitionally equal objects of type A

Π

Σ

1. Formation Rules

$(x:A) \rightarrow B(x)$

$(x:A) * B(x)$

2. Introduction Rules

$\lambda (x:A) \rightarrow B(x)$

(a,b)

3. Elimination Rules

$f a = B(a)$

$.1, .2$

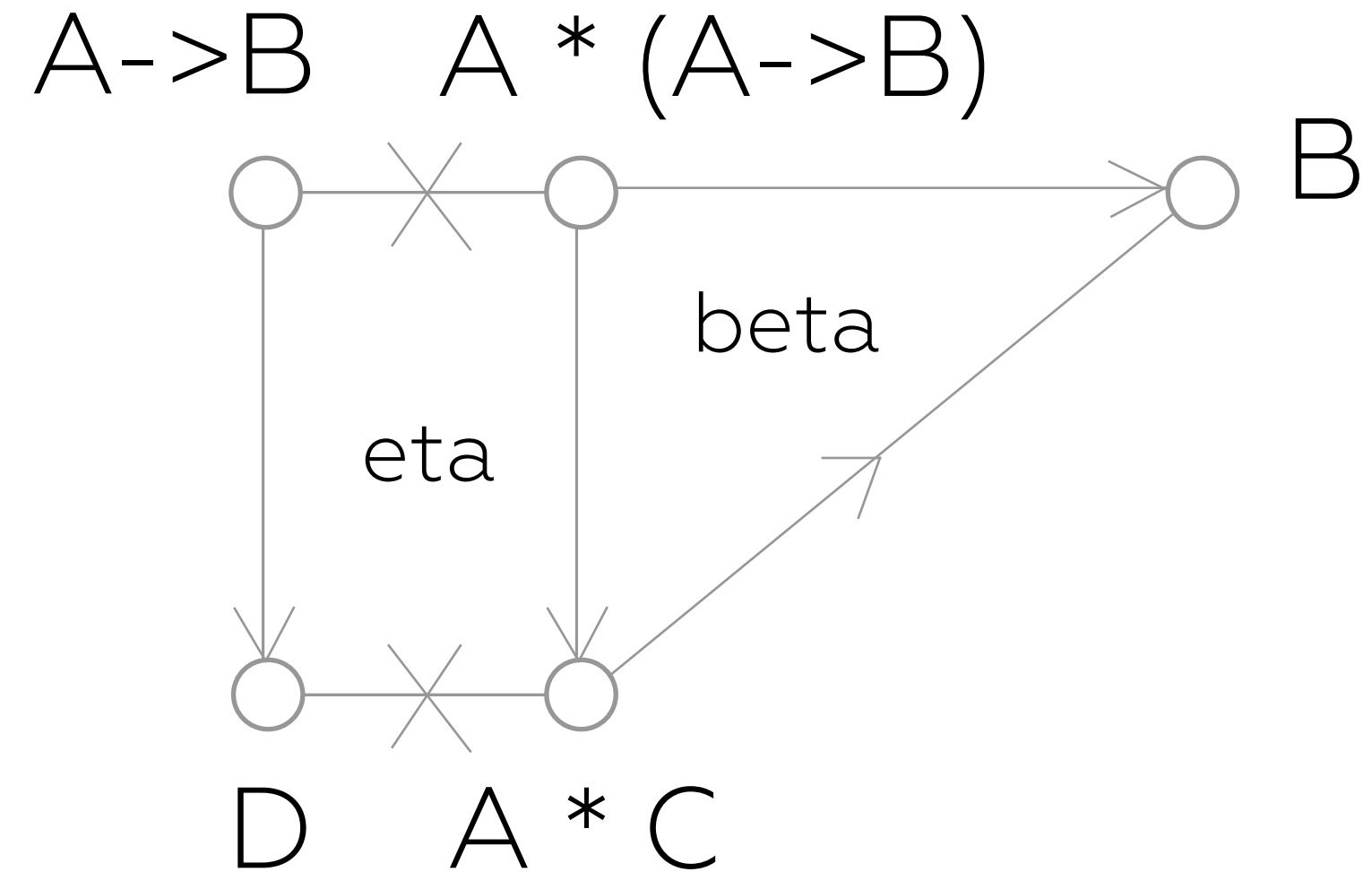
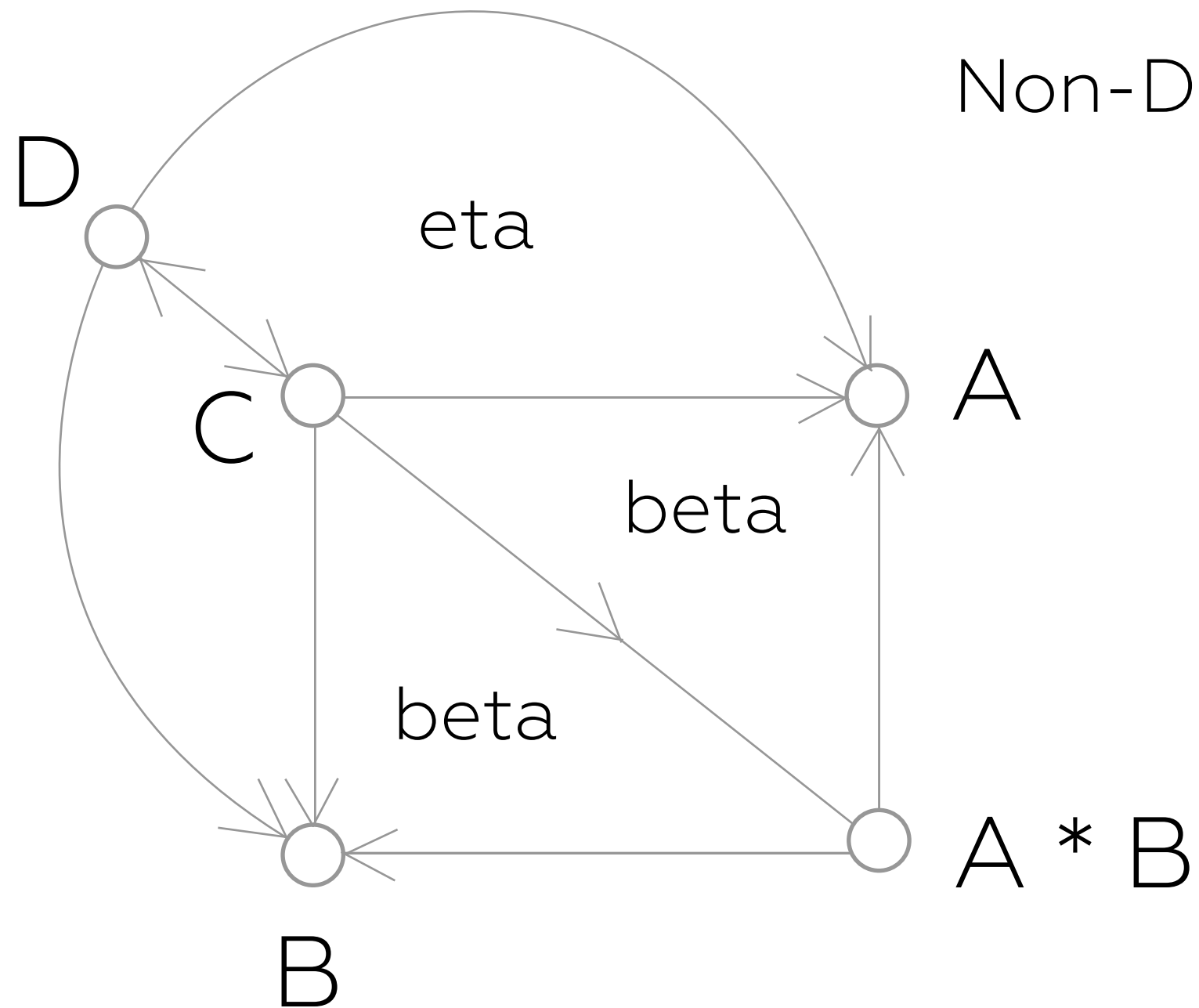
4. Computational Rules

two

three

Beta and Eta

Duality of Intro and Elim and its Uniqueness
Non-Dep Case (CCC). Homework: Proof LCCC case.



MLTT 1975, 1984

Grothendieck Universe (containing all sets), Countable Universes

$U_0 : U_1 : U_2 : U_3 : \dots \infty$ — infinite hierarchy of universes

$S(n : \text{nat}) = U_n$

$A_1(n\ m : \text{nat}) = U_n : U_m$ where $[m > n]$ — cumulative, $[n+1=m]$ — non-cumulative

$R_1(m\ n : \text{nat}) = U_m \longrightarrow U_n : U_x$ where $[x = \max(m, n)]$ — predicative,
 $[x = n]$ — impredicative

1. Formation	data nat	data list	$x:A = y:A$	data W
2. Introduction	zero, succ	nil, cons	refl A x	sup
3. Elimination	natInd	listInd	J	wInd
4. Computational	Beta, Eta	Beta, Eta	Beta, Eta	Beta, Eta

Intuitionistic Propositional Logic

According to Brouwer–Heyting–Kolmogorov interpretation

\forall	\exists	Path	0	1	+
$x:A \rightarrow B(x)$	$x:A * B(x)$	$x:A = y:A$	data empty	data unit	data either
$\lambda (x:A) \rightarrow B(x)$	$(x, B(x))$	refl A x		tt	inl, inr
$f a = B(a)$	pr1, pr2	J	elim0	elim1	eitherInd
Beta, Eta	Beta, Eta	Eta	Beta, Eta	Beta, Eta	Beta, Eta

Proto (Prelude)

For run-time and I/O applications

maybe

$U \rightarrow U$

nothing, just

maybeInd

Beta, Eta

either

$U \rightarrow U \rightarrow U$

inl, inr

eitherInd

Beta, Eta

stream

$U \rightarrow U$

cons

streamInd

Beta, Eta

bool

U

true, false

boolInd

Beta, Eta

vector

$\text{nat} \rightarrow U$

vz, vs

vecInd

Beta, Eta

fin

$\text{nat} \rightarrow U$

fz, fs

finInd

Beta, Eta

Homework: Add I/O interface for finite and infinite loop.

Induction Principle

Natural Numbers Example

`natCase (C:U) (a b: C): nat -> C`
`= split { zero -> a ; succ n -> b }`

`natRec (C:U) (z: C) (s: nat->C->C): (n:nat) -> C`
`= split { zero -> z ; succ n -> s n (natRec C z s n) }`

`natInd (C:nat->U) (z: C zero) (s: (n:nat)->C(n)->C(succ n)): (n:nat) -> C(n)`
`= split { zero -> z ; succ n -> s n (natInd C z s n) }`

Induction Principle could be the ultimate programming tool.

Inductive AST

Data Definition and Case Analysis

`data` tele (A: U) = emp | tel (n: name) (b: A) (t: tele A)

`data` branch (A: U) = br (n: name) (args: list name) (term: A)

`data` label (A: U) = lab (n: name) (t: tele A)

`data` ind = data_ (n: name) (t: tele lang) (labels: list (label lang))
 | case (n: name) (t: lang) (branches: list (branch lang))
 | ctor (n: name) (args: list lang)

Homework: Add HITs elements as Path Equalities to data declarations.

Hint: use your imagination.

Pi Type : Definition

Family of Types, Fibrations, Fiber Space $A \rightarrow U$, Fiber $B(x)$,
Section $b(x)$, Space of Sections $\Pi(A, B)$

Syntax

$\langle \rangle ::= \#option$

$T ::= \#identifier$

$U ::= * \langle \#number \rangle$

$O_1 ::= U \mid T \mid (O) \mid O O \mid O \rightarrow O$
 $\mid \lambda (l: O) \rightarrow O \mid (l: O) \rightarrow O$

Model

`data` pts = star (n: nat)

| var (x: name) (l: nat)

| pi (x: name) (l: nat) (d c: lang)

| lambda (x: name) (l: nat) (d c: lang)

| app (f a: lang)

Pure Type System (PTS), Single Axiom System, Calculus of Constructions (CoC)
Henk, Morte, Om and many many others.

Pi Type : Inference Rules

Formal Definition

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

$\text{lambda } (A : U) (B: A \rightarrow U) (a : A) (b: B a): A \rightarrow B a = ?$

$\text{app } (A : U) (B: A \rightarrow U) (a : A) (f: A \rightarrow B a): B a = ?$

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

$\text{Eta } (A: U) (B: A \rightarrow U) (a: A) (f: A \rightarrow B a) : \text{Path } (A \rightarrow B a) f (\lambda(x:A) \rightarrow f x)$

One beta rule and one eta rule for Pi types.

Sigma Type : Definition

Total Space $\text{Sigma}(A,B)$, Point in Base with Section (a,b)

Syntax $O_2 := (x: O) * O \mid (O,O) \mid O.1 \mid O.2$

Model `data` exists = sigma (n: name) (a b: lang)
| pair (a b: lang)
| fst (p: lang)
| snd (p: lang)

Sigma is a part of the MLTT earliest core.

It models Type Refinement and Proofs by Existence (Construction).

Sigma is a chain link of telescopes (contexts), the curried notion of records.

Sigma Type : Inference Rules

Existential Quantifier

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

$\text{pair } (A : U) (B : A \rightarrow U) (a : A) (b : B a) : \text{Sigma } A B = ?$

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

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

$\text{Beta1 } (B : A \rightarrow U) (a : A) (b : B a) \rightarrow \text{Path } A a (\text{pr1 } A B (\text{pair } A B a b))$

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

$\text{Eta } (B : A \rightarrow U) (p : \text{Sigma } A B) \rightarrow \text{Path } (\text{Sigma } A B) p (\text{pr1 } A B p, \text{pr2 } A B p)$

$\text{sigRec } (A : U) (B : A \rightarrow U) (C : U) (g : (x : A) \rightarrow B(x) \rightarrow C) (p : \text{Sigma } A B) : C = g p.1 p.2$

$\text{sigInd } (A : U) (B : A \rightarrow U) (C : \text{Sigma } A B \rightarrow U)$

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

Sigma Type in Pi

Typing and Introduction Rules in Church-Bohm-Berarducci Encoding

-- Sigma/@

 \ \backslash (A: *)

-> \ \backslash (P: A -> *)

-> \ \backslash (n: A)

-> \ \bigvee (Exists: *)

-> \ \bigvee (Intro: A -> P n -> Exists)

-> Exists

-- Sigma/Intro

 \ \backslash (A: *)

-> \ \backslash (P: A -> *)

-> \ \backslash (x: A)

-> \ \backslash (y: P x)

-> \ \backslash (Exists: *)

-> \ \backslash (Intro: \bigvee (x:A) -> P x -> Exists)

-> Intro x y

Sigma Type in Pi

Eliminators in Church-Bohm-Berarducci Encoding

-- Sigma/fst

\ (A: *)

-> \ (B: A -> *)

-> \ (n: A)

-> \ (S: #Sigma/@ A B n)

-> S A (\ (x: A) -> \ (y: B n) -> x)

-- Sigma/snd

\ (A: *)

-> \ (B: A -> *)

-> \ (n: A)

-> \ (S: #Sigma/@ A B n)

-> S (B n) (\ (: A) -> \ (y: B n) -> y)

Control (Haskell)

Port of Haskell-style erased 2-categorical structures for flow modeling

```
pure_sig      (F:U->U):U= (A: U) ->          A -> F A
appl_sig      (F:U->U):U= (A B: U) ->  F (A -> B) -> F A -> F B
fmap_sig      (F:U->U):U= (A B: U) ->  (A -> B) -> F A -> F B
bind_sig      (F:U->U):U= (A B: U) ->  F A ->(A -> F B)-> F B
functor: U = (F: U -> U) * fmap_sig F
applicative: U = (F: U -> U) * (_: pure_sig F) * (_: fmap_sig F) * appl_sig F
monad: U = (F:U->U)*(_:pure_sig F)*(_:fmap_sig F)*(_:appl_sig F) * bind_sig F
FUNCTOR: U = (f: functor) * isFunctor f
APPLICATIVE: U = (f: applicative) * (_: isFunctor (f.1,f.2.2.1)) * isApplicative f
MONAD: U = (f: monad) * (_: isFunctor (f.1,f.2.2.1))
          * (_: isApplicative (f.1,f.2.1,f.2.2.1,f.2.2.2.1)) * isMonad f
```

F-Algebras

Inductive Type Modeling with Varmo Vene style Recursion Schemes

```
data fix (F:U->U) = Fix (point: F (fix F))
data nu (F:U->U) (A B:U) = CoBind (a: A) (f: F B)
data cofree (F:U->U) (A:U) = CoFree (_: fix (nu F A))
ind (F: U -> U) (A: U): U = (in_: F (fix F) -> fix F) * (in_rev: fix F -> F (fix F))
* ((F A -> A) -> fix F -> A) * (cofree_: (F (cofree F A) -> A) -> fix F -> A)
inductive (F: functor) (A: U): ind F.1 A = (in_ F.1,out_ F.1,cata A F,histo A F,tt)
```

Backported to cubicaltt.

Bishop's Constructive Analysis

Reflexivity, Transitivity, Symmetry

Setoid $(A: U): U$

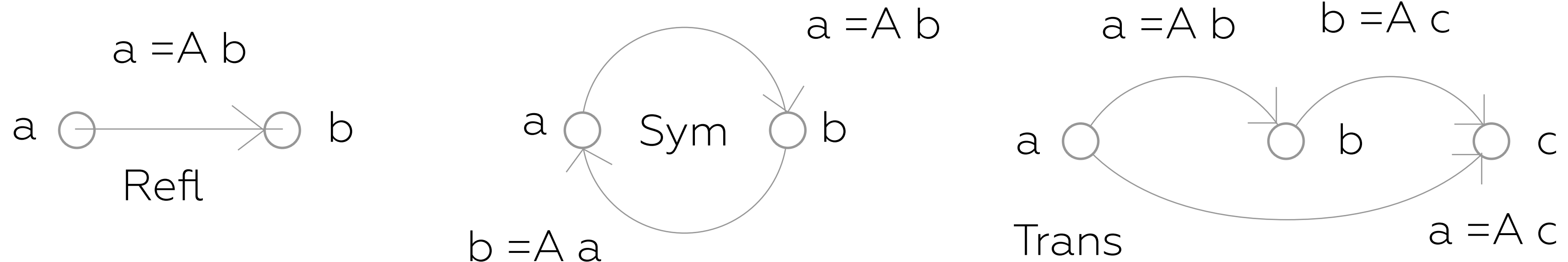
= (Carrier: A)

* (Equ: $(a\ b: A) \rightarrow$ Path A a b)

* (Refl: $(x: A) \rightarrow$ Equ x x)

* (Trans: $(x_1, x_2, x_3: A) \rightarrow$ Equ $x_1\ x_2 \rightarrow$ Equ $x_2\ x_3 \rightarrow$ Equ $x_1\ x_3$)

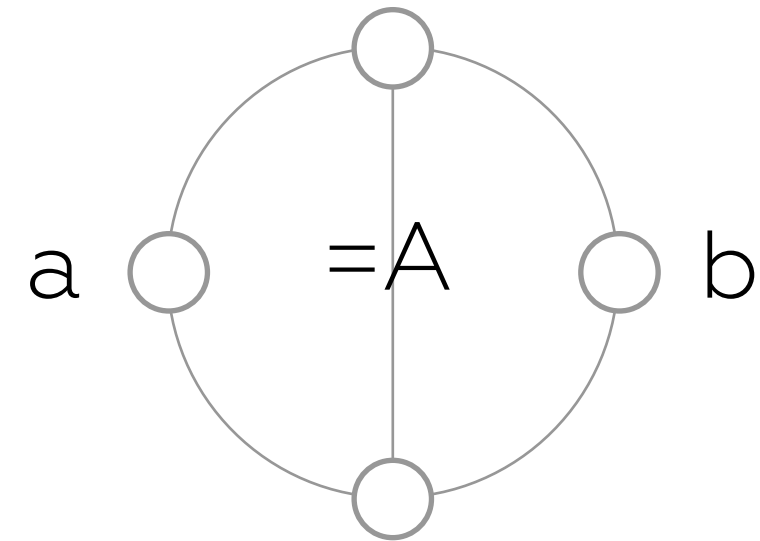
* (Sym: $(x_1, x_2: A) \rightarrow$ Equ $x_1\ x_2 \rightarrow$ Equ $x_2\ x_1$)



Globular Theory

Multidimensional Equality

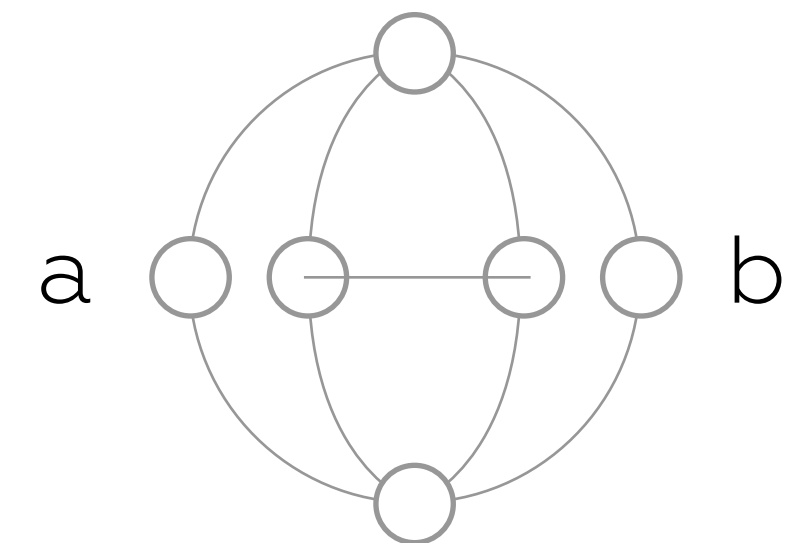
$a =_A b$



$((a =_A b) =_{(=A)} (a =_A b))$

$((a =_A b) =_{(=A)} (a =_A b)) =_{(=(=A))} ((a =_A b) =_{(=A)} (a =_A b))$

$a =_A b$



$a =_A b$

Equ Type a la Martin-Löf

`Path` (A: U) (a b: A): U = `axiom` — `PathP` (<i>A) a b

`HeteroEqu` (A B: U) (a: A) (b: B) (P: Path U A B) : U = `axiom` — `PathP` P a b

`Equ` (A: U) (x y: A): U = `HeteroEqu` A A x y (<i>A)

`refl` (A: U) (a: A): `Equ` A a a = <i> a

`J` (A: U) (a: A) (C: (x : A) -> `Path` A a x -> U)

(d: C a (`refl` A a)) (x: A) (p: `Path` A a x): C x p

`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))

Path Types as Cubes

Syntax and Model

Syntax

$x : [\text{PathP } p \ a \ b, p = (i: I) \rightarrow A]$

$a : A \quad \text{○} \longrightarrow \text{>○} \quad b : A$

de Morgan: $1-i \mid i \mid i \wedge j \mid i \vee j$

Model

`data lang = hts | ...`

`data hts = path (a b: lang)`

`| path_lam (n: name) (a b: lang)`

`| path_app (f: name) (a b: lang)`

`| comp_ (a b: lang)`

`| fill_ (a b c: lang)`

`| glue_ (a b c: lang)`

`| glue_elem (a b: lang)`

`| unglue_elem (a b: lang)`

Homotopy

Syntax and Model

```
data I = i0
      | i1
      | seg <i> [(i=0) -> i0, (i=1) -> i1]
```

```
pathToHtpy (A: U) (x y: A) (p: Path A x y): I -> A
  = split { i0 -> x; i1 -> y; seg @ i -> p @ i }
```

```
homotopy (X Y: U) (f g: X -> Y)
  (p: (x: X) -> Path Y (f x) (g x))
  (x: X): I -> Y = pathToHtpy Y (f x) (g x) (p x)
```

n-Types

Path $(A : U) : U = (a\ b : A) \rightarrow \text{PathP } (\lambda i \rightarrow A) a\ b$
isContr $(A : U) : U = (x : A) * ((y : A) \rightarrow \text{Path } A\ x\ y)$
isProp $(A : U) : U = (a\ b : A) \rightarrow \text{Path } A\ a\ b$
isSet $(A : U) : U = (a\ b : A) \rightarrow \text{isProp } (\text{Path } A\ a\ b)$
isGroupoid $(A : U) : U = (a\ b : A) \rightarrow \text{isSet } (\text{Path } A\ a\ b)$
isGr_2 $(A : U) : U = (a\ b : A) \rightarrow \text{isGroupoid } (\text{Path } A\ a\ b)$
isGr_3 $(A : U) : U = (a\ b : A) \rightarrow \text{isGr}_2\ (\text{Path } A\ a\ b)$

PROP : $U = (X : U) * \text{isProp } X$

SET : $U = (X : U) * \text{isSet } X$

GROUPOID : $U = (X : U) * \text{isGroupoid } X$

INF_GROUPOID : $U = (X : U) * \text{isInfinityGroupoid } X$

Subtyping in MLTT

Subsets and Subtypes

hsubtypes (X: U): U = X -> PROP

subset (A: U) (_: isSet A): U = A -> PROP

sethsubtypes (X : U) : isSet (hsubtypes X)

hsubtypespair (A B: U) (H0: hsubtypes A) (H1: hsubtypes B) (x: prod A B): PROP

subtypeEquality (A: U) (B: A -> U)

(pB: (x : A) -> isProp (B x))

(s t: Sigma A B) : Path A s.1 t.1 -> Path (Sigma A B) s t

iseqclass (X : U) (R : hrel X) (A : hsubtypes X) : U

propiseqclass (X : U) (R : hrel X) (A : hsubtypes X) : isProp (iseqclass X R A)

Elements of Set Theory

Set Theory Theorems

$$\begin{aligned} \text{ac} \quad & (A \ B: U) (R: A \rightarrow B \rightarrow U): (p: (x:A) \rightarrow (y:B) * (R \ x \ y)) \rightarrow (f:A \rightarrow B) * ((x:A) \rightarrow R(x)(f \ x)) \\ & = \backslash (g: (x:A) \rightarrow (y:B) * (R \ x \ y)) \rightarrow (\backslash (i:A) \rightarrow (g \ i).1, \backslash (j:A) \rightarrow (g \ j).2) \end{aligned}$$

$$\begin{aligned} \text{total} \quad & (A:U) (B \ C : A \rightarrow U) (f : (x:A) \rightarrow B \ x \rightarrow C \ x) (w:\text{Sigma } A \ B) : \text{Sigma } A \ C \\ & = (w.1, f \ (w.1) \ (w.2)) \end{aligned}$$

Prop Logic

Set Theory Theorems

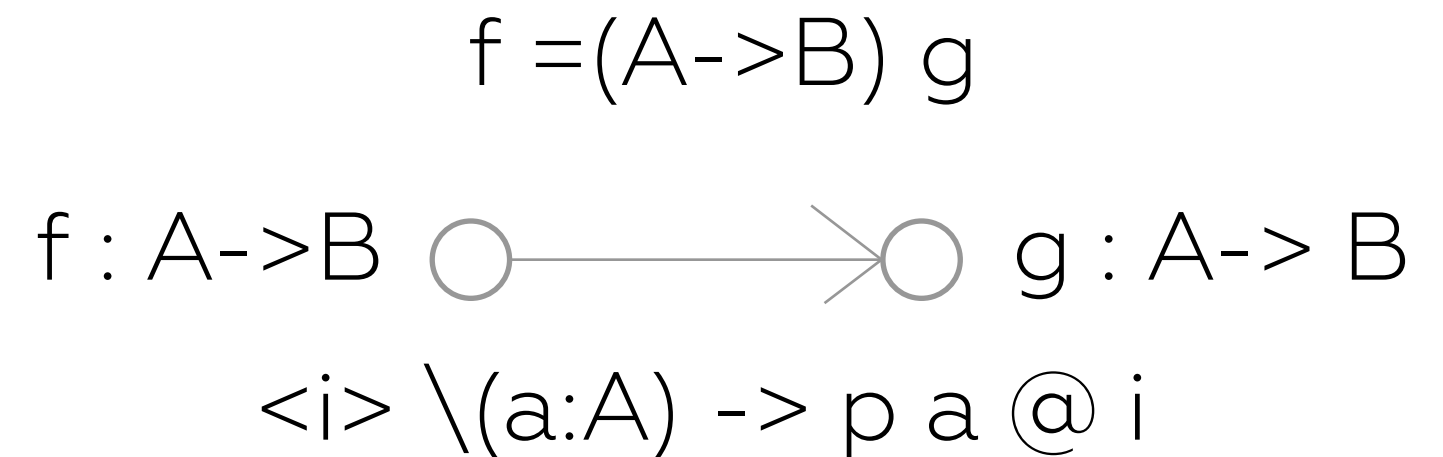
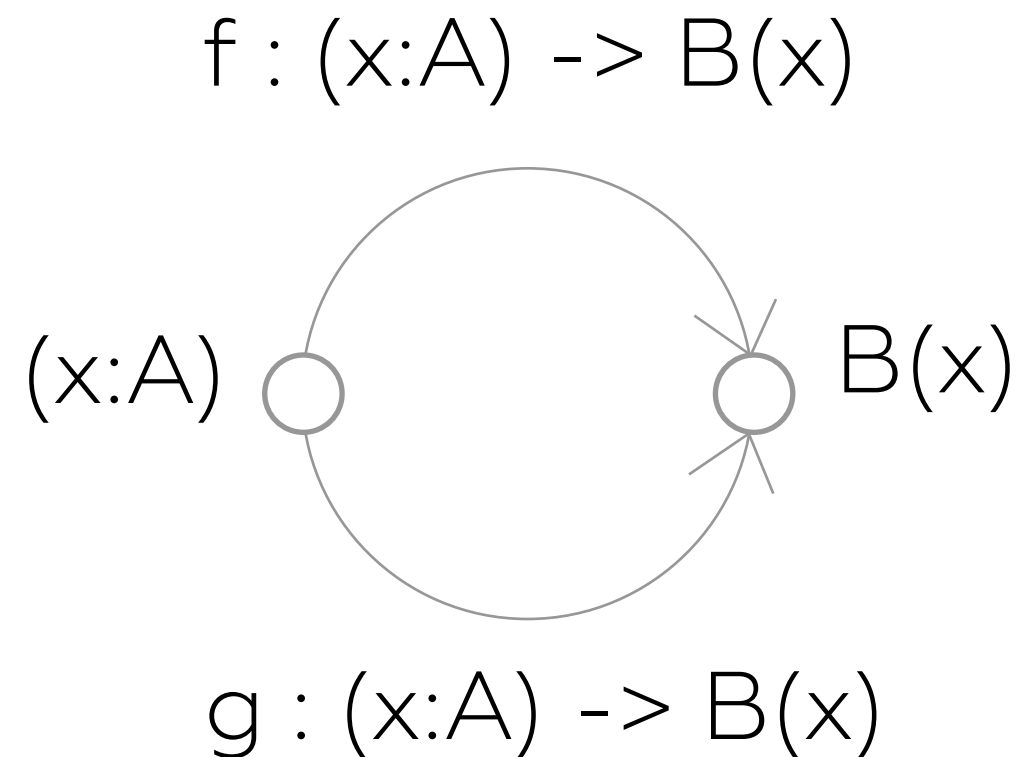
efq (A: U): **empty** -> A = emptyRec A
neg (A: U): U = A -> **empty**
dneg (A:U) (a:A): neg (neg A) = \ (h: neg A) -> h a
neg (A: U): U = A -> **empty**
dec (A: U): U = **either** A (neg A)
stable (A: U): U = neg (neg A) -> A
discrete (A: U): U = (a b: A) -> dec (Path A a b)

propDec (A : U) (a: isProp A) : isProp (dec A)
propAnd (A B : U) (a: isProp A) (b: isProp B) : isProp (**prod** A B)
propOr (A B : U) (a: isProp A) (b: isProp B) (x: A -> neg B) : isProp (**either** A B)
propNeg (A : U) : isProp (neg A)
propN0 : isProp **empty**

FunExt

Syntax and Model

```
funext (A: U) (B: A -> U) (f g: (x:A) -> B x)
  (p: (x:A) -> Path (B x) (f x) (g x))
: Path ((y:A) -> B y) f g
= <i> \ (a: A) -> (p a) @ i
= <j> (\ (x : A) -> homotopy A B f g p x (seg{I} @ j))
```



FunExt

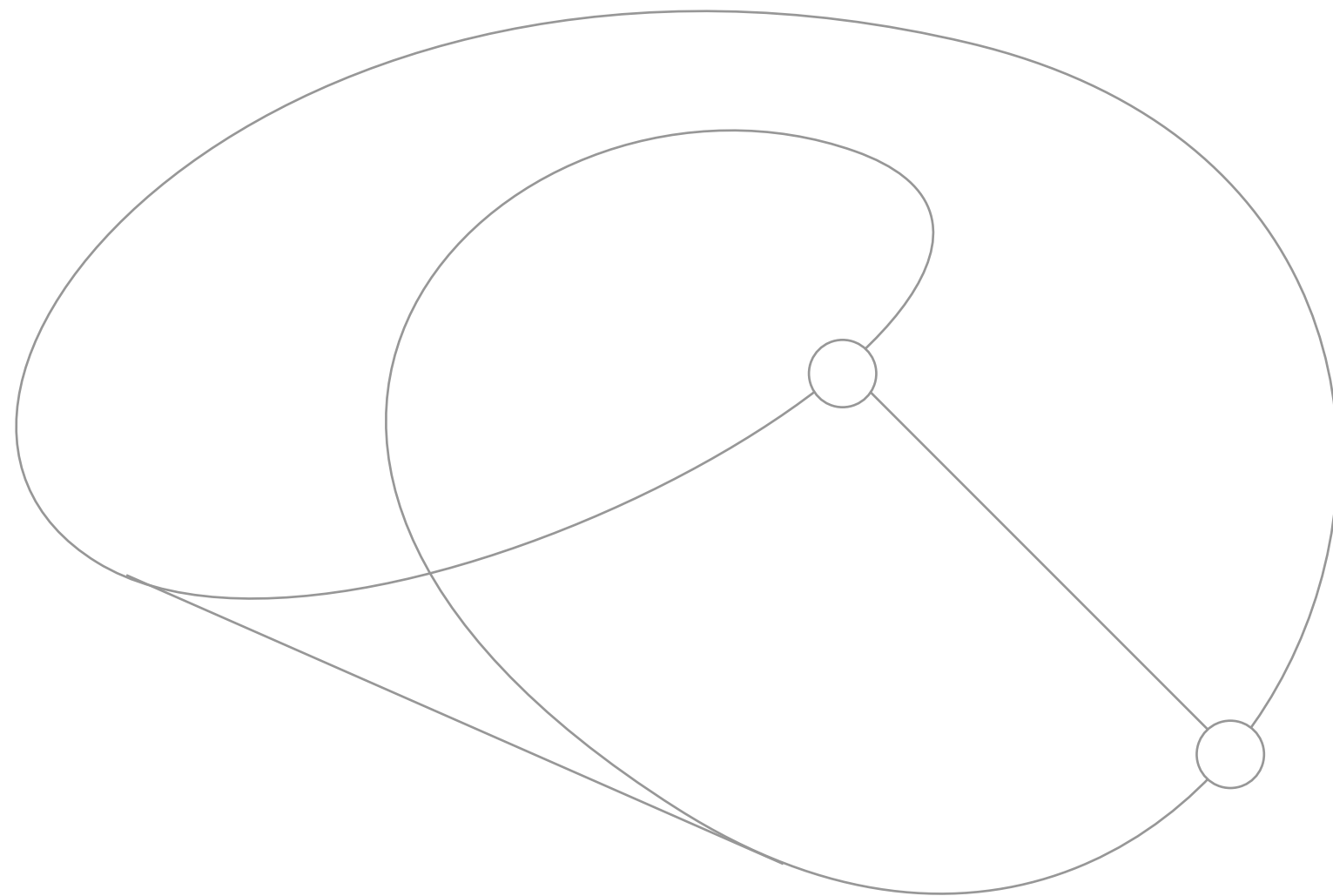
Formation, Intro, Elim, Beta, Eta

```
funext_form (A B: U) (f g: A -> B): U = Path (A -> B) f g
funext (A B: U) (f g: A -> B) (p: (x:A) -> Path B (f x) (g x)) : funext_form A B f g
happly (A B: U) (f g: A -> B) (p: funext_form A B f g) (x: A) : Path B (f x) (g x)
funext_Beta (A B: U) (f g: A -> B) (p: (x:A) -> Path B (f x) (g x))
    : (x:A) -> Path B (f x) (g x)
funext_Eta (A B: U) (f g: A -> B) (p: funext_form A B f g)
    : Path (funext_form A B f g) (funext A B f g (happly A B f g p)) p
```


Weak Equivalence

Fibrational

```
fiber (A B: U) (f: A -> B) (y: B): U = (x: A) * Path B y (f x)
isEquiv (A B: U) (f: A -> B): U = (y: B) -> isContr (fiber A B f y)
equiv (A B: U): U = (f: A -> B) * isEquiv A B f
```



Fiber Bundle: $F \rightarrow E \rightarrow B$

Moebius $E = S^1$ 'twisted $*$ ' $[0,1]$

Trivial: $E = B * F$

$p : \text{total} \rightarrow B$

$F = \text{fiber} : B \rightarrow \text{total}$

$\text{total} = (y: B) * \text{fiber}(y)$

Fiber=Pi (B: U) (F: B -> U) (y: B)

: Path U (fiber (total B F) B (trivial B F) y) (F y)

Isomorphism

isIso (A B: U): U --- A = XML, B = JSON

= (f: A -> B)

* (g: B -> A)

* (s: section A B f g)

* (t: retract A B f g)

* unit

isoPath (A B: U) (f: A -> B) (g: B -> A)

(s: section A B f g) (t: retract A B f g): Path U A B

= <i> Glue B [(i = 0) -> (A,f,isoToEquiv A B f g s t),
(i = 1) -> (B,idfun B,idlsEquiv B)]

iso: U

= (A: U)

* (B: U)

* isIso A B

isoToPath (i: iso): Path U i.1 i.2.1

= isoPath i.1 i.2.1 i.2.2.1 i.2.2.2.1 i.2.2.2.2.1 i.2.2.2.2.2.1

section (A B: U) (f: A -> B) (g: B -> A): U = (b: B) -> Path B (f (g b)) b

retract (A B: U) (f: A -> B) (g: B -> A): U = (a: A) -> Path A (g (f a)) a

Univalence Axiom

All Equalities Should Be Equal

$\text{ua} (A B : U) : U = \text{equiv } A B \rightarrow \text{Path } U A B$

$\text{uaIntro} (A B : U) : \text{ua } A B$

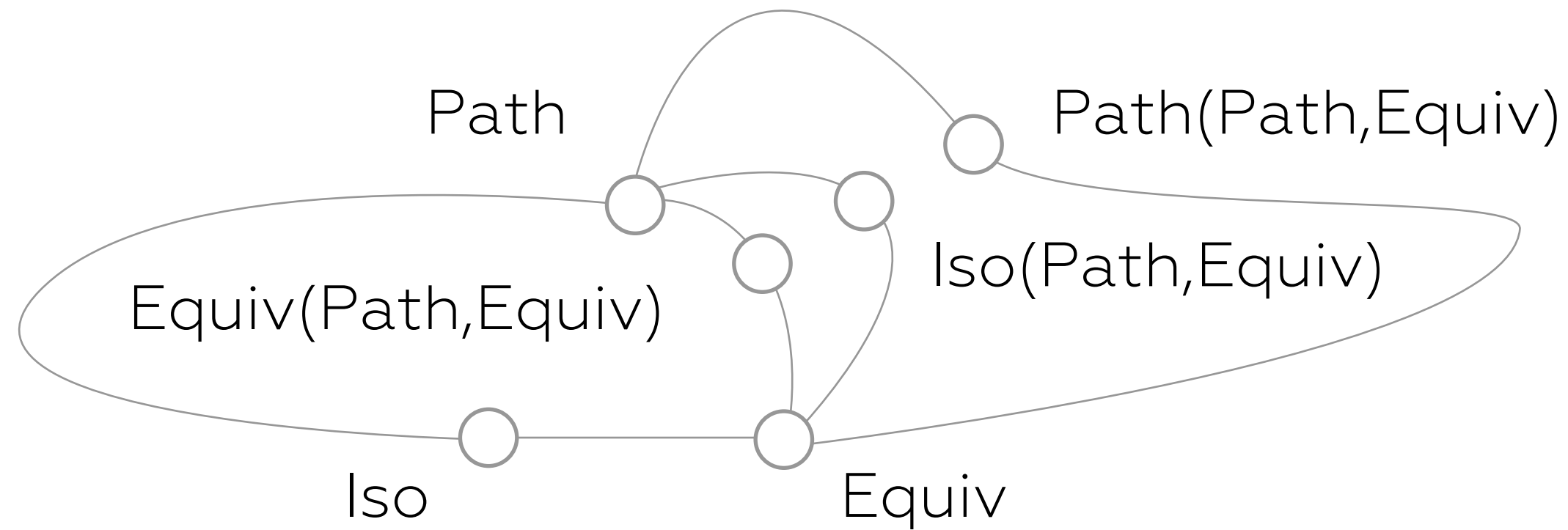
$\text{uaElim} (A B : U) (p : \text{Path } U A B) : \text{equiv } A B$

$\text{uaComp} (A B : U) (p : \text{Path } U A B)$
 $: \text{Path} (\text{Path } U A B) (\text{uaIntro } A B (\text{uaElim } A B p)) p$

$\text{uaUniqueness} (A B : U) (w : \text{equiv } A B)$
 $: \text{Path} (A \rightarrow B) w.1 (\text{uaElim } A B (\text{uaIntro } A B w)).1$

Univalence Axiom

All Equalities Should Be Equal



```

lem2 (B: U) (F: B -> U) (y: B) (x: F y)
  : Path (F y) (comp (<i>F (refl B y @ i)) x []) x
  = <j> comp (<i>F ((refl B y) @ j /\ i)) x [(j=1) -> <k>x]

```

Trivial Fiber = Pi

```

lem3 (B: U) (F: B -> U) (y: B) (x: fiber (total B F) B (trivial B F) y)
  : Path (fiber (total B F) B (trivial B F) y) ((y,encode B F y x),refl B y) x
  = <i> ((x.2 @ -i,comp (<j> F (x.2 @ -i /\ j)) x.1.2 [(i=1) -> <_> x.1.2 ]),<j> x.2 @ -i \/ j)

```

```

FiberPi (B: U) (F: B -> U) (y: B) : Path U (fiber (total B F) B (trivial B F) y) (F y)
= isoPath T A f g s t where
  T: U = fiber (total B F) B (trivial B F) y
  A: U = F y
  f: T -> A = encode B F y
  g: A -> T = decode B F y
  s (x: A): Path A (f (g x)) x = lem2 B F y x
  t (x: T): Path T (g (f x)) x = lem3 B F y x

```

I. Mathematics

Category Theory

Categories

cat: U = (A: U) * (A -> A -> U)

isPrecategory (C: cat): U

= (id: (x: C.1) -> C.2 x x)

* (c: (x y z: C.1) -> C.2 x y -> C.2 y z -> C.2 x z)

* (homSet: (x y: C.1) -> isSet (C.2 x y))

* (left: (x y: C.1) -> (f: C.2 x y) -> Path (C.2 x y) (c x x y (id x) f) f)

* (right: (x y: C.1) -> (f: C.2 x y) -> Path (C.2 x y) (c x y y f (id y)) f)

* ((x y z w: C.1) -> (f: C.2 x y) -> (g: C.2 y z) -> (h: C.2 z w) ->
Path (C.2 x w) (c x z w (c x y z f g) h) (c x y w f (c y z w g h)))

precategory: U = (C: cat) * isPrecategory C

Instances:

Set, Functions, Category, Functors, Commutative Monoids, Abelian Groups

Category Theory

Functors

```
catfunctor (A B: precategory): U
= (ob: carrier A -> carrier B)
* (mor: (x y: carrier A) -> hom A x y -> hom B (ob x) (ob y))
* (id: (x: carrier A) -> Path (hom B (ob x) (ob x)) (mor x x (path A x)) (path B (ob x)))
* ((x y z: carrier A) -> (f: hom A x y) -> (g: hom A y z) ->
  Path (hom B (ob x) (ob z)) (mor x z (compose A x y z f g))
  (compose B (ob x) (ob y) (ob z) (mor x y f) (mor y z g)))
```

Category Equivalence, Id and Composition Functors, Slice and Coslice

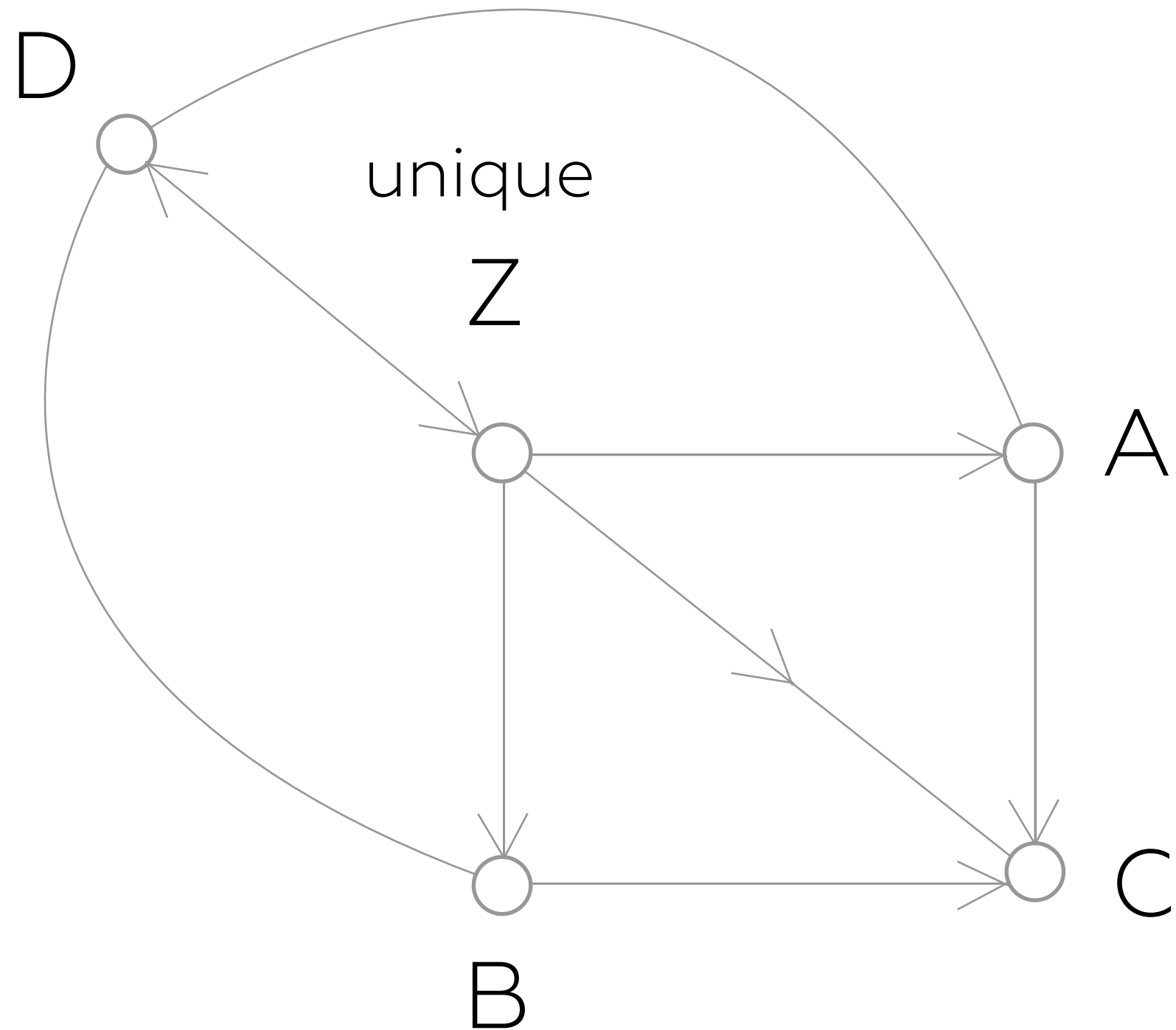
Category of Sets

Formal Model of Set Theory

```
Set: precategory = ((Ob,Hom),id,c,HomSet,L,R,Q) where
  Ob: U = SET
  Hom (A B: Ob): U = A.1 -> B.1
  id (A: Ob): Hom A A = idfun A.1
  c (A B C: Ob) (f: Hom A B) (g: Hom B C): Hom A C = o A.1 B.1 C.1 g f
  HomSet (A B: Ob): isSet (Hom A B) = setFun A.1 B.1 B.2
  L (A B: Ob) (f: Hom A B): Path (Hom A B) (c A A B (id A) f) f = refl (Hom A B) f
  R (A B: Ob) (f: Hom A B): Path (Hom A B) (c A B B f (id B)) f = refl (Hom A B) f
  Q (A B C D: Ob) (f: Hom A B) (g: Hom B C) (h: Hom C D)
    : Path (Hom A D) (c A C D (c A B C f g) h) (c A B D f (c B C D g h))
    = refl (Hom A D) (c A B D f (c B C D g h))
```

Pullback Completeness

Pullbacks and Fibers as edge case



Examples:
Products, Fibers

Dual Examples (Pushout):
Coproducts, Cofibers

Topos Theory

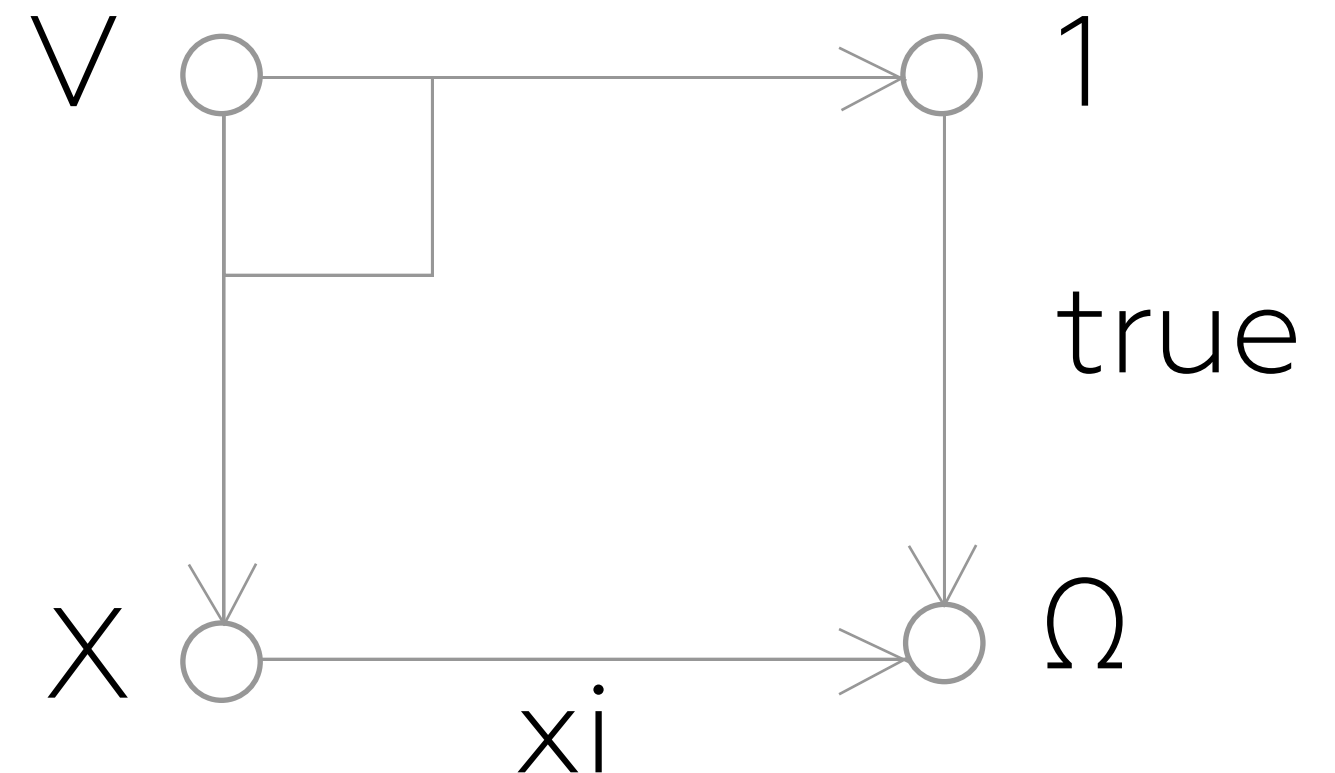
Categories

```

subobjectClassifier (C: precategory): U
= (omega: carrier C)
* (end: terminal C)
* (trueHom: hom C end.1 omega)
* (xi: (V X: carrier C) (j: hom C V X) -> hom C X omega)
* (square: (V X: carrier C) (j: hom C V X) -> mono C V X j
  -> hasPullback C (omega,(end.1,trueHom),(X,xi V X j)))
* ((V X: carrier C) (j: hom C V X) (k: hom C X omega)
  -> mono C V X j
  -> hasPullback C (omega,(end.1,trueHom),(X,k))
  -> Path (hom C X omega) (xi V X j) k)
  
```

```

Topos (cat: precategory): U
= (rezk: isCategory cat)
* (cartesianClosed: isCCC cat)
* subobjectClassifier cat
  
```



Basic Abstract Algebra

Structures

isMonoid (M: SET): U

= (op: M.1 -> M.1 -> M.1)

* (_: isAssociative M.1 op)

* (id: M.1)

* (hasIdentity M.1 op id)

isCMonoid (M: SET): U

= (m: isMonoid M)

* (isCommutative M.1 m.1)

isGroup (G: SET): U

= (m: isMonoid G)

* (inv: G.1 -> G.1)

* (hasInverse G.1 m.1 m.2.2.1 inv)

isAbGroup (G: SET): U

= (g: isGroup G)

* (isCommutative G.1 g.1.1)

isRing (R: SET): U

= (mul: isMonoid R)

* (add: isAbGroup R)

* (isDistributive R.1 add.1.1.1 mul.1)

isAbRing (R: SET): U

= (mul: isCMonoid R)

* (add: isAbGroup R)

* (isDistributive R.1 add.1.1.1 mul.1.1)

Basic Abstract Algebra

Objects and Morphisms for Categorical Setup

monoid: $U = (X: \text{SET}) * \text{isMonoid } X$

cmonoid: $U = (X: \text{SET}) * \text{isCMonoid } X$

group: $U = (X: \text{SET}) * \text{isGroup } X$

abgroup: $U = (X: \text{SET}) * \text{isAbGroup } X$

ring: $U = (X: \text{SET}) * \text{isRing } X$

abring: $U = (X: \text{SET}) * \text{isAbRing } X$

monoidhom (a b: monoid): U
= (f: a.1.1 \rightarrow b.1.1)
* (ismonoidhom a b f)

cmonoidhom (a b: cmonoid): $U = \text{monoidhom } (a.1, a.2.1) \ (b.1, b.2.1)$

grouphom (a b: group): $U = \text{monoidhom } (a.1, a.2.1) \ (b.1, b.2.1)$

abgrouphom (a b: abgroup): $U = \text{monoidhom } (a.1, a.2.1.1) \ (b.1, b.2.1.1)$

cmonabgroupom (a: cmonoid) (b: abgroup): $U = \text{monoidhom } (a.1, a.2.1) \ (b.1, b.2.1.1)$

Ordinals

Structures

```
data ord = zero
         | succ (n:      ord)
         | lim  (f: nat -> ord)
```

```
data ord2 = zero
          | succ (n:      ord2)
          | lim  (f: nat -> ord2)
          | lim2 (f: ord  -> ord2)
```

```
data ord3 = zero
          | succ (n:      ord3)
          | lim  (f: nat -> ord3)
          | lim2 (f: ord  -> ord3)
          | lim3 (f: ord2 -> ord3)
```

<http://www.cse.chalmers.se/~coquand/ordinal.ps>

data V

= pi_ (x: V) (y: Elv x -> V)

| uni_ (f: (x: V) -> (Elv x -> V) -> V)

(g: (x: V) -> (y: Elv x -> V) -> (Elv (f x y) -> V) -> V)

Elv: V -> U = split

pi_ a b -> (x: Elv a) -> Elv (b x)

uni_ f g -> Universe f g

[http://www.cs.swan.ac.uk/
~csetzer/articles/uppermahlo.ps](http://www.cs.swan.ac.uk/~csetzer/articles/uppermahlo.ps)

cubical: Resolver.hs:(293,26)-
(316,29): Non-exhaustive patterns
in case

Mahlo Universe

Structures

data Universe

(f: (x: V) -> (Elv x -> V) -> V)

(g: (x: V) -> (y: Elv x -> V) -> (Elv (f x y) -> V) -> V)

= fun_ (x: Universe f g) (_: Elt f g x -> Universe f g)

| f_ (x: Universe f g) (_: Elt f g x -> Universe f g)

| g_ (x: Universe f g)

(y: Elt f g x -> Universe f g)

(z: Elv (f (Elt f g x) (\(a: Elt f g x) -> y a)))

Elt: (f: (x: V) -> (Elv x -> V) -> V) ->

(g: (x: V) -> (y: Elv x -> V) -> (Elv (f x y) -> V) -> V) ->

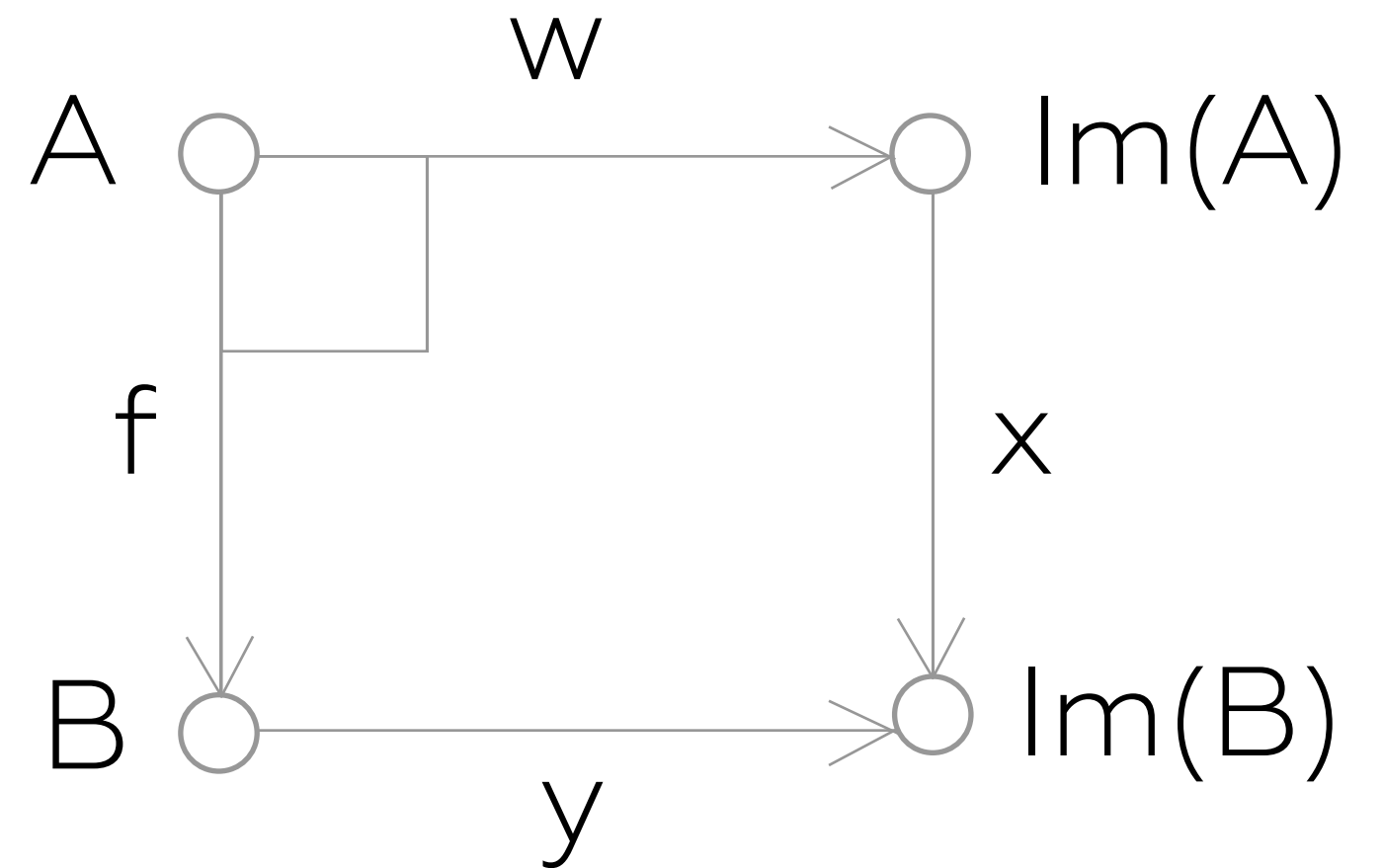
Universe f g -> V = undefined

Differential Topology

Etale Maps

```
EtaleMap (A B: U): U
= (f: A -> B)
* isÉtaleMap A B f
```

```
isÉtaleMap (A B: U) (f: A -> B): U
= isPullbackSq A iA B (Im B) x y w f h where
iA : U = Im A
iB : U = Im B
x: iA -> iB = ImApp A B f
y: B -> iB = ImUnit B
w: A -> iA = ImUnit A
c1: A -> iB = o A iA iB x w
c2: A -> iB = o A B iB y f
T2: U = (a:A) -> Path iB (c1 a) (c2 a)
h: T2 = \ (a : A) -> <i> ImNaturality A B f a @ -i
```



Differential Topology

Manifolds

HomogeneousStructure (V: U): U
et (A B: U): EtaleMap A B -> (A -> B)
isSurjective (A B: U) (f: A -> B): U

manifold (V': U) (V: HomogeneousStructure V'): U
= (M: U)
* (W: U)
* (w: EtaleMap W M)
* (covers: isSurjective W M (et W M w))
* (EtaleMap W V')

<https://ncatlab.org/schreiber/show/thesis+Wellen>

Infinitesimal Modality

in Cohesive Topos

$\text{Im} : U \rightarrow U = \text{undefined}$

$\text{ImUnit} (A: U) : A \rightarrow \text{Im } A = \text{undefined}$

$\text{isCoreduced} (A:U): U = \text{isEquiv } A (\text{Im } A) (\text{ImUnit } A)$

$\text{ImCoreduced} (A:U): \text{isCoreduced} (\text{Im } A)$

$\text{ImApp} (A \ B: U) (f: A \rightarrow B): \text{Im } A \rightarrow \text{Im } B$

$= \text{ImRecursion } A (\text{Im } B) (\text{ImCoreduced } B) (\circ A \ B (\text{Im } B) (\text{ImUnit } B) f)$

$\text{ImNaturality} (A \ B:U) (f:A \rightarrow B): (a:A) \rightarrow \text{Path} (\text{Im } B)((\text{ImUnit } B)(f \ a))((\text{ImApp } A \ B \ f)(\text{ImUnit } A \ a))$

$\text{ImInduction} (A:U)(B:\text{Im } A \rightarrow U)(x: (a: \text{Im } A) \rightarrow \text{isCoreduced}(B \ a))$

$(y:(a: A) \rightarrow B(\text{ImUnit } A \ a)):(a:\text{Im } A) \rightarrow B \ a$

$\text{ImComputeInduction} (A:U)(B:\text{Im } A \rightarrow U) (c:(a:\text{Im } A) \rightarrow \text{isCoreduced}(B \ a))$

$(f:(a:A) \rightarrow B(\text{ImUnit } A \ a))(a:A)$

$: \text{Path} (B (\text{ImUnit } A \ a)) (f \ a) ((\text{ImInduction } A \ B \ c \ f) (\text{ImUnit } A \ a))$

Higher Spheres

Fiber Bundle of Spheres

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

```
data susp (A : U) = north
                  | south
                  | merid (a : A) <i> [ (i=0) -> north, (i=1) -> south ]
```

```
S2 : U = susp S1
```

```
S3 : U = susp S2
```

```
S4 : U = susp S3
```

```
S: nat -> U = split
  zero -> susp bool
  succ x -> susp (S x)
```

Hopf Fibrations

Fiber Bundle of Spheres

ua (A B : U) (e : equiv A B) : Path U A B = <i> Glue B [(i = 0) -> (A,e), (i = 1) -> (B,idEquiv B)]
rot: (x : S1) -> Path 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 }
TH : U = (c : S2) * H c

Sequences

```
data Seq (A: U) (B: A -> A -> U) (X Y: A)
  = seqNil (_: A)
  | seqCons (X Y Z: A) (_: B X Y) (_: Seq A B Y Z)
```

fiberSeq: pointed -> pointed -> U = Seq pointed pmap

fiberNil (X: pointed): fiberSeq X X = seqNil X

fiberCons (X Y Z: pointed) (h: pmap X Y) (t: fiberSeq Y Z): fiberSeq X Z = seqCons X Y Z h t

homSeq: group -> group -> U = Seq group grouphom

homNil (X: group): homSeq X X = seqNil X

homCons (X Y Z: group) (h: grouphom X Y) (t: homSeq Y Z): homSeq X Z = seqCons X Y Z h t

abSeq: abgroup -> abgroup -> U = Seq abgroup abgrouphom

abNil (X: abgroup): abSeq X X = seqNil X

abCons (X Y Z: abgroup) (h: abgrouphom X Y) (t: abSeq Y Z): abSeq X Z = seqCons X Y Z h t

Chain Complexes

ChainComplex: U

= (head: abgroup)

* (chain: **nat** -> abgroup)

* (augment: abgrouphom (chain **zero**) head)

* ((n: **nat**) -> abgrouphom (chain (**succ** n)) (chain n))

CochainComplex: U

= (head: abgroup)

* (cochain: **nat** -> abgroup)

* (augment: abgrouphom head (cochain **zero**))

* ((n: **nat**) -> abgrouphom (cochain n) (cochain (**succ** n)))

Impredicative Encoding

As in version of Steve Awodey, HITs encoding

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

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

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

$1 = (\text{one}: \text{Unit}) * ((X \ Y: U) (x: \text{isSet } X) (y: \text{isSet } Y) (f: X \rightarrow Y) \rightarrow \text{naturalness } X \ Y \ f \ (\text{one } X \ x) (\text{one } Y \ y))$

$N = (\text{one}: \text{Nat}) * ((X \ Y: U) (x: \text{isSet } X) (y: \text{isSet } Y) (f: X \rightarrow Y) \rightarrow \text{naturalness } X \ Y \ f \ (\text{one } X \ x) (\text{one } Y \ y))$

Truncation $\|A\|$ parametrized by $(A:U)$ type $= (X: U) \rightarrow \text{isProp } X \rightarrow (A \rightarrow X) \rightarrow X$

$S^1 = (X:U) \rightarrow \text{isGroupoid } X \rightarrow (x:X) \rightarrow \text{Path } X \ x \ x \rightarrow X$

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

Impredicative Encoding

Encode Unit. Homework: Bool, Circle, Sphere

$\text{unitEnc}' : U = (X : U) \rightarrow \text{isSet } X \rightarrow X \rightarrow X$

$\text{naturality } (X \ Y : U) (f : X \rightarrow Y) (a : X \rightarrow X) (b : Y \rightarrow Y) : U = \text{Path } (X \rightarrow Y) (\text{o } X \ X \ Y \ f \ a) (\text{o } X \ Y \ Y \ b \ f)$

$\text{isUnitEnc } (\text{one} : \text{unitEnc}') : U$

$= (X \ Y : U) (x : \text{isSet } X) (y : \text{isSet } Y) (f : X \rightarrow Y) \rightarrow \text{naturality } X \ Y \ f \ (\text{one } X \ x) (\text{one } Y \ y)$

$\text{unitEnc} : U = (x : \text{unitEnc}') * \text{isUnitEnc } x$

$\text{unitEncStar} : \text{unitEnc} = \backslash (X : U) (_ : \text{isSet } X) \rightarrow \text{idfun } X, \backslash (X \ Y : U) (_ : \text{isSet } X) (_ : \text{isSet } Y) \rightarrow \text{refl } (X \rightarrow Y)$

$\text{unitEncRec } (C : U) (s : \text{isSet } C) (c : C) : \text{unitEnc} \rightarrow C = \backslash (z : \text{unitEnc}) \rightarrow z.1 \ C \ s \ c$

$\text{unitEncBeta } (C : U) (s : \text{isSet } C) (c : C) : \text{Path } C (\text{unitEncRec } C \ s \ c \ \text{unitEncStar}) \ c$

$\text{unitEncEta } (z : \text{unitEnc}) : \text{Path } \text{unitEnc} \ \text{unitEncStar } z$

$\text{unitEncInd } (P : \text{unitEnc} \rightarrow U) (a : \text{unitEnc}) : P \ \text{unitEncStar} \rightarrow P \ a$

$\text{unitEncCondition } (n : \text{unitEnc}') : \text{isProp } (\text{isUnitEnc } n)$

<https://github.com/groupoid/cafe>

Thank You!

<https://groupoid.space>