

A Groupoidal Natural Model of HoTT in Lean 4

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0.1 Natural Models

In this section we describe the categorical semantics of HoTT via Natural Models. This will not be a detailed account of the syntax of HoTT, but will be a detailed account of what is needed to interpret such syntax. It will follow [Awo17], but with a more compact description of identity types using the technology of polynomial endofunctors, and a universe of small types.

Notation. We will have two universe sizes - one small and one large. We denote the category of small sets as **set** and the large sets as **Set**. For example, we could take the small sets **set** to be those in **Set** bounded in cardinality by some inaccessible cardinal.

0.1.1 Types

Let \mathbb{C} be a small category, i.e. a category whose class of objects is a **set** and whose hom-classes are from **set**. We write $\mathbf{Psh}(\mathbb{C})$ for the category of presheaves over \mathbb{C} ,

$$\mathbf{Psh}(\mathbb{C}) =_{\text{def}} [\mathbb{C}^{\text{op}}, \mathbf{Set}]$$

Definition 0.1.1. Following Awodey [Awo17], we say that a map $\text{tp} : \mathbf{Tm} \rightarrow \mathbf{Ty}$ is presentable when any fiber of a representable is representable. In other words, given any $\Gamma \in \mathbb{C}$ and a map $A : y(\Gamma) \rightarrow \mathbf{Ty}$, there is some representable $\Gamma \cdot A \in \mathbb{C}$ and maps $\text{disp}_A : \Gamma \cdot A \rightarrow \Gamma$ and $\text{var}_A : y(\Gamma \cdot A) \rightarrow \mathbf{Tm}$ forming a pullback

$$\begin{array}{ccc} y(\Gamma \cdot A) & \xrightarrow{\text{var}_A} & \mathbf{Tm} \\ y(\text{disp}_A) \downarrow & & \downarrow \text{tp} \\ y(\Gamma) & \xrightarrow{A} & \mathbf{Ty} \end{array}$$

The Natural Model associated to a presentable map $\text{tp} : \mathbf{Tm} \rightarrow \mathbf{Ty}$ consists of

- contexts as objects $\Gamma, \Delta, \dots \in \mathbb{C}$,
- a type in context $y(\Gamma)$ as a map $A : y(\Gamma) \rightarrow \mathbf{Ty}$,
- a term of type A in context Γ as a map $a : y(\Gamma) \rightarrow \mathbf{Tm}$ such that

$$\begin{array}{ccc} & & \mathbf{Tm} \\ & \nearrow a & \downarrow \text{tp} \\ \Gamma & \xrightarrow{A} & \mathbf{Ty} \end{array}$$

commutes,

- an operation called “context extension” which given a context Γ and a type $A : y(\Gamma) \rightarrow \mathbf{Ty}$ produces a context $\Gamma \cdot A$ which fits into a pullback diagram below.

$$\begin{array}{ccc} y(\Gamma \cdot A) & \longrightarrow & \mathbf{Tm} \\ \downarrow & & \downarrow \\ y(\Gamma) & \xrightarrow{A} & \mathbf{Ty} \end{array}$$

Remark. Sometimes, we first construct a presheaf X over Γ and observe that it can be classified by a map into \mathbf{Ty} . We write

$$\begin{array}{ccc} X & \longrightarrow & \mathbf{Tm} \\ \downarrow & & \downarrow \\ y(\Gamma) & \xrightarrow{\ulcorner X \urcorner} & \mathbf{Ty} \end{array}$$

to express this situation, i.e. $X \cong y(\Gamma \cdot \ulcorner X \urcorner)$.

0.1.2 Pi types

We will use Poly_{tp} to denote the polynomial endofunctor (definition 0.3.1) associated with our presentable map tp . Then an interpretation of Π types consists of a pullback square

$$\begin{array}{ccc} \text{Poly}_{\text{tp}} \mathbf{Tm} & \xrightarrow{\lambda} & \mathbf{Tm} \\ \text{Poly}_{\text{tp}} \text{tp} \downarrow & \lrcorner & \downarrow \text{tp} \\ \text{Poly}_{\text{tp}} \mathbf{Ty} & \xrightarrow{\Pi} & \mathbf{Ty} \end{array}$$

0.1.3 Sigma types

An interpretation of Σ types consists of a pullback square

$$\begin{array}{ccc} Q & \xrightarrow{\text{pair}} & \mathbf{Tm} \\ \text{tp} \lrcorner \text{tp} \downarrow & \lrcorner & \downarrow \text{tp} \\ \text{Poly}_{\text{tp}} \mathbf{Ty} & \xrightarrow{\Sigma} & \mathbf{Ty} \end{array}$$

0.1.4 Identity types

To interpret the formation and introduction rules for identity types we require a commutative square (this need not be pullback)

$$\begin{array}{ccc} \mathbf{Tm} & \xrightarrow{\text{refl}} & \mathbf{Tm} \\ \delta \downarrow & & \downarrow \text{tp} \\ \text{tp} \times_{\mathbf{Ty}} \text{tp} & \xrightarrow{\text{Id}} & \mathbf{Ty} \end{array}$$

where δ is the diagonal:

$$\begin{array}{ccccc} \mathbf{Tm} & & & & \\ & \searrow \delta & & \nearrow & \\ & \text{tp} \times_{\mathbf{Ty}} \text{tp} & \longrightarrow & \mathbf{Tm} & \\ & \downarrow & \lrcorner & \downarrow \text{tp} & \\ & \mathbf{Tm} & \xrightarrow{\text{tp}} & \mathbf{Ty} & \end{array}$$

Then let I be the pullback. We get a comparison map ρ

$$\begin{array}{ccccc}
 \mathsf{Tm} & & \xrightarrow{\text{refl}} & & \mathsf{Tm} \\
 \downarrow \delta & \dashrightarrow \rho & & \downarrow j & \downarrow \text{tp} \\
 & I & \longrightarrow & & \mathsf{Tm} \\
 & \downarrow & & & \downarrow \text{tp} \\
 \mathsf{tp} \times_{\mathsf{Ty}} \mathsf{tp} & \xrightarrow{\text{id}} & & & \mathsf{Ty}
 \end{array}$$

Then view $\rho : \mathsf{tp} \rightarrow q$ as a map in the slice over Ty .

$$\begin{array}{ccc}
 \mathsf{Tm} & \xrightarrow{\rho} & I \\
 \downarrow \delta & & \downarrow j \\
 \mathsf{tp} \times_{\mathsf{Ty}} \mathsf{tp} & \xrightarrow{\text{fst}} & \mathsf{Tm} \\
 \downarrow \text{tp} & & \downarrow \text{tp} \\
 \mathsf{Ty} & & \mathsf{Ty}
 \end{array}$$

Now (by definition 0.3.6) applying $\text{Poly}_- : (\mathbf{Psh}(\mathbb{C})/\mathsf{Ty})^{\text{op}} \rightarrow [\mathbf{Psh}(\mathbb{C}), \mathbf{Psh}(\mathbb{C})]$ to $\rho : \mathsf{tp} \rightarrow q$ gives us a naturality square (this also need not be pullback).

$$\begin{array}{ccc}
 \text{Poly}_q \mathsf{Tm} & \xrightarrow{\rho^* \mathsf{Tm}} & \text{Poly}_{\mathsf{tp}} \mathsf{Tm} \\
 \text{Poly}_q \mathsf{tp} \downarrow & & \downarrow \text{Poly}_{\mathsf{tp}} \mathsf{tp} \\
 \text{Poly}_q \mathsf{Ty} & \xrightarrow{\rho^* \mathsf{Ty}} & \text{Poly}_{\mathsf{tp}} \mathsf{Tm}
 \end{array}$$

Taking the pullback T and the comparison map ε we have

$$\begin{array}{ccccc}
 \text{Poly}_q \mathsf{Tm} & & \xrightarrow{\rho^* \mathsf{Tm}} & & \text{Poly}_{\mathsf{tp}} \mathsf{Tm} \\
 \downarrow \text{Poly}_q \mathsf{tp} & \dashrightarrow \varepsilon & & \downarrow j & \downarrow \text{Poly}_{\mathsf{tp}} \mathsf{tp} \\
 & T & \longrightarrow & & \text{Poly}_{\mathsf{tp}} \mathsf{Tm} \\
 & \downarrow & & & \downarrow \text{Poly}_{\mathsf{tp}} \mathsf{tp} \\
 & \text{Poly}_q \mathsf{Ty} & \xrightarrow{\rho^* \mathsf{Ty}} & & \text{Poly}_{\mathsf{tp}} \mathsf{Tm}
 \end{array}$$

Finally, we require a section $J : T \rightarrow \text{Poly}_q \mathsf{Tm}$ of ε , to interpret the identity elimination rule.

0.1.5 A type of small types

We now wish to formulate a condition that allows us to have a type of small types, written U , not just *judgement* expressing that something is a type. With this notation, the judgements that we would like to derive is

$$\mathsf{U} : \mathsf{Ty} \quad \frac{a : \mathsf{U}}{\text{El}(a) : \mathsf{Ty}}$$

(A sufficient and natural condition for this seems to be that we now have another inaccessible cardinal κ , with $\kappa < \lambda$.)

In the Natural Model, a universe U is postulated by a map

$$\pi : E \rightarrow U$$

In the Natural Model:

- There is a pullback diagram of the form

$$\begin{array}{ccc} U & \longrightarrow & Tm \\ \downarrow & & \downarrow \\ 1 & \xrightarrow{\tau_U} & Ty \end{array}$$

- There is an inclusion of U into Ty

$$El : U \hookrightarrow Ty$$

- $\pi : E \rightarrow U$ is obtained as pullback of tp ; There is a pullback diagram

$$\begin{array}{ccc} E & \xrightarrow{\quad} & Tm \\ \downarrow & & \downarrow \\ U & \xrightarrow{El} & Ty \end{array}$$

With the notation above, we get

$$\begin{array}{ccccc} y(\Gamma.El(a)) & \longrightarrow & E & \longrightarrow & Tm \\ \downarrow & & \downarrow & & \downarrow \\ y(\Gamma) & \xrightarrow{a} & U & \xrightarrow{El} & Ty \\ & \searrow & \text{A} & \nearrow & \end{array}$$

Both squares above are pullback squares.

0.1.6 The Universe in Embedded Type Theory (HoTT0) and the relationship to the Natural Model

0.2 The Groupoid Model

In this section we construct a natural model in $\mathbf{Psh}(\mathbf{grp d})$ the presheaf category indexed by the category $\mathbf{grp d}$ of (small) groupoids. We will build the classifier for display maps in the style of Hofmann and Streicher [HS98] and Awodey [Awo23]. To interpret the type constructors, we will make use of the weak factorization system on $\mathbf{grp d}$ - which comes from restricting the “classical Quillen model structure” on \mathbf{cat} [Joy] to $\mathbf{grp d}$.

0.2.1 Classifying display maps

Notation. We denote the category of small categories as **cat** and the large categories as **Cat**. We denote the category of small groupoids as **grpd**.

We are primarily working in the category of large presheaves indexed by small groupoids, which we will denote by

$$\mathbf{Psh}(\mathbf{grpd}) = [\mathbf{grpd}^{\text{op}}, \mathbf{Set}]$$

In this section, **Tm** and **Ty** and so on will refer to the natural model semantics in this specific model.

Definition 0.2.1 (Pointed). We will take the category of pointed small categories **cat_•** to have objects as pairs $(\mathbb{C} \in \mathbf{cat}, c \in \mathbb{C})$ and morphisms as pairs

$$(F : \mathbb{C}_1 \rightarrow \mathbb{C}_0, \phi : Fc_1 \rightarrow c_0) : (\mathbb{C}_1, c_1) \rightarrow (\mathbb{C}_0, c_0)$$

Then the category of pointed small groupoids **grpd_•** will be the full subcategory of objects (Γ, c) with Γ a groupoid.

Definition 0.2.2 (The display map classifier). We would like to define a natural transformation in **Psh(grpd)**

$$\text{tp} : \mathbf{Tm} \rightarrow \mathbf{Ty}$$

with representable fibers.

Consider the functor that forgets the point

$$U : \mathbf{grpd}_{\bullet} \rightarrow \mathbf{grpd} \quad \text{in} \quad \mathbf{Cat}.$$

If we apply the Yoneda embedding $y : \mathbf{Cat} \rightarrow \mathbf{Psh}(\mathbf{Cat})$ to U we obtain

$$U \circ [-, \mathbf{grpd}_{\bullet}] \rightarrow [-, \mathbf{grpd}] \quad \text{in} \quad \mathbf{Psh}(\mathbf{Cat}).$$

Since any small groupoid is also a large category $\mathbf{grpd} \hookrightarrow \mathbf{Cat}$, we can restrict **Cat** indexed presheaves to be **grpd** indexed presheaves. We define $\text{tp} : \mathbf{Tm} \rightarrow \mathbf{Ty}$ as the image of $U \circ$ under this restriction.

$$\mathbf{Cat} \xrightarrow{y} \mathbf{Psh}(\mathbf{Cat}) \xrightarrow{\text{res}} \mathbf{Psh}(\mathbf{grpd})$$

$$\mathbf{grpd} \longmapsto [-, \mathbf{grpd}] \longmapsto \mathbf{Ty}$$

Note that **Tm** and **Ty** are not representable in **Psh(grpd)**.

Remark 0.2.3. By Yoneda we can identify maps with representable domain into the type classifier

$$A : y\Gamma \rightarrow \mathbf{Ty} \quad \text{in} \quad \mathbf{Psh}(\mathbf{grpd})$$

with functors

$$A : \Gamma \rightarrow \mathbf{grpd} \quad \text{in} \quad \mathbf{Cat}$$

Definition 0.2.4 (Grothendieck construction). From \mathbb{C} a small category and $F : \mathbb{C} \rightarrow \mathbf{cat}$ a functor, we construct a small category $\int F$. For any $c \in \mathbb{C}$ we refer to Fc as the fiber over c . The objects of $\int F$ consist of pairs $(c \in \mathbb{C}, x \in Fc)$, and

morphisms between (c, x) and (d, y) are pairs $(f : c \rightarrow d, \phi : F f x \rightarrow y)$. This makes the following pullback in **Cat**

$$(c, x) \longmapsto (Fc, x)$$

$$\begin{array}{ccccc} (c, x) & & \int F & \longrightarrow & \mathbf{cat}_\bullet & & (C, c) \\ \downarrow & & \downarrow & \lrcorner & \downarrow & & \downarrow \\ c & & \mathbb{C} & \xrightarrow{F} & \mathbf{cat} & & C \end{array}$$

Definition 0.2.5 (Grothendieck construction for groupoids). Let Γ be a groupoid and $A : \Gamma \rightarrow \mathbf{grpd}$ a functor, we can compose F with the inclusion $i : \mathbf{grpd} \hookrightarrow \mathbf{Cat}$ and form the Grothendieck construction which we denote as

$$\Gamma \cdot A := \int i \circ A \quad \text{disp}_A : \Gamma \cdot A \rightarrow \Gamma$$

This is also a small groupoid since the underlying morphisms are pairs of morphisms from groupoids Γ and Ax for $x \in \Gamma$. Furthermore the pullback factors through (pointed) groupoids.

$$\begin{array}{ccccc} \Gamma \cdot A & \longrightarrow & \mathbf{grpd}_\bullet & \longrightarrow & \mathbf{cat}_\bullet \\ \text{disp}_A \downarrow & \lrcorner & \downarrow & \lrcorner & \downarrow \\ \Gamma & \xrightarrow{A} & \mathbf{grpd} & \longrightarrow & \mathbf{cat} \end{array}$$

Corollary 0.2.6 (The display map classifier is presentable). *For any small groupoid Γ and $A : y\Gamma \rightarrow \mathbf{Ty}$, the pullback of \mathbf{tp} along A can be given by the representable map $y\text{disp}_A$.*

$$\begin{array}{ccc} y\Gamma \cdot A & \longrightarrow & \mathbf{Tm} \\ y\text{disp}_A \downarrow & \lrcorner & \text{tp} \downarrow \\ y\Gamma & \xrightarrow{A} & \mathbf{Ty} \end{array}$$

Proof. Consider the pullback in **Cat**

$$\begin{array}{ccc} \Gamma \cdot A & \longrightarrow & \mathbf{grpd}_\bullet \\ \downarrow & \lrcorner & \downarrow \\ \Gamma & \xrightarrow{A} & \mathbf{grpd} \end{array}$$

We send this square along $\text{res} \circ y$ in the following

$$\begin{array}{ccc} \mathbf{Cat} & \xrightarrow{y} & \mathbf{Psh}(\mathbf{Cat}) \\ \uparrow & \searrow & \downarrow \text{res} \\ \mathbf{grpd} & \xrightarrow{y} & \mathbf{Psh}(\mathbf{grpd}) \end{array}$$

The Yoneda embedding $y : \mathbf{Cat} \rightarrow \mathbf{Psh}(\mathbf{Cat})$ preserves pullbacks, as does res since it is a right adjoint (with left Kan extension $\iota_1 \dashv \text{res}_\iota$). \square

0.2.2 Groupoid fibrations

Definition 0.2.7 (Fibration). Let $p : \mathbb{C}_1 \rightarrow \mathbb{C}_0$ be a functor. We say p is a *split Grothendieck fibration* if we have a dependent function $\text{lift } a f$ satisfying the following: for any object a in \mathbb{C}_1 and morphism $f : p a \rightarrow y$ in the base \mathbb{C}_0 we have $\text{lift } a f : a \rightarrow b$ in \mathbb{C}_1 such that $p(\text{lift } a f) = f$ and moreover $\text{lift } a g \circ f = \text{lift } b g \circ \text{lift } a f$

$$\begin{array}{ccc} a & \xrightarrow{\text{lift } a f} & b \\ \downarrow & \begin{array}{c} \pi \\ \parallel \\ \downarrow \end{array} & \downarrow \\ x & \xrightarrow{f} & y \end{array}$$

In particular, we are interested in split Grothendieck fibrations of groupoids, which are the same as *isofibrations* (replace all the morphisms with isomorphisms in the definition).

Unless specified otherwise, by a *fibration* we will mean a split Grothendieck fibration of groupoids. Let us denote the category of fibrations over a groupoid Γ as \mathbf{Fib}_Γ , which is a full subcategory of the slice \mathbf{grpd}/Γ . We will decorate an arrow with \rightarrow to indicate it is a fibration.

Note that $\text{disp}_A : \Gamma \cdot A \rightarrow \Gamma$ is a fibration, since for any $(x \in \Gamma, a \in Ax)$ and $f : x \rightarrow y$ in Γ we have a morphism $(f, \text{id}_{Afa}) : (x, a) \rightarrow (y, Afa)$ lifting f . Furthermore

Proposition 0.2.8. *There is an adjoint equivalence*

$$[\Gamma, \mathbf{grpd}] \begin{array}{c} \xrightarrow{\text{disp}} \\ \xleftarrow[\text{fiber}]{\simeq} \end{array} \mathbf{Fib}_\Gamma$$

where for each fibration $\delta : \Delta \rightarrow \Gamma$ and each object $x \in \Gamma$

$$\text{fiber}_\delta x = \text{full subcategory } \{a \in \Delta \mid \delta a = x\}$$

It follows that all fibrations are pullbacks of the classifier $U : \mathbf{grpd}_\bullet \rightarrow \mathbf{grpd}$, when viewed as morphisms in \mathbf{Cat} .

Pullback of fibrations along groupoid functors is not strictly coherent, in the sense that for $\tau : \Xi \rightarrow \Delta$ and $\sigma : \Delta \rightarrow \Gamma$ and a fibration $p \in \mathbf{Fib}_\Gamma$ we only have an isomorphism

$$\tau^* \sigma^* p \cong (\sigma \circ \tau)^* p$$

rather than equality.

In order to interpret reindexing/substitution strictly, it is convenient to work with classifiers $[\Gamma, \mathbf{grpd}]$ instead of fibrations.

Proposition 0.2.9 (Strictly coherent pullback). *Let $\sigma : \Delta \rightarrow \Gamma$ be a functor between groupoids. Since display maps are pullbacks of the classifier $U : \mathbf{grpd}_\bullet \rightarrow \mathbf{grpd}$ we have the pasting diagram*

$$\begin{array}{ccccc}
 & & \Delta.A\sigma & \xrightarrow{\quad \sigma_A \quad} & \Gamma.A & \longrightarrow & \mathbf{grpd}_\bullet \\
 & & \downarrow \text{disp}_{A\sigma} & \lrcorner & \downarrow \text{disp}_A & \lrcorner & \downarrow \\
 \Delta & \xrightarrow{\quad \sigma \quad} & \Gamma & \xrightarrow{\quad A \quad} & \mathbf{grpd}
 \end{array}$$

This gives us a functor $\circ\sigma : [\Gamma, \mathbf{grpd}] \rightarrow [\Delta, \mathbf{grpd}]$ which is our strict version of pullback.

Corollary 0.2.10 (Fibrations are stable under pullback).

$$\begin{array}{ccc}
 [\Gamma, \mathbf{grpd}] & \xleftarrow{\text{fiber}} & \mathbf{Fib}_\Gamma \\
 \circ\sigma \downarrow & & \downarrow \sigma^* \\
 [\Delta, \mathbf{grpd}] & \xrightarrow{\text{disp}} & \mathbf{Fib}_\Delta
 \end{array}$$

We can deduce a corresponding fact about fibrations: since fibrations are closed under isomorphism, and since any pullback in \mathbf{grpd} of a fibration p is isomorphic to the display map $\text{disp}_{\text{fiber } p \circ \sigma}$, any pullback of a fibration is a fibration.

A strict interpretation of type theory would require Σ and Π -formers to be stable under pullback (Beck-Chevalley). Thus we again define these as operations on classifiers $[\Gamma, \mathbf{grpd}]$.

Definition 0.2.11 (Σ -former operation). Then given $A : \Gamma \rightarrow \mathbf{grpd}$ and $B : \Gamma \cdot A \rightarrow \mathbf{grpd}$ we define $\Sigma_A B : \Gamma \rightarrow \mathbf{grpd}$ such that $\Sigma_A B$ acts on objects by forming fiberwise Grothendieck constructions

$$\Sigma_A B(x) := A(x) \cdot B \circ x_A$$

where $x_A : A(x) \rightarrow \Gamma \cdot A$ takes $f : a_0 \rightarrow a_1$ to $(\text{id}_x, f) : (x, a_0) \rightarrow (x, a_1)$

$$\begin{array}{ccccc}
 A(x) \cdot B \circ x_A & \dashrightarrow & \Gamma.A.B & \longrightarrow & \bullet \\
 \downarrow \text{disp}_{B \circ x_A} & & \downarrow \text{disp}_B & & \\
 A(x) & \xrightarrow{x_A} & \Gamma.A & \xrightarrow{B} & \mathbf{grpd} \\
 \downarrow \text{!} & \lrcorner & \downarrow \text{disp}_A & \lrcorner & \\
 \bullet & \xrightarrow{x} & \Gamma & \xrightarrow{A} & \mathbf{grpd}
 \end{array}$$

$\Sigma_A B$ acts on morphism $f : x \rightarrow y$ in Γ and $(a \in A(x), b \in B(x, a))$ by

$$\Sigma_A B f(a, b) := (A f a, B(f, \text{id}_{A f a}) b)$$

and for morphism $(\alpha : a_0 \rightarrow a_1 \in A(x), \beta : B(\text{id}_x, \alpha) b_0 \rightarrow b_1 \in B(x, a_1))$ in $\Sigma_A B x$

$$\Sigma_A B f(\alpha, \beta) := (A f \alpha, B(f, \text{id}_{A f a_1}) \beta)$$

Let us also define the natural transformation $\text{fst} : \Sigma_A B \rightarrow A$ by

$$\text{fst}_x : (a, b) \mapsto a$$

Proposition 0.2.12 (Fibrations are closed under composition). *The corresponding fact about fibrations is that the composition of two fibrations is a fibration.*

$$\begin{array}{ccc} \Xi & & \\ \downarrow & \dashrightarrow & \\ \Delta & \longrightarrow & \Gamma \end{array}$$

We can compare the two fibrations

$$\text{disp}_B \circ \text{disp}_A \quad \text{and} \quad \text{disp}_{\Sigma_A(B)}$$

An object in the composition would look like $((x, a), b)$ for $x \in \Gamma$, $a \in A(x)$ and $b \in B(x, a)$, whereas an object in $\Gamma \cdot \Sigma_A(B)$ would instead be $(x, (a, b))$.

Proposition 0.2.13 (Strict Beck-Chevalley for Σ). *Let $\sigma : \Delta \rightarrow \Gamma$, $A : \Gamma \rightarrow \mathbf{grpd}$ and $B : \Gamma \cdot A \rightarrow \mathbf{grpd}$. Then*

$$(\Sigma_A B) \circ \sigma = \Sigma_{A \circ \sigma}(B \circ \sigma_A)$$

where σ_A is uniquely determined by the pullback in

$$\begin{array}{ccccc} \Delta \cdot A\sigma \cdot B \circ \sigma_A & \xrightarrow{\sigma_{A \cdot B}} & \Gamma \cdot A \cdot B & & \\ \downarrow \text{disp}_{B \circ \sigma_A} & & \downarrow \text{disp}_B & & \\ \Delta \cdot A\sigma & \xrightarrow{\sigma_A} & \Gamma \cdot A & \xrightarrow{B} & \mathbf{grpd} \\ \downarrow \text{disp}_{A\sigma} & \lrcorner & \downarrow \text{disp}_A & \lrcorner & \\ \mathbf{grpd} \xleftarrow[\Sigma_{A \circ \sigma}(B \circ \sigma_A)]{(\Sigma_A B) \circ \sigma} \Delta & \xrightarrow{\sigma} & \Gamma & \xrightarrow{A} & \mathbf{grpd} \end{array}$$

Proof. By checking pointwise at $x \in \Delta$, this boils down to showing

$$(\sigma x)_A = \sigma_A \circ x_{A \circ \sigma} : A(\sigma x) \rightarrow \Gamma \cdot A$$

$$\begin{array}{ccccccc} & & (\sigma x)_A & & & & \\ & \searrow & & \swarrow & & & \\ A(\sigma x) & \xrightarrow{x_{A\sigma}} & \Delta \cdot A\sigma & \xrightarrow{\sigma_A} & \Gamma \cdot A & \xrightarrow{B} & \mathbf{grpd} \\ \downarrow \text{!} & \lrcorner & \downarrow \text{disp}_{A\sigma} & \lrcorner & \downarrow \text{disp}_A & \lrcorner & \\ \bullet & \xrightarrow{x} & \Delta & \xrightarrow{\sigma} & \Gamma & \xrightarrow{A} & \mathbf{grpd} \end{array}$$

which holds because of the universal property of pullback. \square

Definition 0.2.14 (Π -former operation). Given $A : \Gamma \rightarrow \mathbf{grpd}$ and $B : \Gamma \cdot A \rightarrow \mathbf{grpd}$ we will define $\Pi_A B : \Gamma \rightarrow \mathbf{grpd}$ such that for any $C : \Gamma \rightarrow \mathbf{grpd}$ we have an isomorphism

$$[\Gamma \cdot A, \mathbf{grpd}](\text{disp}_A \circ C, B) \cong [\Gamma, \mathbf{grpd}](C, \Pi_A B)$$

natural in both B and C .

Proof. $\Pi_A B$ acts on objects by taking fiberwise sections

$$\Pi_A B(x) := \{s \in [A(x), \Sigma_A B(x)] \mid \text{fst}_x \circ s = \text{id}_{A(x)}\}$$

Where we have taken the full subcategory of the functor category $[A(x), \Sigma_A B(x)]$. This is a groupoid since any natural transformation of functors into groupoids are natural isomorphisms.

$\Pi_A B$ acts on morphisms via conjugation

$$\begin{array}{ccccc}
x & & \Pi_A B(x) & & A(x) \xrightarrow{s} \Sigma_A B(x) \\
\downarrow f & \xrightarrow{\Pi_A B} & \downarrow \Sigma_A B(f) \circ \circ A(f^{-1}) & & \uparrow A(f^{-1}) \\
y & & \Pi_A B(y) & & A(y) \xrightarrow{\Pi_A B(f)(s)} \Sigma_A B(y)
\end{array}$$

Note that conjugation is functorial and invertible. \square

Corollary 0.2.15 (Fibrations are closed under pushforward). *Stated in terms of fibrations, we have*

$$\begin{array}{ccc}
\Xi & & \Gamma \downarrow \sigma_* \tau \\
\tau \downarrow & & \downarrow \sigma_* \tau \\
\Delta & \xrightarrow{\sigma} & \Gamma
\end{array}$$

with the universal property of pushforward

$$\text{Fib}_\Delta(\sigma^* \rho, \tau) \cong \text{Fib}_\Gamma(\rho, \sigma_* \tau)$$

natural in both τ and ρ .

Proposition 0.2.16 (Strict Beck-Chevalley for Π). *Let $\sigma : \Delta \rightarrow \Gamma$, $A : \Gamma \rightarrow \mathbf{grpd}$ and $B : \Gamma \cdot A \rightarrow \mathbf{grpd}$. Then*

$$(\Pi_A B) \circ \sigma = \Pi_{A \circ \sigma}(B \circ \sigma_A)$$

where σ_A is uniquely determined by the pullback in

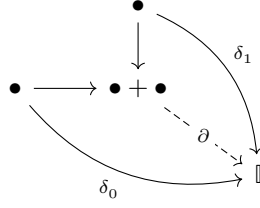
$$\begin{array}{ccccc}
\Delta \cdot A \sigma \cdot B \circ \sigma_A & \xrightarrow{\sigma_{A \cdot B}} & \Gamma \cdot A \cdot B \\
\downarrow \text{disp}_{B \circ \sigma_A} & & \downarrow \text{disp}_B \\
\Delta \cdot A \sigma & \xrightarrow{\sigma_A} & \Gamma \cdot A & \xrightarrow{B} & \mathbf{grpd} \\
\downarrow \text{disp}_{A \sigma} & & \downarrow \text{disp}_A \\
\mathbf{grpd} & \xleftarrow[\Pi_{A \circ \sigma}(B \circ \sigma_A)]{\Pi_A B \circ \sigma} \Delta & \xrightarrow{\sigma} & \Gamma & \xrightarrow{A} \mathbf{grpd}
\end{array}$$

Proof. By checking pointwise, this boils down to Beck-Chevalley for Σ . \square

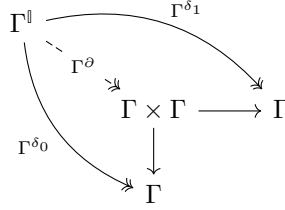
Proposition 0.2.17 (All objects are fibrant). *Let \bullet denote the terminal groupoid, namely that with a single object and morphism. Then the unique map $\Gamma \rightarrow \bullet$ is a fibration.*

Definition 0.2.18 (Interval). Let the interval groupoid \mathbb{I} be the small groupoid with two objects and a single non-identity isomorphism. There are two distinct morphisms $\delta_0, \delta_1 : \bullet \rightarrow \mathbb{I}$ and a natural isomorphism $i : \delta_0 \Rightarrow \delta_1$. Note that δ_0 and δ_1 both form adjoint equivalences with the unique map $! : \mathbb{I} \rightarrow \bullet$.

Denote by $\bullet + \bullet$ the small groupoid with two objects and only identity morphisms. Then let $\partial : \bullet + \bullet \rightarrow \mathbb{I}$ be the unique map factoring δ_0 and δ_1 .



Proposition 0.2.19 (Path object fibration). *Let Γ be a small groupoid. Recall that \mathbf{grpd} is Cartesian closed, so we can take the image of the above diagram under the functor Γ^- .*



Then the indicated morphisms are fibrations, and $\Gamma^{\delta_0}, \Gamma^{\delta_1}$ form adjoint equivalences with $\Gamma^\parallel : \Gamma \rightarrow \Gamma^\parallel$.

0.2.3 Classifying type dependency

Proposition 0.2.20 ($\mathbf{Poly}_{\mathbf{tp}}$ classifies type dependency). *Specialized to $\mathbf{tp} : \mathbf{Tm} \rightarrow \mathbf{Ty}$ in $\mathbf{Psh}(\mathbf{grpd})$, the characterizing property of polynomial endofunctors proposition 0.3.2 says that a map from a representable $\Gamma \rightarrow \mathbf{Poly}_{\mathbf{tp}} X$ corresponds to the data of*

$$A : \Gamma \rightarrow \mathbf{Ty} \quad \text{and} \quad B : \Gamma \cdot A \rightarrow X$$

The special case of when X is also \mathbf{Ty} gives us a classifier for dependent types; by Yoneda the above corresponds to the data in \mathbf{Cat} of

$$A : \Gamma \rightarrow \mathbf{grpd} \quad \text{and} \quad B : \Gamma \cdot A \rightarrow \mathbf{grpd}$$

Furthermore, precomposition by a substitution $\sigma : \Delta \rightarrow \Gamma$ acts on such a pair by

$$\begin{array}{ccc} \Delta & & \\ \sigma \downarrow & \searrow^{(A \circ \sigma, B \circ \mathbf{tp}^* \sigma)} & \\ \Gamma & \xrightarrow{(A, B)} & \mathbf{Poly}_{\mathbf{tp}} X \end{array}$$

where $\mathbf{tp}^ \sigma$ is given by*

$$\begin{array}{ccccc} \Delta \cdot A \circ \sigma & \xrightarrow{\mathbf{tp}^* \sigma} & \Gamma \cdot A & \longrightarrow & \mathbf{grpd}_\bullet \\ \downarrow & & \downarrow & & \downarrow \\ \Delta & \xrightarrow{\sigma} & \Gamma & \xrightarrow{A} & \mathbf{grpd} \end{array}$$

0.2.4 Pi and Sigma structure

Lemma 0.2.21. $X \in \mathbf{Psh}(\mathbf{grpd})$ be a presheaf. Let F be an operation that takes a groupoid Γ , a functor $A : \Gamma \rightarrow \mathbf{grpd}$ and $B : \Gamma \cdot A \rightarrow X$ and returns a natural transformation $F_A B : \Gamma \rightarrow X$.

Then using Yoneda to define $\tilde{F} : \mathbf{Poly}_{\mathbf{tp}} X \rightarrow X$ pointwise as

$$\begin{aligned} \tilde{F}_\Gamma : \mathbf{Psh}(\mathbf{grpd})(\Gamma, \mathbf{Poly}_{\mathbf{tp}} X) &\rightarrow \mathbf{Psh}(\mathbf{grpd})(\Gamma, X) \\ (A, B) &\mapsto F_A B \end{aligned}$$

gives us a natural transformation if and only if F satisfies the strict Beck-Chevalley condition

$$(F_A B) \circ \sigma = F_{A \circ \sigma} (B \circ \mathbf{tp}^* \sigma)$$

for every $\sigma : \Delta \rightarrow \Gamma$ in \mathbf{grpd} .

Proof. Using proposition 0.2.20

$$\begin{array}{ccc} (A, B) & \xrightarrow{\quad\quad\quad} & F_A B \\ \downarrow & & \downarrow \\ \mathbf{Psh}(\mathbf{grpd})(\Gamma, \mathbf{Poly}_{\mathbf{tp}} X) & \xrightarrow{\tilde{F}_\Gamma} & \mathbf{Psh}(\mathbf{grpd})(\Gamma, X) \\ \downarrow - \circ \sigma & & \downarrow - \circ \sigma \\ \mathbf{Psh}(\mathbf{grpd})(\Delta, \mathbf{Poly}_{\mathbf{tp}} X) & \xrightarrow{\tilde{F}_\Delta} & \mathbf{Psh}(\mathbf{grpd})(\Delta, X) \\ \downarrow & & \downarrow \\ (A \circ \sigma, B \circ \mathbf{tp}^* \sigma) & \xrightarrow{\quad\quad\quad} & F_{A \circ \sigma} B \circ \mathbf{tp}^* \sigma \quad \text{=====} \quad (F_A B) \circ \sigma \end{array}$$

□

Definition 0.2.22 (Interpretation of Π types). We define the natural transformation $\Pi : \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty} \rightarrow \mathbf{Ty}$ as that which is induced (lemma 0.2.21) by the Π -former operation (definition 0.2.14).

Then we define the natural transformation $\lambda : \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty} \rightarrow \mathbf{Ty}$ as the natural transformation induced by the following operation: given $A : \Gamma \rightarrow \mathbf{grpd}$ and $\beta : \Gamma \cdot A \rightarrow \mathbf{grpd}_\bullet$, $\lambda_A \beta : \Gamma \rightarrow \mathbf{grpd}_\bullet$ will be the functor such that on objects $x \in \Gamma$

$$\lambda_A \beta(x) := (\Pi_A B(x), a \mapsto (a, b(x, a)))$$

where $B := U \circ \beta : \Gamma \cdot A \rightarrow \mathbf{grpd}$ and $b(x, a)$ is the point in $\beta(x, a)$. On morphisms $f : x \rightarrow y$ in Γ we have

$$\lambda_A \beta(f) := (\Pi_A B(f), \eta)$$

where $\eta : \Pi_A B f s_x \rightarrow s_y$ is a natural isomorphism between functors $A_y \rightarrow \Sigma_A B y$ given on objects $a \in A_y$ by

$$\eta_a := (\text{id}_a, \text{id}_{b(y, a)})$$

These combine to give us a pullback square

$$\begin{array}{ccc} \mathbf{Poly}_{\mathbf{tp}} \mathbf{Tm} & \xrightarrow{\lambda} & \mathbf{Tm} \\ \mathbf{Poly}_{\mathbf{tp}} \mathbf{tp} \downarrow & \lrcorner & \downarrow \mathbf{tp} \\ \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty} & \xrightarrow{\Pi} & \mathbf{Ty} \end{array}$$

Proof. We should check that the λ operation satisfied Beck-Chevalley. This follows from the Π satisfying Beck-Chevalley and extensionality results for functors.

The square commutes and is a pullback if and only if it pointwise commutes and pointwise gives pullbacks, i.e. for each groupoid Γ

$$\begin{array}{ccc}
(A, \beta) & \xrightarrow{\quad\quad\quad} & \lambda_A \beta \\
\downarrow & & \downarrow \\
\begin{array}{ccc}
\mathbf{Psh}(\mathbf{grpd})(\Gamma, \mathbf{Poly}_{\mathbf{tp}} \mathbf{Tm}) & \xrightarrow{\lambda_\Gamma} & [\Gamma, \mathbf{grpd}_\bullet] \\
\mathbf{Psh}(\mathbf{grpd})(\Gamma, \mathbf{Poly}_{\mathbf{tp}} \mathbf{tp}) \downarrow & \lrcorner & \downarrow U \circ - \\
\mathbf{Psh}(\mathbf{grpd})(\Gamma, \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty}) & \xrightarrow{\Pi_\Gamma} & [\Gamma, \mathbf{grpd}]
\end{array} & & \\
(A, U \circ \beta) & \xrightarrow{\quad\quad\quad} & \Pi_\Gamma U \circ \beta = U \circ \lambda_A \beta
\end{array}$$

where we have used proposition 0.2.20. That this commutes follows from the definitions of Π and λ .

To show it is pullback it suffices to note that for any $f : \Gamma \rightarrow \mathbf{grpd}_\bullet$ and $(A, B) : \Gamma \rightarrow \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty}$ such that $U \circ f = \Pi_A B$, there exists a unique $(A, \beta) : \Gamma \rightarrow \mathbf{Poly}_{\mathbf{tp}} \mathbf{Tm}$ such that $U \circ \beta = B$ and $\lambda_A \beta = f$. Indeed β is fully determined by the above conditions to be

$$\begin{aligned}
\beta : \Gamma \cdot A &\rightarrow \mathbf{grpd}_\bullet \\
(x, a) &\mapsto (B(x, a), f x a)
\end{aligned}$$

□

Lemma 0.2.23. *This is a specialization of lemma 0.3.3. Use R to denote the fiber product*

$$\begin{array}{ccc}
R & \xrightarrow{\rho_{\mathbf{Poly}}} & \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty} \\
\mathbf{tp}^* \mathbf{tp}_* \mathbf{Tm}^* \mathbf{Ty} = \rho_{\mathbf{Tm}} \downarrow & \lrcorner & \downarrow \mathbf{tp}_* \mathbf{Tm}^* \mathbf{Ty} \\
\mathbf{Tm} & \xrightarrow{\mathbf{tp}} & \mathbf{Ty}
\end{array}$$

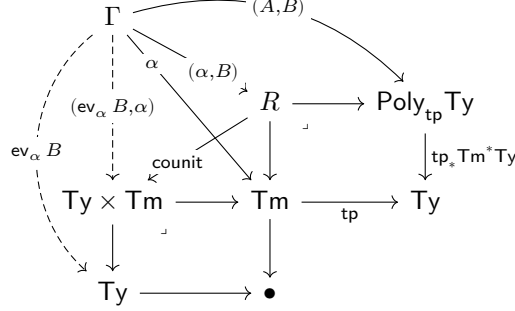
By the universal property of pullbacks, The data of a map from a representable $\varepsilon : \Gamma \rightarrow R$ corresponds to the data of $\alpha : \Gamma \rightarrow \mathbf{Tm}$ and $(U \circ \alpha, B) : \Gamma \rightarrow \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty}$. Then by proposition 0.2.20 this corresponds to the data of $\alpha : \Gamma \rightarrow \mathbf{Tm}$ and $B : \Gamma \cdot U \circ \alpha \rightarrow \mathbf{Ty}$.

$$\begin{array}{ccc}
\Gamma & \xrightarrow{(U \circ \alpha, B)} & \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty} \\
\downarrow (\alpha, B) & & \downarrow \rho_{\mathbf{Poly}} \\
R & \xrightarrow{\quad\quad\quad} & \mathbf{Poly}_{\mathbf{tp}} \mathbf{Ty} \\
\downarrow \rho_{\mathbf{Tm}} & \lrcorner & \downarrow \mathbf{tp}_* \mathbf{Tm}^* \mathbf{Ty} \\
\Gamma & \xrightarrow{\alpha} & \mathbf{Tm} \xrightarrow{\mathbf{tp}} \mathbf{Ty}
\end{array}$$

Precomposition by a substitution $\sigma : \Delta \rightarrow \Gamma$ then acts on such a pair by

$$\begin{array}{ccc}
\Delta & & \\
\sigma \downarrow & \searrow (\alpha \circ \sigma, B \circ \mathbf{tp}^* \sigma) & \\
\Gamma & \xrightarrow{(\alpha, B)} & R
\end{array}$$

Definition 0.2.24 (Evaluation). Define the operation of evaluation $\text{ev}_\alpha B$ to take $\alpha : \Gamma \rightarrow \mathbf{grpd}_\bullet$ and $B : \Gamma \cdot U \circ \alpha \rightarrow \mathbf{grpd}$ and return $\text{ev}_\alpha B : \Gamma \rightarrow \mathbf{grpd}$, described below.



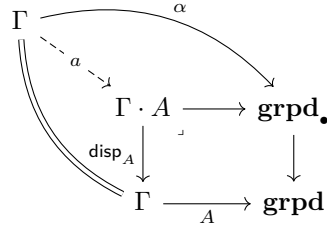
where we write $A := U \circ \alpha$ and treat a map $\Gamma \rightarrow \mathbf{grpd}$ as the same as a map $\Gamma \rightarrow \mathbf{Ty}$. More concisely, evaluation is a natural transformation $\text{ev} : R \rightarrow \mathbf{Ty}$, given by

$$\text{ev} = \pi_{\mathbf{Ty}} \circ \text{counit}$$

Lemma 0.2.25. *The functor $\text{ev}_\alpha B : \Gamma \rightarrow \mathbf{grpd}$ can be computed as*

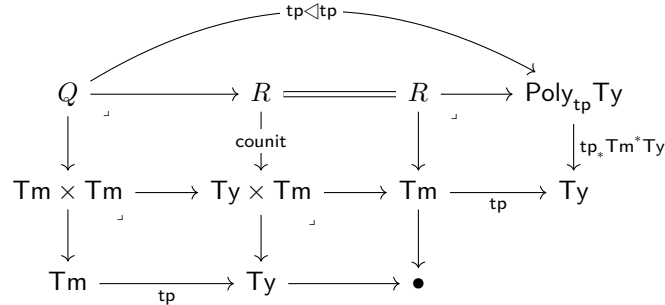
$$\text{ev}_\alpha B = B \circ a$$

where



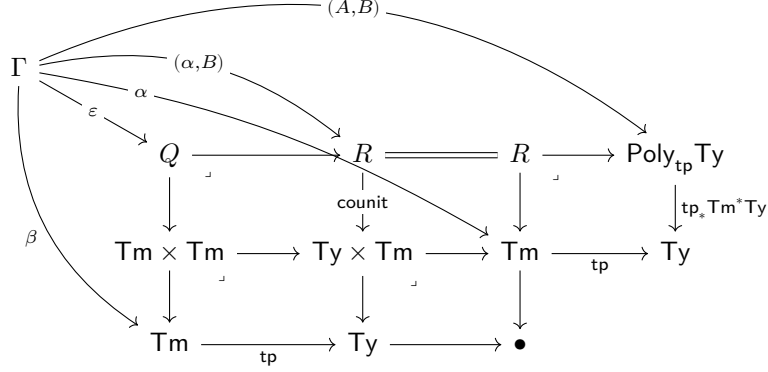
Proof. This is a specialization of lemma 0.3.4 with liberal applications of Yoneda. \square

Definition 0.2.26 (Classifier for dependent pairs). Recall the following definition of composition of polynomial endofunctors, specialized to our situation



By the universal property of pullbacks, the data of a map with representable domain $\varepsilon : \Gamma \rightarrow Q$ corresponds to the data of a triple of maps $\alpha, \beta : \Gamma \rightarrow \mathbf{Tm}$ and $(A, B) :$

$\Gamma \rightarrow \text{Poly}_{\text{tp}} \text{Ty}$ such that $\text{tp} \circ \beta = \pi_{\text{Ty}} \circ \text{counit} \circ (\alpha, B)$ and $A = \text{tp} \circ \alpha$.



This in turn corresponds to three functors $\alpha, \beta : \Gamma \rightarrow \mathbf{grpd}_\bullet$ and $B : \Gamma \cdot U \circ \alpha \rightarrow \mathbf{grpd}_\bullet$, such that $U \circ \beta = \text{ev}_\alpha B$. So we will write

$$\varepsilon = (\beta, \alpha, B)$$

Type theoretically $\alpha = (A, a : A)$ and $\text{ev}_\alpha B = Ba$ and $\beta = (Ba, b : Ba)$. Then composing ε with $\text{tp} \triangleleft \text{tp}$ returns γ , which consists of (A, B) . It is in this sense that Q classifies pairs of dependent terms, and $\text{tp} \triangleleft \text{tp}$ extracts the underlying types.

Precomposition with a substitution $\sigma : \Delta \rightarrow \Gamma$ acts on this triple by

$$\begin{array}{ccc} \Delta & & \\ \sigma \downarrow & \searrow^{(\beta \circ \sigma, \alpha \circ \sigma, B \circ \text{tp}^* \sigma)} & \\ \Gamma & \xrightarrow{(\beta, \alpha, B)} & Q \end{array}$$

Definition 0.2.27 (Interpretation of Σ). We define the natural transformation

$$\Sigma : \text{Poly}_{\text{tp}} \text{Ty} \rightarrow \text{Ty}$$

as that which is induced (lemma 0.2.21) by the Σ -former operation (definition 0.2.14).

To define $\text{pair} : Q \rightarrow \text{Tm}$, let Γ be a groupoid and $(\beta, \alpha, B) : \Gamma \rightarrow Q$ (such that $U \circ \beta = \text{ev}_\alpha \beta$). We define a functor $\text{pair}_\Gamma(\beta, \alpha, B) : \Gamma \rightarrow \mathbf{grpd}_\bullet$ such that on objects $x \in \Gamma$, the functor returns $(\Sigma_A Bx, (a_x, b_{a_x}))$, where (using lemma 0.2.25 $U \circ \beta x = \text{ev}_\alpha Bx = B(x, a_x)$)

$$\alpha x = (Ax, a_x) \quad \text{and} \quad \beta x = (B(x, a_x), b_{a_x})$$

and on morphisms $f : x \rightarrow y$, the functor returns $(\Sigma_A Bf, (\phi_f, \psi_f))$, where (using lemma 0.2.25 $U \circ \beta f = \text{ev}_\alpha Bf = B(f, \phi_f)$)

$$\alpha f = (Af, \phi_f : Af a_x \rightarrow a_y) \quad \text{and} \quad \beta f = (B(f, \phi_f), \psi_f : B(f, \phi_f) b_{a_x} \rightarrow b_{a_y})$$

Σ and pair combine to give us a pullback square

$$\begin{array}{ccc} Q & \xrightarrow{\text{pair}} & \text{Tm} \\ \text{tp} \triangleleft \text{tp} \downarrow & \lrcorner & \downarrow \text{tp} \\ \text{Poly}_{\text{tp}} \text{Ty} & \xrightarrow{\Sigma} & \text{Ty} \end{array}$$

Proof. To show naturality of **pair**, suppose $\sigma : \Delta \rightarrow \Gamma$ is a functor between groupoids.

$$\begin{array}{ccc}
\mathbf{Psh}(\mathbf{grpd})(\Delta, Q) & \xrightarrow{\text{pair}_\Delta} & [\Delta, \mathbf{grpd}_\bullet] \\
\uparrow \circ \sigma & & \uparrow \circ \sigma \\
& (\beta \circ \sigma, \alpha \circ \sigma, B \circ \text{tp}^* \sigma) \mapsto ? & \\
& \uparrow \quad \quad \quad \uparrow & \\
& (\beta, \alpha, B) \mapsto \text{pair}_\Gamma(\beta, \alpha, B) & \\
\mathbf{Psh}(\mathbf{grpd})(\Gamma, Q) & \xrightarrow{\text{pair}_\Gamma} & [\Gamma, \mathbf{grpd}_\bullet]
\end{array}$$

So we check that for any $x \in \Gamma$,

$$\begin{aligned}
& \text{pair}_\Delta(\beta \circ \sigma, \alpha \circ \sigma, B \circ \sigma_A) x \\
&= (\Sigma_{A \circ \sigma} B \circ \sigma_A x, (a_x, b_{a_x})) \\
&= ((\Sigma_A B) \circ \sigma x, (a_x, b_{a_x})) \\
&= \text{pair}_\Gamma(\beta, \alpha, B) \circ \sigma x
\end{aligned}$$

where

$$\alpha \circ \sigma x = (A \circ \sigma x, a_x) \quad \text{and} \quad \beta \circ \sigma x = (\text{ev}_\alpha B \circ \sigma x, b_{a_x})$$

and so on.

It follows from the definition of **pair** that the square commutes. To show that it is pullback, it suffices to show that for each Γ ,

$$\begin{array}{ccc}
\mathbf{Psh}(\mathbf{grpd})(\Gamma, Q) & \xrightarrow{\text{pair}_\Gamma} & [\Gamma, \mathbf{grpd}_\bullet] \\
\text{tp} \triangleleft \text{tp} \circ - \downarrow & & \downarrow U \circ - \\
\mathbf{Psh}(\mathbf{grpd})(\Gamma, \text{Poly}_{\text{tp}} \text{Ty}) & \xrightarrow{\Sigma_\Gamma} & [\Gamma, \mathbf{grpd}]
\end{array}$$

is a pullback. Since we are in **Set**, it suffices to just show the universal property applied to a point: so for any $A : \Gamma \rightarrow \mathbf{grpd}$, any $B : \Gamma \cdot A \rightarrow \mathbf{grpd}$, and any $p : \Gamma \rightarrow \mathbf{grpd}_\bullet$, such that

$$U \circ p = \Sigma_\Gamma(A, B)$$

there exists a unique $(\beta, \alpha, B) : \Gamma \rightarrow Q$ such that

$$\text{pair}_\Gamma(\beta, \alpha, B) = p \quad \text{and} \quad \text{tp} \triangleleft \text{tp} \circ (B, \alpha, B) = (A, B)$$

Indeed if we write

$$p x = (\Sigma_A B x, (a_x \in A x, b_x \in B(x, a_x)))$$

this uniquely determines α and β as

$$\alpha x = (A x, a_x) \quad \text{and} \quad \beta x = (\text{ev}_\alpha B x, b_x)$$

0.2.5 Identity types

□

0.3 Polynomial Endofunctors

In this section we develop some of the definitions and lemmas related to polynomial endofunctors that we will use in the rest of the notes.

Definition 0.3.1 (Polynomial endofunctor). Let \mathbb{C} be a locally Cartesian closed category (in our case, presheaves on the category of contexts). This means for each morphism $t : B \rightarrow A$ we have an adjoint triple

$$\begin{array}{ccc} & \mathbb{C}/B & \\ t_! \left(\begin{array}{c} \dashv \uparrow t^* \dashv \\ \downarrow \quad \downarrow \end{array} \right) t_* & & \\ & \mathbb{C}/A & \end{array}$$

where t^* is pullback, and $t_!$ is composition with t .

Let $t : B \rightarrow A$ be a morphism in \mathbb{C} . Then define $\text{Poly}_t : \mathbb{C} \rightarrow \mathbb{C}$ be the composition

$$\text{Poly}_t := A_! \circ t_* \circ B^* \quad \mathbb{C} \xrightarrow{B^*} \mathbb{C}/B \xrightarrow{t_*} \mathbb{C}/A \xrightarrow{A_!} \mathbb{C}$$

Proposition 0.3.2 (Characterising property of Polynomial Endofunctors). *The data of a map into the polynomial applied to an object in \mathbb{C}*

$$\Gamma \longrightarrow \text{Poly}_t Y$$

corresponds to

$$\begin{array}{ccc} \Gamma & \xrightarrow{\phi} & \text{Poly}_t Y \\ \searrow \alpha & & \swarrow t_* B^* Y \\ & A & \end{array}$$

Applying the adjunction $A_! \dashv A^*$, this corresponds to

$$\alpha : \Gamma \rightarrow A \quad \text{and} \quad \begin{array}{ccc} B_! t^* \alpha & \xrightarrow{\tilde{\phi}} & B \times Y \\ \searrow t^* \alpha & & \swarrow B^* Y \\ & B & \end{array}$$

Applying the adjunction $t^* \dashv t_*$, this corresponds to

$$\alpha : \Gamma \rightarrow A \quad \text{and} \quad \Gamma \cdot \alpha := B_! t^* \alpha \xrightarrow{\beta} Y$$

Henceforth we will write

$$(\alpha, \beta) : \Gamma \rightarrow \text{Poly}_t Y$$

for this map, since it is uniquely determined by this data. Furthermore, precomposition by $\sigma : \Delta \rightarrow \Gamma$, acts on such a pair by

$$\begin{array}{ccc} \Delta & & \\ \sigma \downarrow & \searrow (\alpha \circ \sigma, \beta \circ t^* \sigma) & \\ \Gamma & \xrightarrow{(\alpha, \beta)} & \text{Poly}_t Y \end{array}$$

and given a morphism $f : X \rightarrow Y$, the morphism $\text{Poly}_t f$ acts on such a pair by

$$\begin{array}{ccc} \Gamma & \xrightarrow{(\alpha, \beta)} & \text{Poly}_t X \\ & \searrow (\alpha, f \circ \beta) & \downarrow \text{Poly}_t f \\ & & \text{Poly}_t Y \end{array}$$

Lemma 0.3.3. Use R to denote the fiber product

$$\begin{array}{ccc} R & \xrightarrow{\rho_{\text{Poly}}} & \text{Poly}_t Y \\ t^* t_* B^* Y = \rho_{\text{Tm}} \downarrow & \lrcorner & \downarrow t_* B^* Y \\ B & \xrightarrow{t} & A \end{array}$$

By the universal property of pullbacks and proposition 0.3.2, The data of a map $\Gamma \rightarrow R$ corresponds to the data of $\beta : \Gamma \rightarrow B$ and $(t \circ \beta, y) : \Gamma \rightarrow \text{Poly}_t Y$, or just $\beta : \Gamma \rightarrow B$ and $y : \Gamma \cdot t \circ \beta \rightarrow Y$

$$\begin{array}{ccccc} & & & & (t \circ \beta, y) \\ & & & & \searrow \\ \Gamma & & & & \text{Poly}_t Y \\ & \searrow (\beta, y) & \xrightarrow{\rho_{\text{Poly}}} & & \\ & R & & & \\ & \downarrow \rho_{\text{Tm}} & \lrcorner & & \downarrow t_* B^* Y \\ & B & \xrightarrow{t} & & A \\ & \beta & & & \end{array}$$

By uniqueness in the universal property of pullbacks and proposition 0.3.2, Precomposition by a map $\sigma : \Delta \rightarrow \Gamma$ acts on such a pair by

$$\begin{array}{ccc} \Delta & & \\ \sigma \downarrow & \searrow (\beta \circ \sigma, y \circ t^* \sigma) & \\ \Gamma & \xrightarrow{(\beta, y)} & R \end{array}$$

Lemma 0.3.4 (Evaluation). Suppose $(\beta, y) : \Gamma \rightarrow R$, as in lemma 0.3.3

$$\beta : \Gamma \rightarrow B \quad \text{and} \quad y : \Gamma \cdot t \circ \beta \rightarrow Y$$

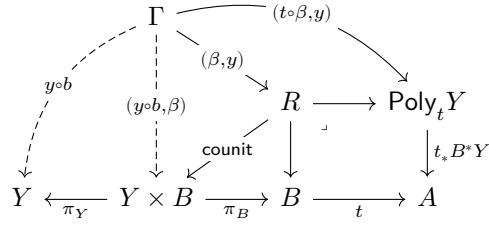
Then the evaluation of y at β can be described in the following two ways

$$y \circ b = \pi_Y \circ \text{counit} \circ (\beta, y)$$

where

$$\begin{array}{ccccc} \Gamma & & & & \beta \\ & \searrow b & & & \searrow \\ & \Gamma \cdot t \circ \beta & \xrightarrow{v} & & B \\ & \downarrow d & \lrcorner & & \downarrow t \\ & \Gamma & \xrightarrow{t \circ \beta} & & A \end{array}$$

and



Proof. It suffices to show $(\text{counit} \circ (\beta, y)) = (y \circ b, \beta)$ instead.

$$\begin{aligned}
& \text{counit} \circ (\beta, y) \\
&= \text{counit} \circ (v \circ b, y \circ t^* d \circ t^* b) && \text{fig. 1} \\
&= \text{counit} \circ (v, y \circ t^* d) \circ b && \text{lemma 0.3.3 and fig. 2} \\
&= \text{counit} \circ t^*(t \circ \beta, y) \circ b && \text{fig. 3} \\
&= \overline{(t \circ \beta, y)} \circ b && \text{fig. 4} \\
&= (y, v) \circ b && \text{fig. 5} \\
&= (y \circ b, v \circ b) \\
&= (y \circ b, \beta)
\end{aligned}$$

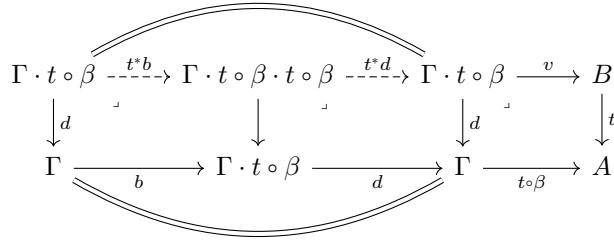


Figure 1: $t^* d \circ t^* b = \text{id}_{\Gamma \cdot t \circ \beta}$

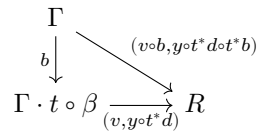
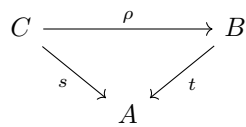


Figure 2: $(v, y \circ t^* d) \circ b = (v \circ b, y \circ t^* d \circ t^* b)$

□

Definition 0.3.5. Suppose



$$\begin{array}{ccc}
& \xrightarrow{\quad v \quad} & \\
\Gamma \cdot t \circ \beta & \xrightarrow{(v, y \circ t^* d)} R & \longrightarrow B \\
\downarrow d & \lrcorner & \downarrow t \\
\Gamma & \xrightarrow{(t \circ \beta, y)} \text{Poly}_t Y & \xrightarrow{t_* B^* Y} A \\
& \xleftarrow{\quad t \circ \beta \quad} &
\end{array}
\quad
\begin{array}{ccc}
\Gamma \cdot t \circ \beta & \xrightarrow{(t \circ \beta \circ d, y \circ t^* d)} & \text{Poly}_t Y \\
\downarrow d & \searrow & \downarrow (t \circ \beta, y)
\end{array}$$

using proposition 0.3.2 and lemma 0.3.3

Figure 3: $t^*(t \circ \beta, y) = (v, y \circ t^* d)$

$$\begin{array}{ccc}
t^*(t \circ \beta) & & t \circ \beta \\
t^*(t \circ \beta, y) \downarrow & \xrightarrow{\overline{(t \circ \beta, y)}} & (t \circ \beta, y) \downarrow \\
t^* t_* B^* Y & \xrightarrow{\text{counit}} B^* Y & t_* B^* Y \xrightarrow{\text{counit}} t_* B^* Y \\
& & \parallel \\
& & t^* \dashv t_*
\end{array}$$

Figure 4: $\text{counit} \circ t^*(t \circ \beta, y) = \overline{(t \circ \beta, y)}$

Then we have a mate $\mu_! : \rho_! \circ s^* \Rightarrow t^*$. This is given by the universal property of pullbacks: given $f : x \rightarrow y$ in the slice \mathbb{C}/A we have

$$\begin{array}{ccccc}
\bullet & \xrightarrow{\mu_! x} & \bullet & \longrightarrow & X \\
s^* f \downarrow & \lrcorner & \downarrow t^* f & \lrcorner & \downarrow f \\
\bullet & \xrightarrow{\mu_! y} & \bullet & \longrightarrow & Y \\
s^* y \downarrow & \lrcorner & \downarrow t^* y & \lrcorner & \downarrow y \\
C & \xrightarrow{\rho} & B & \xrightarrow{t} & A
\end{array}
\quad
\begin{array}{c}
\curvearrowright x \\
\leftarrow
\end{array}$$

By the calculus of mates we also have a reversed mate between the right adjoints $\mu^* : t_* \rightarrow s_* \circ \rho^*$. Explicitly μ^* is the composition

$$t_* \xrightarrow{\text{unit } t_*} s_* \rho^* \rho_! s^* t_* \xrightarrow{s_* \rho^* \mu_! t_*} s_* \rho^* t^* t_* \xrightarrow{s_* \rho^* \text{counit}} s_* \rho^*$$

Definition 0.3.6 (Poly_ action on a slice morphism). Let $\text{Poly}_- : (\mathbb{C}/A)^{\text{op}} \rightarrow [\mathbb{C}, \mathbb{C}]$ be defined by taking $s \mapsto \text{Poly}_s$ on objects and act on a morphism

$$\begin{array}{ccc}
C & \xrightarrow{\rho} & B \\
& \searrow s & \swarrow t \\
& & A
\end{array}$$

$$\begin{array}{ccc}
\Gamma \cdot t \circ \beta & \xrightarrow{(y,v)} & Y \times B \\
\downarrow v=t^*(t \circ \beta) & \swarrow B^*Y & \\
B & &
\end{array}
\quad
\begin{array}{c}
\parallel \\
t^* \dashv t_*
\end{array}
\quad
\begin{array}{ccc}
\Gamma & \xrightarrow{(t \circ \beta, y)} & \text{Poly}_t Y \\
\downarrow t \circ \beta & \swarrow t_* B^* Y & \\
A & &
\end{array}$$

Figure 5: $\overline{(t \circ \beta, y)} = (y, v)$

by $\rho \mapsto \rho^* := A_!(s_* \eta \circ \mu B^*) : \text{Poly}_t \text{tpPoly}_s$

$$\begin{array}{ccc}
\mathbb{C} & & \\
\downarrow C^* & \searrow B^* & \\
\mathbb{C}/C & \xleftarrow{\rho^*} \mathbb{C}/B & \\
\downarrow s_* & \swarrow \mu & \downarrow t_* \\
\mathbb{C}/A & & \\
\downarrow A_! & & \\
\mathbb{C} & &
\end{array}
\quad
\begin{array}{c}
\text{Poly}_s \quad \text{Poly}_t
\end{array}$$

where $\mu = \mu^*$ is the mate from definition 0.3.5, and η is the natural isomorphism given by pullback pasting.

Pointwise, this natural transformation acts on a pair $(\alpha, \beta) : \Gamma \rightarrow \text{Poly}_t X$ by

$$\begin{array}{ccc}
\Gamma & \xrightarrow{(\alpha, \beta)} & \text{Poly}_t X \\
\searrow (\alpha, \beta \circ \alpha^* \rho) & & \downarrow \rho_X^* \\
& & \text{Poly}_s X
\end{array}$$

where $\alpha^* \rho$ is defined as

$$\begin{array}{ccc}
\Gamma \cdot_s \alpha & \xrightarrow{s^* y} & C \\
\downarrow \alpha^* \rho & \lrcorner & \downarrow \rho \\
\Gamma \cdot_t \alpha & \xrightarrow{t^* y} & B \\
\downarrow & \lrcorner & \downarrow t \\
\Gamma & \xrightarrow{\alpha} & A
\end{array}$$

We prove this now.

Proof. Firstly $\rho_X^* = A_!(s_* \eta_X \circ \mu_{B^* X})$, so the first component $\alpha : \Gamma \rightarrow A$ is preserved by ρ_X^* and it suffices to show, in \mathbb{C}/A

$$\begin{array}{ccc}
\alpha & \xrightarrow{(\alpha, \beta)} & t_* B^* X \\
\searrow (\alpha, \beta \circ \alpha^* \rho) & & \downarrow s_* \eta_X \circ \mu_{B^* X} \\
& & s_* C^* X
\end{array}$$

By the adjunction $s^* \dashv s_*$, it suffices to show, in \mathbb{C}/C

$$\begin{array}{ccc} s^* \alpha & \xrightarrow{s^*(\alpha, \beta)} & s^* t_* B^* X \\ & \searrow & \downarrow \overline{s_* \eta_{X^o} \mu_{B^* X}} \\ & & C^* X \end{array}$$

Now we calculate $s_*\eta_X \circ \overline{\mu_{B^*X}} = \eta_X \circ \overline{\mu_{B^*X}}$. So that our goal is to show

$$\begin{array}{ccccc}
s^* \alpha & \xrightarrow{s^*(\alpha, \beta)} & s^* t_* B^* X & \xrightarrow{\mu_{B^* X}} & \rho^* B^* X \\
& \searrow & & \swarrow \sim & \\
& & C^* X & &
\end{array}$$

Since η_X is an isomorphism between two limits of the same diagram, namely $X \times C \cong C_! C^* X \cong C_! \rho^* B^* X$, it suffices to show that both $\overline{\mu_{B^* X}} \circ s^*(\alpha, \beta)$ and $\overline{(\alpha, \beta \circ \alpha^* \rho)}$ are uniquely determined by the same two maps into X and C .

By the characterising property of polynomial endofunctors (proposition 0.3.2) we calculate

$$\overline{(\alpha, \beta \circ \alpha^* \rho)} = (\beta \circ \alpha^* \rho, s^* \alpha)$$

$$\alpha \xrightarrow{(\alpha, \beta \circ \alpha^* \rho)} s_* C^* X \qquad \qquad \qquad s^* \alpha_{(\beta \circ \alpha^* \rho, s^* \alpha)}^{\overline{(\alpha, \beta \circ \alpha^* \rho)}} C^* X \qquad \qquad \qquad C_! s^* \alpha \xrightarrow{\beta \circ \alpha^* \rho} X$$

More formally, this means $\beta \circ \alpha^* \rho : C_1 s^* \alpha \rightarrow X$ and $s^* \alpha : C_1 s^* \alpha \rightarrow C$ are the two maps that uniquely determine the map $C_1 \alpha, \beta \circ \alpha^* \rho : C_1 s^* \alpha \rightarrow X \times C$.

On the other hand,

$$\begin{array}{c}
\alpha \xrightarrow{(\alpha, \beta)} t_* B^* X \xrightarrow{\text{unit}_{t_* B^* X}} s_* \rho^* \rho_! s^* t_* B^* X \xrightarrow{s_* \rho^* \mu_! t_* B^* X} s_* \rho^* t^* t_* B^* X \xrightarrow{s_* \rho^* \text{counit}_{B^* X}} s_* \rho^* B^* X \\
\quad \searrow \mu_{B^* X} \nearrow \\
\hline \hline s^* \dashv s_* \\
\\
s^* \alpha \xrightarrow{s^*(\alpha, \beta)} s^* t_* B^* X \xrightarrow{\overline{\text{unit}_{t_* B^* X}}} \rho^* \rho_! s^* t_* B^* X \xrightarrow{\rho^* \mu_! t_* B^* X} \rho^* t^* t_* B^* X \xrightarrow{\rho^* \text{counit}_{B^* X}} \rho^* B^* X \\
\quad \searrow \overline{\mu_{B^* X}} \nearrow \\
\hline \hline \rho_! \dashv \rho^* \\
\\
\rho_! s^* \alpha \xrightarrow{\rho_! s^*(\alpha, \beta)} \rho_! s^* t_* B^* X \xrightarrow[\equiv]{\text{unit}_{t_* B^* X}} \rho_! s^* t_* B^* X \xrightarrow{\mu_! t_* B^* X} t^* t_* B^* X \xrightarrow{\text{counit}_{B^* X}} B^* X \\
\begin{array}{ccccccc}
\parallel & & \parallel & & \parallel & & \parallel \\
\Gamma \cdot_s \alpha & & S & & R & & X \times B
\end{array}
\end{array}$$

The mate $\mu_!$ is calculated via the universal map into the pullback R (dotted below).

$$\begin{array}{ccccc}
\Gamma \cdot_s \alpha & \longrightarrow & \Gamma \cdot_t \alpha & \longrightarrow & \Gamma \\
\downarrow s^*(\alpha, \beta) & & \downarrow & & \downarrow (\alpha, \beta) \\
S & \overset{\mu_! t_* B^* X}{\dashrightarrow} & R & \longrightarrow & \text{Poly}_t X \\
\downarrow s^* t_* B^* X & & \downarrow t^* t_* B^* X & & \downarrow t_* B^* X \\
C & \xrightarrow{\rho} & B & \xrightarrow{t} & A
\end{array}$$

$\left(\begin{array}{c} \text{Left curved arrow: } s^* \alpha \\ \text{Right curved arrow: } \alpha \end{array} \right)$

Using the characterization of maps into R from lemma 0.3.3 we can calculate

$$\mu_! t_* B^* X \circ s^*(\alpha, \beta) = (\rho \circ s^* \alpha, \beta \circ t^* \alpha^* s)$$

since the first component is simply the map $\Gamma \cdot_s \alpha \rightarrow B$ and the second component is the second component of the map

$$(\alpha \circ \alpha^* s, \beta \circ t^* \alpha^* s) = (\alpha, \beta) \circ \alpha^* s : \Gamma \cdot_s \alpha \rightarrow \text{Poly}_t X$$

Then using lemma 0.3.4

$$\overline{\mu_{B^* X} \circ s^*(\alpha, \beta)} \quad (0.3.1)$$

$$= \text{counit}_{B^* X} \circ \mu_! t_* B^* X \circ s^*(\alpha, \beta) \quad (0.3.2)$$

$$= \text{counit}_{B^* X} \circ (\rho \circ s^* \alpha, \beta \circ t^* \alpha^* s) \quad (0.3.3)$$

$$= (\beta \circ t^* \alpha^* s \circ r, \rho \circ s^* \alpha) \quad (0.3.4)$$

$$= (\beta \circ \alpha^* \rho, \rho \circ s^* \alpha) \quad (0.3.5)$$

$$: \Gamma \cdot_s \alpha \rightarrow X \times B \quad (0.3.6)$$

where

$$\begin{array}{ccc}
\Gamma \cdot_s \alpha & \xrightarrow{\rho \circ s^* \alpha} & B \\
\downarrow r & \searrow & \downarrow t \\
& \Gamma \cdot_s \alpha \cdot_t \alpha \circ \alpha^* s & \\
\downarrow & \downarrow & \\
\Gamma \cdot_s \alpha & \xrightarrow{\alpha \circ \alpha^* s} & A
\end{array}$$

and

$$\left(\begin{array}{ccccc}
\Gamma \cdot_s \alpha & \xlongequal{\quad} & \Gamma \cdot_s \alpha & \xrightarrow{s^* \alpha} & C \\
\downarrow r & & \downarrow \alpha^* \rho & & \downarrow \rho \\
\Gamma \cdot_s \alpha \cdot_t \alpha \circ \alpha^* s & \dashrightarrow & \Gamma \cdot_t \alpha & \longrightarrow & B \\
\downarrow & & \downarrow & & \downarrow t \\
\Gamma \cdot_s \alpha & \xrightarrow{\alpha^* s} & \Gamma & \xrightarrow{\alpha} & A
\end{array} \right) s$$

Moving back along the adjunction $\rho_! \dashv \rho^*$ eq. (0.3.1) tells us that

$$\begin{array}{ccccc}
 \Gamma \cdot_s \alpha & \xrightarrow{s^* \alpha} & & & \\
 \searrow \overline{\mu_{B^* X} \circ s^*}(\alpha, \beta) & & X \times C & \longrightarrow & C \\
 \searrow \overline{\mu_{B^* X} \circ s^*}(\alpha, \beta) & & \downarrow \lrcorner & & \downarrow \rho \\
 & & X \times B & \longrightarrow & B \\
 & & \downarrow \lrcorner & & \downarrow \\
 & & X & \longrightarrow & 1 \\
 \nearrow \beta \circ \alpha^* \rho & & & &
 \end{array}$$

So that, as required, $\overline{\mu_{B^* X} \circ s^*}(\alpha, \beta)$ and $\overline{(\alpha, \beta \circ \alpha^* \rho)}$ are uniquely determined by the same two maps into X and C . \square

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