HoTTLean
Formalizing the Meta-Theory of HoTT in Lean
Warning: this blueprint is very outdated. Consult the GitHub README instead.

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Chapter 1

Syntax of HoTT0

For HoTT, most of the rules are standard. Here, we will go over them.

The Context Rules

$$\frac{}{\epsilon \text{ ctx}} \quad \frac{\Gamma \text{ ctx} \qquad \Gamma \vdash A \text{ type}}{\Gamma, x : A \text{ ctx}} \quad \frac{\Gamma, x : A \text{ ctx}}{\Gamma, x : A \vdash x : A} \quad \frac{\Gamma, x : A \text{ ctx} \qquad \Gamma \vdash y : B}{\Gamma, x : A \vdash y : B}$$

The Pi Rules

$$\frac{\Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \prod_{a:A} B(a) \text{ type}} \quad \frac{\Gamma, x : A \vdash b(x) : B(x)}{\Gamma \vdash \lambda(a : A).b(a) : \prod_{a:A} B(a)}$$

$$\frac{\Gamma \vdash f : \prod_{a:A} B(a) \qquad \Gamma \vdash x : A}{f(x) : B(x)} \quad \frac{\Gamma, x : A \vdash b(x) : B(x)}{\Gamma, a : A \vdash \lambda(x : A).b(x)(a) \equiv b(a) : B(a)}$$

The Sigma Rules

$$\frac{\Gamma, x : A \vdash B(x) \text{ type}}{\Gamma \vdash \sum_{a:A} B(a) \text{ type}} \quad \frac{\Gamma \vdash a : A \qquad \Gamma \vdash b : B(a)}{\Gamma \vdash \langle a, b \rangle : \sum_{x:A} B(x)}$$

$$\frac{\Gamma \vdash p : \sum_{x:A} B(x)}{\Gamma \vdash \text{fst}(p) : A} \quad \frac{\Gamma \vdash p : \sum_{x:A} B(x)}{\Gamma \vdash \text{snd}(p) : B(\text{fst}(p))}$$

$$\frac{\Gamma \vdash a : A \qquad \Gamma \vdash b : B(a)}{\Gamma \vdash \text{fst}(\langle a, b \rangle) \equiv a : A} \quad \frac{\Gamma \vdash a : A \qquad \Gamma \vdash b : B(a)}{\Gamma \vdash \text{snd}(\langle a, b \rangle) \equiv b : B(a)}$$

The Id Rules

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

$$\frac{\Gamma, x : A, y : A, u : \text{Id}_A(x, y) \vdash C(x, y, u) \text{ type} \qquad \Gamma, x : A \vdash c(x) : C(x, x, \text{refl}(x))}{\Gamma, x : A, y : A, u : \text{Id}_A(x, y) \vdash \text{J}(x, y, u, c) : C(x, y, u)}$$

The Universe

$$\frac{\Gamma \text{ ctx}}{\Gamma \vdash \text{U type}} \quad \frac{\Gamma \vdash a : \text{U}}{\Gamma \vdash \text{El}(a) \text{ type}}$$

$$\frac{\Gamma, a : \mathrm{U}, x : \mathrm{El}(a) \vdash b(x) : \mathrm{U}}{\Gamma, a : \mathrm{U} \vdash \pi(a, b(x)) : \mathrm{U}} \qquad \frac{\Gamma, a : \mathrm{U}, x : \mathrm{El}(a) \vdash b(x) : \mathrm{U}}{\Gamma, a : \mathrm{U} \vdash \sigma(a, b(x)) : \mathrm{U}} \qquad \frac{\Gamma, a : \mathrm{U} \vdash \alpha : \mathrm{El}(a) \qquad \Gamma, a : \mathrm{U} \vdash \beta : \mathrm{El}(a)}{\Gamma, a : \mathrm{U} \vdash \iota(\alpha, \beta) : \mathrm{U}}$$

$$\frac{\Gamma, a : \mathrm{U}, x : \mathrm{El}(a) \vdash b(x) : \mathrm{U}}{\Gamma, a : \mathrm{U} \vdash \mathrm{El}(\pi(a, b(x))) \equiv \prod_{x:\mathrm{El}(a)} \mathrm{El}(b(x)) \text{ type}} \qquad \frac{\Gamma, a : \mathrm{U}, x : \mathrm{El}(a) \vdash b(x) : \mathrm{U}}{\Gamma, a : \mathrm{U} \vdash \mathrm{El}(\sigma(a, b(x))) \equiv \sum_{x:\mathrm{El}(a)} \mathrm{El}(b(x)) \text{ type}}$$

Definitions and Axioms

To simplify, we denote non-dependent products and functions with $\times$ and $\to$. This is not part of the type theory but improves readability.

Truncation Levels

$$\begin{aligned} \mathrm{isContr}(A) &:= \sum_{x:A} \prod_{y:A} \mathrm{id}_A(y, x) \\ \mathrm{isProp}(A) &:= \prod_{x:A} \prod_{y:A} \mathrm{id}_A(x, y) \\ \mathrm{isSet}(A) &:= \prod_{x:A} \prod_{y:A} \mathrm{isProp}(\mathrm{Id}_A(x, y)) \end{aligned}$$

The Set Universe

$$\mathrm{Set} := \sum_{u:\mathrm{U}} \mathrm{isSet}(\mathrm{El}(u))$$

Type Equivalence

$$A \simeq B := \sum_{f:A\to B} \sum_{g:B\to A} \sum_{h:B\to A} \Big(\prod_{a:A} \mathrm{id}_A(g(f(a)), a) \Big) \times \Big(\prod_{b:B} \mathrm{id}_B(f(h(b)), b) \Big)$$

Set Isomorphism

$$A \cong B := \mathrm{isSet}(A) \times \mathrm{isSet}(B) \times \sum_{f:A\to B} \sum_{g:B\to A} \Big(\prod_{a:A} \mathrm{id}_A(g(f(a)), a) \Big) \times \Big(\prod_{b:B} \mathrm{id}_B(f(g(b)), b) \Big)$$

The Univalence Axiom

$$\mathrm{UA} : \prod_{x:\mathrm{U}} \prod_{y:\mathrm{U}} \mathrm{Id}_{\mathrm{U}}(x, y) \simeq \Big(\mathrm{El}(x) \simeq \mathrm{El}(y) \Big)$$

The Univalence Axiom for Sets

$$\mathrm{UASet} : \prod_{x:\mathrm{Set}} \prod_{y:\mathrm{Set}} \mathrm{Id}_{\mathrm{Set}}(x, y) \cong \Big(\mathrm{El}(x) \cong \mathrm{El}(y) \Big)$$

Function Extensionality

$$\mathrm{FunExt} : \prod_{a:\mathrm{U}} \prod_{b:\mathrm{U}} \prod_{f:\mathrm{El}(a)\to\mathrm{El}(b)} \prod_{g:\mathrm{El}(a)\to\mathrm{El}(b)} \Big(\prod_{\alpha:\mathrm{El}(a)} \mathrm{id}_{\mathrm{El(b)}}(f\alpha, g\alpha) \Big) \simeq \mathrm{id}_{\mathrm{El}(a)\to\mathrm{El}(b)}(f, g)$$

Chapter 2

Natural Models

In this chapter we describe the categorical semantics of our syntax via natural models. It follows previous work on natural models [Awo17], with the following additional features

1. A more compact description of identity types exploiting the technology of polynomial endofunctors.
2. A collection of N Russell-style nested universes.
3. universe-variable Π-types and Σ-types, i.e. with possibly different universe level inputs, and landing in the largest universe (imitating the type theory of `Lean4`).

2.1 Interpretation of syntax

A very brief overview of the interpretation of syntax follows. We work in a presheaf category $\mathbf{Psh}(\mathbb{C})$. A context Γ is interpreted as an object $[\![\Gamma]\!] \in \mathbb{C}$. We often take the image of the context under the Yoneda embedding $\mathsf{y}[\![\Gamma]\!] \in \mathbf{Psh}(\mathbb{C})$. If $i \leq N$ is a universe level, then a typing judgment $\Gamma \vdash_i a : A$ is interpreted as a commuting triangle of the following form

$$\begin{array}{ccc} & & \mathsf{Tm}_i \\ & \overset{[\![a]\!]}{\nearrow} & \downarrow \mathsf{tp}_i \\ \mathsf{y}[\![\Gamma]\!] & \xrightarrow[{[\![A]\!]}]{} & \mathsf{Ty}_i \end{array}$$

2.2 Natural model

Fix a small category $\mathbb{C}$.

Definition 2.2.1 (Natural model)**.** Following Awodey [Awo17], we say that a map $\mathsf{tp} : \mathsf{Tm} \to \mathsf{Ty}$ in $\mathbf{Psh}(\mathbb{C})$ is *fiberwise representable* or a *natural model* when every fiber is representable. In other words, given any $\Gamma \in \mathbb{C}$ and any map $A : \mathsf{y}(\Gamma) \to \mathsf{Ty}$, there is some representable $\Gamma \cdot A \in \mathbb{C}$ and maps $\mathsf{disp}_A : \Gamma \cdot A \to \Gamma$ and $\mathsf{var}_A : \mathsf{y}(\Gamma \cdot A) \to \mathsf{Tm}$ forming a pullback

$$\begin{array}{ccc} \mathsf{y}(\Gamma \cdot A) & \xrightarrow{\mathsf{var}_A} & \mathsf{Tm} \\ {\scriptstyle \mathsf{y}(\mathsf{disp}_A)}\downarrow & \lrcorner & \downarrow{\scriptstyle \mathsf{tp}} \\ \mathsf{y}(\Gamma) & \xrightarrow[A]{} & \mathsf{Ty} \end{array}$$

Definition 2.2.2 (Russell universes)**.** A collection of $N+1$ natural models with N Russell style universes and lifts consists of

- For each $i \leq N$ a natural model $\mathsf{tp}_i : \mathsf{Tm}_i \to \mathsf{Ty}_i$
- For each $i < N$ a lift $\mathsf{L}_i^{i+1} : \mathsf{Ty}_i \to \mathsf{Ty}_{i+1}$
- For each $i < N$ a point $\mathsf{U}_i : 1 \to \mathsf{Ty}_{i+1}$ such that

$$\begin{array}{ccccc} \mathsf{Ty}_i & \cong & 1 \cdot \mathsf{U}_i & \longrightarrow & \mathsf{Tm}_{i+1} \\ & & \downarrow & \lrcorner & \downarrow{\scriptstyle \mathsf{tp}_{i+1}} \\ & & 1 & \xrightarrow[\mathsf{U}_i]{} & \mathsf{Ty}_{i+1} \end{array}$$

2.3 Product types

Definition 2.3.1. We will use P_{tp_i} to denote the polynomial endofunctor 5.0.1 associated with a natural model tp_i. Then additional structure of Π types on our N universes consists of, for each $i, j \leq N$, a pullback square

$$\begin{array}{ccc} P_{\mathsf{tp}_i}\mathsf{Tm}_j & \xrightarrow{\lambda} & \mathsf{Tm}_{\max(i,j)} \\ {\scriptstyle P_{\mathsf{tp}_i}\mathsf{tp}_j}\downarrow & \lrcorner & \downarrow{\scriptstyle \mathsf{tp}_{\max(i,j)}} \\ P_{\mathsf{tp}_i}\mathsf{Ty}_j & \xrightarrow[\Pi]{} & \mathsf{Ty}_{\max(i,j)} \end{array} \tag{2.3.1}$$

2.4 Sum types

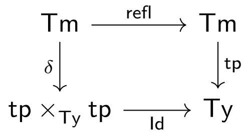
Definition 2.4.1.

We will use the polynomial composition of two maps 5.0.6, $\mathsf{tp}_i \lhd \mathsf{tp}_j : Q \to P_{\mathsf{tp}_i}(\mathsf{Ty}_j)$. Then additional structure of Σ types on our N universes consists of, for each $i, j \leq N$, a pullback square

$$\begin{array}{ccc} Q & \xrightarrow{\mathsf{pair}} & \mathsf{Tm}_{\max(i,j)} \\ {\scriptstyle \mathsf{tp}_i \lhd \mathsf{tp}_j}\downarrow & \lrcorner & \downarrow{\scriptstyle \mathsf{tp}_{\max(i,j)}} \\ P_{\mathsf{tp}_i}\mathsf{Ty}_j & \xrightarrow[\Sigma]{} & \mathsf{Ty}_{\max(i,j)} \end{array} \tag{2.4.1}$$

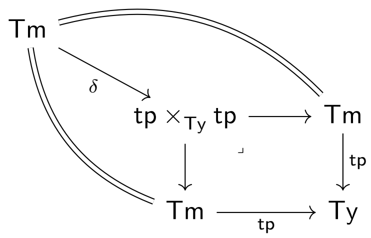
2.5 Identity types

Definition 2.5.1. Suppose $\mathsf{tp} : \mathsf{Tm} \to \mathsf{Ty}$ is a natural model and we have a commutative square (this need not be a pullback)

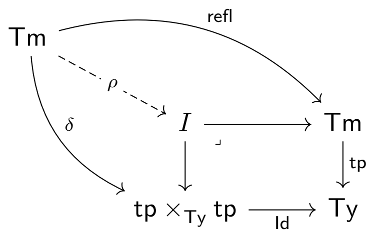


(2.5.1)

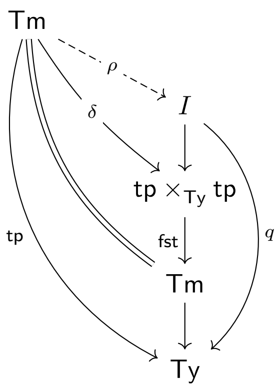
where δ is the diagonal:



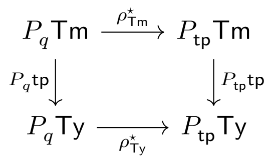
Then let I be the pullback. We get a comparison map ρ



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

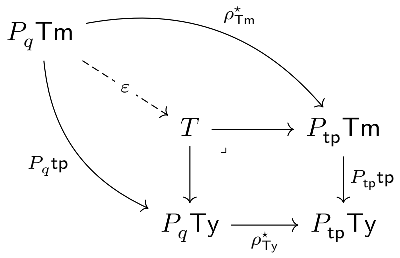


Now (by 5.0.8) applying $P_{\_} : (\mathbf{Psh}(\mathbb{C})/\mathsf{Ty})^{\mathrm{op}} \to [\mathbf{Psh}(\mathbb{C}), \mathbf{Psh}(\mathbb{C})]$ to $\rho : \mathsf{tp} \to q$ gives us a naturality square (this also need not be a pullback).



(2.5.2)

Taking the pullback T and the comparison map ε we have



(2.5.3)

Then a natural model tp with identity types consists of a commutative square 2.5.1, with a section $\mathsf{J} : T \to P_q\mathsf{Tm}$ of ε.

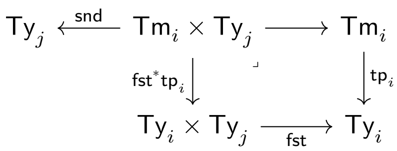
2.6 Binary products and Exponentials

It is convenient to specialize Σ and Π types to their non-dependent counterparts $\times$ and Exp.

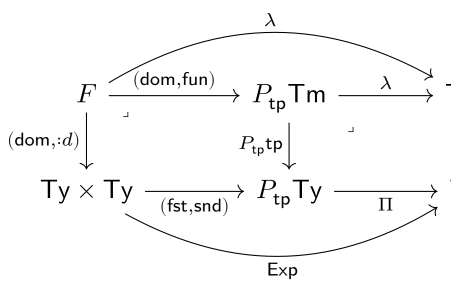
Definition 2.6.1 (Products and exponentials)**.** In the natural model we can construct these by considering first the map

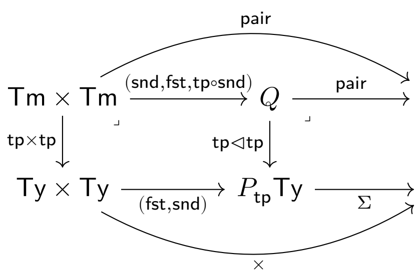
$$(\mathsf{fst}, \mathsf{snd}) : \mathsf{Ty}_i \times \mathsf{Ty}_j \to P_{\mathsf{tp}_i}\mathsf{Ty}_j$$

defined using the characterising property of polynomials 5.0.2, which we can visualize in

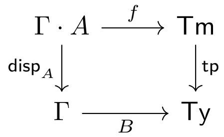


Then, respectively, the pullback of the diagrams 2.3.1 and 2.4.1 for interpreting Π and Σ rules along this map give us pullback diagrams for interpreting function types and product types. (We simplify the situation to where $i = j$.)

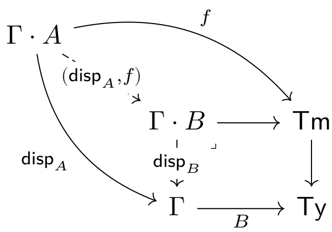




By the universal property of pullbacks and 5.0.2 we can write a map $\Gamma \to F$ as a triple (A, B, f) such that $A, B : \Gamma \to \mathsf{Ty}$ and

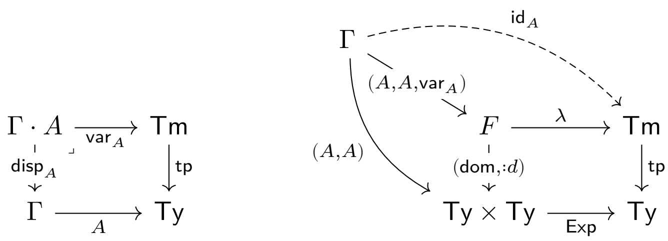


This gives us four equivalent ways we can view a function. Namely, as $f : \Gamma \cdot A \to \mathsf{Tm}$ in the above diagram, $\lambda \circ f : \Gamma \to \mathsf{Tm}$, as $(A, B, f) : \Gamma \to F$, or as a map between the displays $\mathsf{disp}_A \to \mathsf{disp}_B$

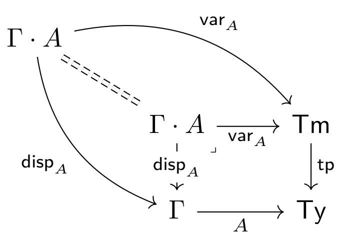


For the formalization, we need not prove that the pullback of $\mathsf{tp} \triangleleft \mathsf{tp}$ is $\mathsf{tp} \times \mathsf{tp}$. Rather, we can also use the universal property of pullbacks and 5.0.2 to classify a map into the pullback (whatever it may be) as a pair (α, β), where $\alpha, \beta : \Gamma \to \mathsf{Tm}$. This could then be adapted to a proof that the pullback is what the diagram claims it to be.

Definition 2.6.2. The identity function $\mathsf{id}_A : \Gamma \to \mathsf{Tm}$ of type $\mathsf{Exp} \circ (A, A) : \Gamma \to \mathsf{Ty}$ can be defined by the following



Viewed as a map between the display maps, this is simply the identity $\Gamma \cdot A \to \Gamma \cdot A$.



Composition is also simplest when viewed as an operation on maps between fibers. Given $f : \mathsf{disp}_A \to \mathsf{disp}_B$ and $g : \mathsf{disp}_B \to \mathsf{disp}_C$, the composition is $g \circ f : \mathsf{disp}_A \to \mathsf{disp}_C$.

2.7 Univalence

For two types $A, B : \Gamma \to \mathsf{Ty}$ and two functions $f, g : A \to B$ we can define internally a *homotopy* from f to g as

$$f \sim g := \Pi_{a:A} \, \mathsf{Id}(f\, a, g\, a)$$

We define the types of left and right inverses of $f : A \to B$ as

$$\mathsf{BigLinv} f := \Sigma_{g:B\to A}\, g \circ f \sim \mathsf{id}_A$$

$$\mathsf{BigRinv} f := \Sigma_{g:B\to A}\, f \circ g \sim \mathsf{id}_B$$

and the property of being an equivalence

$$\mathsf{IsBigEquiv} f := \mathsf{BigLinv} f \times \mathsf{BigRinv} f$$

We could do the same for two small types $A, B : \Gamma \to \mathsf{U}$

$$\mathsf{IsEquiv} f := \mathsf{Linv} f \times \mathsf{Rinv} f$$

$$\mathsf{Equiv} A\, B := \Sigma_{f:A\to B} \mathsf{IsEquiv} f$$

Again, internally we can define a function

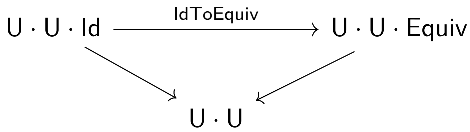
$$\mathsf{IdToEquiv} A\, B : \mathsf{Id}(A, B) \to \mathsf{Equiv} A\, B$$

which uses J to transport along the proof of equality to produce an equivalence.

Definition 2.7.1. Univalence for universe U states that $\mathsf{IdToEquiv}$ itself is an equivalence

$$\mathsf{ua} : \mathsf{IsBigEquiv}(\mathsf{IdToEquiv} A\, B)$$

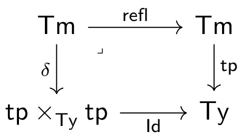
Note that this statement is large, i.e. not a type in the universe U.



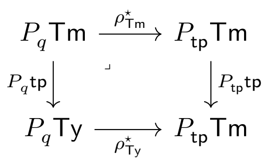
2.8 Extensional identity types and UIP

In this section we outline variations on the identity type in the natural model. We will describe these as additional structure on Id, as opposed to introducing different identity types.

Definition 2.8.1 (Extensional types)**.** The first option is fully extensional identity types, i.e. those satisfying equality reflection and uniqueness of identity proofs (UIP). Equality reflection says that if one can construct a term satisfying $\mathsf{Id}(a, b)$ then we have that definitionally $a \equiv b$, i.e. they are equal morphisms in the natural model. This amounts to just requiring that 2.5.1 is a pullback, i.e. ρ is an isomorphism



Note that this means $\rho^\star$ is an isomorphism, from which it follows that 2.5.2 is also a pullback, i.e. ε is an isomorphism.



We could only require UIP:

Definition 2.8.2 (Identity types satisfying UIP)**.** Say an identity type in a natural model satisfies UIP if $I \to \mathsf{tp} \times_{\mathsf{Ty}} \mathsf{tp}$ is a strict proposition, meaning for any $(a, b) : \Gamma \to \mathsf{tp} \times_{\mathsf{Ty}} \mathsf{tp}$ there it at most one lift

$$\begin{array}{ccc} & & I \\ & \overset{!}{\nearrow} & \downarrow \\ \Gamma & \xrightarrow[(a,b)]{} & \mathsf{tp} \times_{\mathsf{Ty}} \mathsf{tp} \end{array}$$

One might wonder what other variations we could come up with by tweaking the pullback conditions. In fact, only requiring that ρ has a section is equivalent to requiring that ρ is an isomorphism. So this just the extensional case again.

If we require instead that ε is an isomorphism then this is giving an η-rule for J, from which we can prove equality reflection and UIP [Hof95]. So this just the extensional case again.

Chapter 3

HoTT0 interpreted in natural models

Chapter 4

The Groupoid Model

In this chapter we construct a natural model in **Psh**(**grpd**) the presheaf category indexed by the category **grpd** 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 **grpd** - which comes from restricting the "classical Quillen model structure" on **cat** [Joy] to **grpd**.

4.1 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 the (large, locally small) category of small groupoids, which we will denote by

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

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

Definition 4.1.1 (Pointed)**.** We will take the category of pointed small categories $\mathbf{cat}_\bullet$ to have objects as pairs $(\mathbb{C} \in \mathbf{cat}, c \in \mathbb{C})$ and morphisms as pairs

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

Then the category of pointed small groupoids $\mathbf{grpd}_\bullet$ will be the full subcategory of objects (Γ, c) with Γ a groupoid.

Definition 4.1.2 (The display map classifier)**.** We would like to define a natural transformation in **Psh**(**grpd**)

$$\mathsf{tp} : \mathsf{Tm} \to \mathsf{Ty}$$

with representable fibers.

Consider the functor that forgets the point

$$U : \mathbf{grpd}_\bullet \to \mathbf{grpd} \qquad \text{in} \qquad \mathbf{Cat}.$$

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

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

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

$$\begin{array}{ccccc} \mathbf{Cat} & \xrightarrow{\mathsf{y}} & \mathbf{Psh}(\mathbf{Cat}) & \xrightarrow{\mathsf{res}} & \mathbf{Psh}(\mathbf{grpd}) \\ \mathbf{grpd} & \longmapsto & [-, \mathbf{grpd}] & \longmapsto & \mathsf{Ty} \end{array}$$

Note that Tm and Ty are not representable in $\mathbf{Psh}(\mathbf{grpd})$.

Remark 4.1.3. By Yoneda we can identify maps with representable domain into the type classifier

$$A : \mathsf{y}\Gamma \to \mathsf{Ty} \qquad \text{in} \qquad \mathbf{Psh}(\mathbf{grpd})$$

with functors

$$A : \Gamma \to \mathbf{grpd} \qquad \text{in} \qquad \mathbf{Cat}$$

Definition 4.1.4 (Grothendieck construction)**.** From $\mathbb{C}$ a small category and $F : \mathbb{C} \to \mathbf{cat}$ 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 $(f : c \to d, \phi : F\,f\,x \to y)$. This makes the following pullback in **Cat**

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

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

Definition 4.1.5 (Grothendieck construction for groupoids)**.** Let Γ be a groupoid and $A : \Gamma \to \mathbf{grpd}$ a functor, we can compose F with the inclusion $i : \mathbf{grpd} \hookrightarrow \mathbf{Cat}$ and form the Grothendieck construction which we denote as

$$\Gamma \cdot A := \int i \circ A \qquad \mathsf{disp}_A : \Gamma \cdot A \to \Gamma$$

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.

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

Corollary 4.1.6 (The display map classifier is presentable)**.** *For any small groupoid* Γ *and* $A : \mathsf{y}\Gamma \to \mathsf{Ty}$*, the pullback of* tp *along* A *can be given by the representable map* ydisp_A*.*

$$\begin{array}{ccc} \mathsf{y}\Gamma \cdot A & \longrightarrow & \mathsf{Tm} \\ {\scriptstyle \mathsf{ydisp}_A}\downarrow & \lrcorner & \downarrow{\scriptstyle \mathsf{tp}} \\ \mathsf{y}\Gamma & \xrightarrow[A]{} & \mathsf{Ty} \end{array}$$

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 $\mathsf{res} \circ \mathsf{y}$ in the following

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

The Yoneda embedding $\mathsf{y} : \mathbf{Cat} \to \mathbf{Psh}(\mathbf{Cat})$ preserves pullbacks, as does res since it is a right adjoint (with left Kan extension $\iota_! \dashv \mathsf{res}_\iota$). ☐

4.2 Groupoid fibrations

Definition 4.2.1 (Fibration)**.** Let $p : \mathbb{C}_1 \to \mathbb{C}_0$ be a functor. We say p is a *split Grothendieck fibration* if we have a dependent function $\mathsf{lift}\, a\, f$ satisfying the following: for any object a in $\mathbb{C}_1$ and morphism $f : p\, a \to y$ in the base $\mathbb{C}_0$ we have $\mathsf{lift}\, a\, f : a \to b$ in $\mathbb{C}_1$ such that $p(\mathsf{lift}\, a\, f) = f$ and moreover $\mathsf{lift}\, a\, g \circ f = \mathsf{lift}\, b\, g \circ \mathsf{lift}\, a\, f$

$$\begin{array}{ccc} a & \overset{\mathsf{lift}\, a\, f}{\dashrightarrow} & b \\ \downarrow & \Downarrow & \downarrow \\ x & \xrightarrow[f]{} & y \end{array}$$

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 Fib_Γ, which is a full subcategory of the slice $\mathbf{grpd}/\Gamma$. We will decorate an arrow with $\twoheadrightarrow$ to indicate it is a fibration.

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

Proposition 4.2.2. *There is an adjoint equivalence*

$$[\Gamma, \mathbf{grpd}] \underset{\mathsf{fiber}}{\overset{\mathsf{disp}}{\underset{\longleftarrow}{\overset{\longrightarrow}{\simeq}}}} \mathsf{Fib}_\Gamma$$

where for each fibration $\delta : \Delta \to \Gamma$ and each object $x \in \Gamma$ the fiber $\mathsf{fiber}_\delta\, x$ has objects

$$\{a \in \Delta \mid \delta\, a = x\}$$

and morphisms $f : a \to b$ from Δ such that $\delta\, f = \mathsf{id}_x$. It follows that all fibrations are pullbacks of the classifier $U : \mathbf{grpd}_\bullet \to \mathbf{grpd}$, when viewed as morphisms in **Cat**.

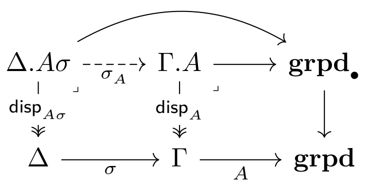
Pullback of fibrations along groupoid functors is not strictly coherent, in the sense that for $\tau : \Xi \to \Delta$ and $\sigma : \Delta \to \Gamma$ and a fibration $p \in \mathsf{Fib}_\Gamma$ we only have an isomorphism

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

rather than equality.

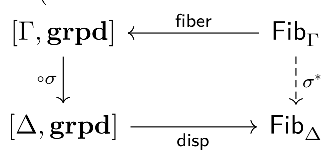
In order to interpret reindexing/substitution strictly, it is convenient to work with classifiers $[\Gamma, \mathbf{grpd}]$ instead of fibrations.

Proposition 4.2.3 (Strictly coherent pullback)**.** *Let $\sigma : \Delta \to \Gamma$ be a functor between groupoids. Since display maps are pullbacks of the classifier $U : \mathbf{grpd}_\bullet \to \mathbf{grpd}$ we have the pasting diagram*



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

Corollary 4.2.4 (Fibrations are stable under pullback)**.**



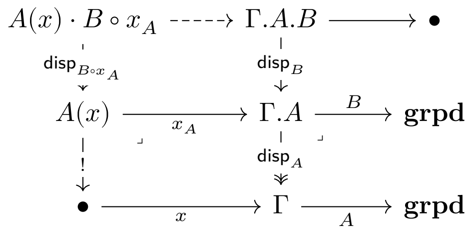
We can deduce a corresponding fact about fibrations: since fibrations are closed under isomorphism, and since any pullback in **grpd** *of a fibration p is isomorphic to the display map $\mathsf{disp}_{\mathsf{fiber}\,p \circ \sigma}$, any pullback of a fibration is a fibration.*

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 4.2.5 (Σ-former operation)**.** Then given $A : \Gamma \to \mathbf{grpd}$ and $B : \Gamma \cdot A \to \mathbf{grpd}$ we define $\Sigma_A B : \Gamma \to \mathbf{grpd}$ 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 $x_A : A(x) \to \Gamma \cdot A$ takes $f : a_0 \to a_1$ to $(\mathsf{id}_x, f) : (x, a_0) \to (x, a_1)$



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

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

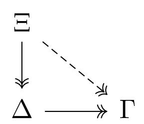
and for morphism $(\alpha : a_0 \to a_1 \in A(x), \beta : B\, (\mathsf{id}_x, \alpha)\, b_0 \to b_1 \in B(x, a_1))$ in $\Sigma_A B\, x$

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

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

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

Proposition 4.2.6 (Fibrations are closed under composition)**.** *The corresponding fact about fibrations is that the composition of two fibrations is a fibration.*



We can compare the two fibrations

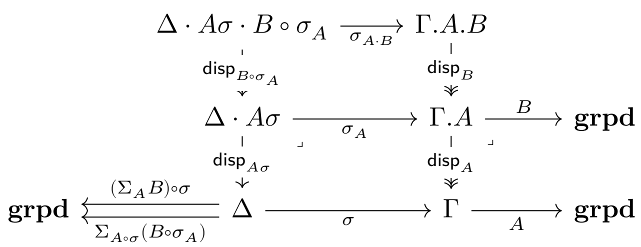
$$\mathsf{disp}_B \circ \mathsf{disp}_A \qquad \text{and} \qquad \mathsf{disp}_{\Sigma_A(B)}$$

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

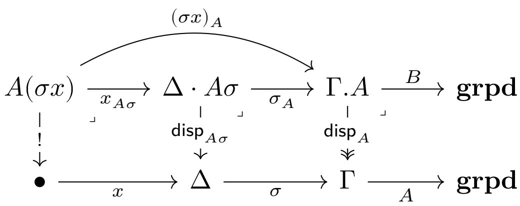
$$(\Sigma_A B) \circ \sigma = \Sigma_{A \circ \sigma}(B \circ \sigma_A)$$

where σ_A *is uniquely determined by the pullback in*



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

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



which holds because of the universal property of pullback. □

Definition 4.2.8 (Π-former operation)**.** Given $A : \Gamma \to \mathbf{grpd}$ and $B : \Gamma \cdot A \to \mathbf{grpd}$ we will define $\Pi_A B : \Gamma \to \mathbf{grpd}$ such that for any $C : \Gamma \to \mathbf{grpd}$ we have an isomorphism

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

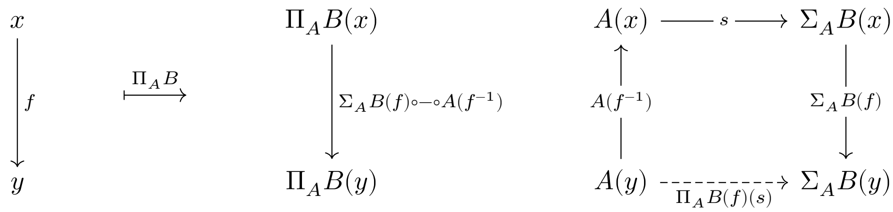
natural in both B and C.

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

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

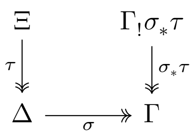
Where we have taken the full subcategory of the functor category $[A(x), \Sigma_A B(x)]$. This is a groupoid since any natural transformation of functors into groupoids are natural isomorphisms.

$\Pi_A B$ acts on morphisms via conjugation



Note that conjugation is functorial and invertible. □

Corollary 4.2.9 (Fibrations are closed under pushforward)**.** *Stated in terms of fibrations, we have*



with the universal property of pushforward

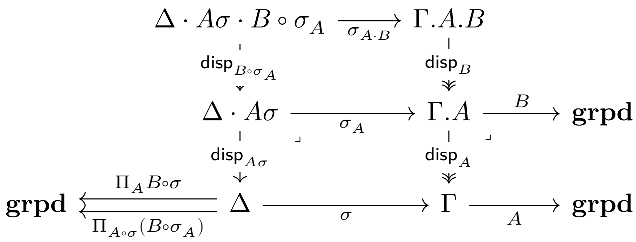
$$\mathsf{Fib}_\Delta(\sigma^* \rho, \tau) \cong \mathsf{Fib}_\Gamma(\rho, \sigma_* \tau)$$

natural in both τ and ρ.

Proposition 4.2.10 (Strict Beck-Chevalley for Π)**.** *Let* $\sigma : \Delta \to \Gamma$*,* $A : \Gamma \to \mathbf{grpd}$ *and* $B : \Gamma \cdot A \to \mathbf{grpd}$*. Then*

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

where σ_A *is uniquely determined by the pullback in*

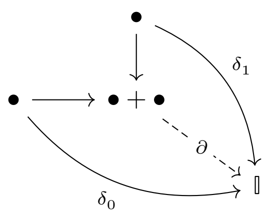


Proof. By checking pointwise, this boils down to Beck-Chevalley for Σ. □

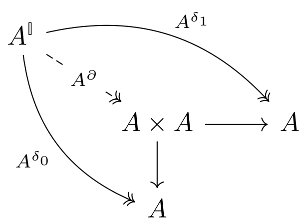
Proposition 4.2.11 (All objects are fibrant)**.** *Let* $\bullet$ *denote the terminal groupoid, namely that with a single object and morphism. Then the unique map* $\Gamma \to \bullet$ *is a fibration.*

Definition 4.2.12 (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 $\delta_0, \delta_1 : \bullet \to \mathbb{I}$ 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 $! : \mathbb{I} \to \bullet$.

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

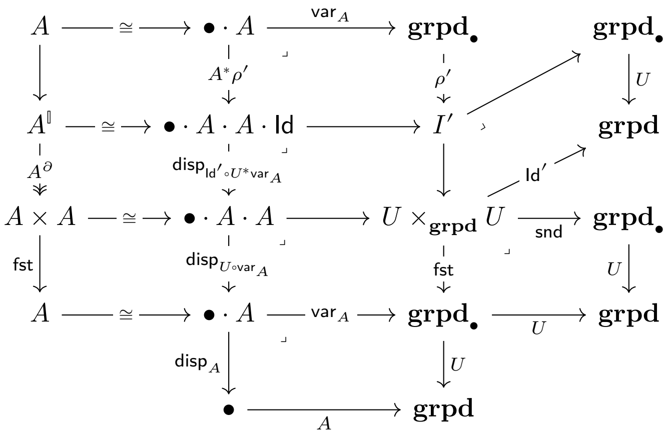


Proposition 4.2.13 (Path object fibration)**.** *Let* A *be a small groupoid. Recall that* **grpd** *is Cartesian closed, so we can take the image of the above diagram under the functor* A^-*.*



Then the indicated morphisms are fibrations, and $A^{\delta_0}, A^{\delta_1}$ *form adjoint equivalences with* $A^! : A \to A^{\mathbb{I}}$*.*

We can use this to justify the interpretation of the identity type later, where we will have the strictified versions (as in strictly stable under substitution) of the above



In general, we will want to build a pathspace for a type in any context, which requires us to pull back the interval along the context, and rebuild the required fibration by exponentiation in the slice.

4.3 Classifying type dependency

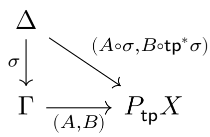
Proposition 4.3.1 (P_{tp} classifies type dependency)**.** *Specialized to* $\mathsf{tp} : \mathsf{Tm} \to \mathsf{Ty}$ *in* $\mathbf{Psh}(\mathbf{grpd})$*, the characterizing property of polynomial endofunctors 5.0.2 says that a map from a representable* $\Gamma \to P_{\mathsf{tp}}X$ *corresponds to the data of*

$$A : \Gamma \to \mathsf{Ty} \qquad \textit{and} \qquad B : \Gamma \cdot A \to X$$

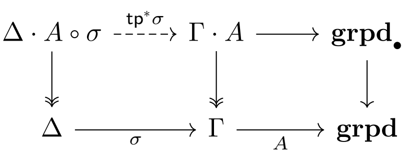
The special case of when X *is also* Ty *gives us a classifier for dependent types; by Yoneda the above corresponds to the data in* $\mathbf{Cat}$ *of*

$$A : \Gamma \to \mathbf{grpd} \qquad \textit{and} \qquad B : \Gamma \cdot A \to \mathbf{grpd}$$

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



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



4.4 Pi and Sigma structure

Lemma 4.4.1. $X \in \mathbf{Psh}(\mathbf{grpd})$ *be a presheaf. Let* F *be an operation that takes a groupoid* Γ*, a functor* $A : \Gamma \to \mathbf{grpd}$ *and* $B : \Gamma \cdot A \to X$ *and returns a natural transformation* $F_A B : \Gamma \to X$*.*

Then using Yoneda to define $\tilde{F} : P_{\mathsf{tp}}X \to X$ *pointwise as*

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

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

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

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

Proof. Using 4.3.1

$$\begin{array}{ccc} (A, B) & \longmapsto & F_A B \\ \downarrow & \begin{array}{ccc} \mathbf{Psh}(\mathbf{grpd})(\Gamma, P_{\mathsf{tp}}X) & \xrightarrow{\tilde{F}_\Gamma} & \mathbf{Psh}(\mathbf{grpd})(\Gamma, X) \\ {\scriptstyle -\circ\sigma}\downarrow & & \downarrow{\scriptstyle -\circ\sigma} \\ \mathbf{Psh}(\mathbf{grpd})(\Delta, P_{\mathsf{tp}}X) & \xrightarrow[\tilde{F}_\Delta]{} & \mathbf{Psh}(\mathbf{grpd})(\Delta, X) \end{array} & \downarrow \\ (A \circ \sigma, B \circ \mathsf{tp}^*\sigma) & \longmapsto & F_{A\circ\sigma} B \circ \mathsf{tp}^*\sigma = (F_A B) \circ \sigma \end{array}$$

□

Definition 4.4.2 (Interpretation of Π types)**.** We define the natural transformation $\Pi : P_{\mathsf{tp}}\mathsf{Ty} \to \mathsf{Ty}$ as that which is induced (4.4.1) by the Π-former operation (4.2.8).

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

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

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

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

where $\eta : \Pi_A B\, f\, s_x \to s_y$ is a natural isomorphism between functors $A_y \to (\Sigma_A B)_y$ defined on objects $a \in A_y$ by

$$\eta_a := (\mathsf{id}_{Afa}, b(f, \mathsf{id}_{Afa}))$$

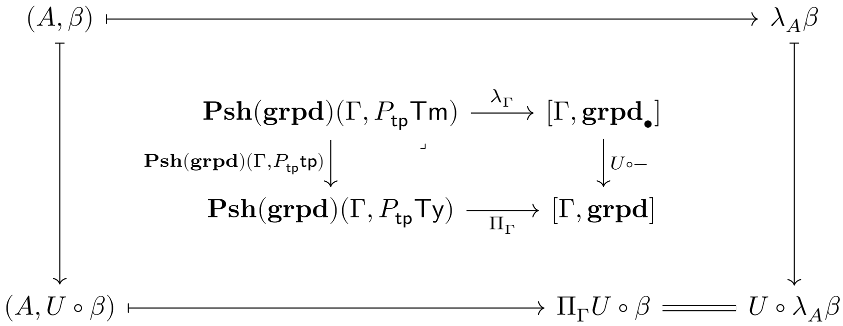
and where $b(f, \mathsf{id}_{Afa}) : B(f, \mathsf{id}_{Afa})(b(x, a)) \to b(y, Afa)$ is the morphism in $B(y, Afa)$ induced by the map between pointed groupoids $\beta(f, \mathsf{id}_{Afa})$.

These combine to give us a pullback square

$$\begin{array}{ccc} P_{\mathsf{tp}}\mathsf{Tm} & \xrightarrow{\lambda} & \mathsf{Tm} \\ {\scriptstyle P_{\mathsf{tp}}\mathsf{tp}}\downarrow & \lrcorner & \downarrow{\scriptstyle \mathsf{tp}} \\ P_{\mathsf{tp}}\mathsf{Ty} & \xrightarrow[\Pi]{} & \mathsf{Ty} \end{array}$$

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 it pointwise commutes and pointwise gives pullbacks, i.e. for each groupoid Γ



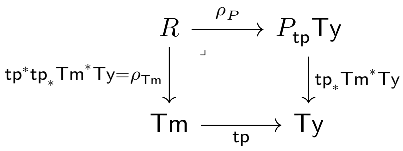
where we have used 4.3.1. That this commutes follows from the definitions of Π and λ.

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

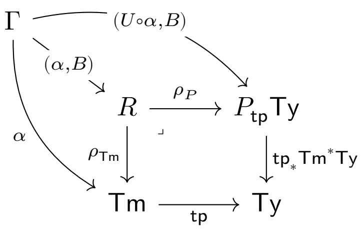
$$\begin{aligned} \beta : \Gamma \cdot A &\to \mathbf{grpd}_\bullet \\ (x, a) &\mapsto (B(x, a), f\, x\, a) \end{aligned}$$

□

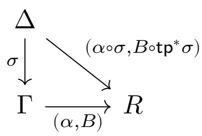
Lemma 4.4.3. *This is a specialization of 5.0.3. Use R to denote the fiber product*



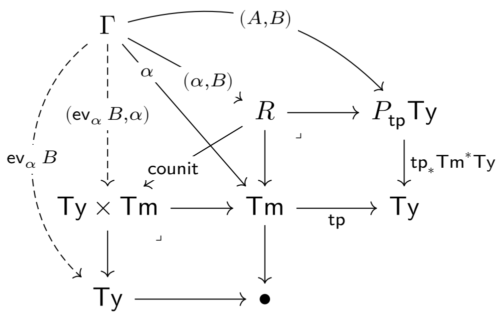
By the universal property of pullbacks, The data of a map from a representable $\varepsilon : \Gamma \to R$ corresponds to the data of $\alpha : \Gamma \to \mathsf{Tm}$ and $(U \circ \alpha, B) : \Gamma \to P_{\mathsf{tp}}\mathsf{Ty}$. Then by 4.3.1 this corresponds to the data of $\alpha : \Gamma \to \mathsf{Tm}$ and $B : \Gamma \cdot U \circ \alpha \to \mathsf{Ty}$.



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



Definition 4.4.4 (Evaluation)**.** Define the operation of evaluation $\mathsf{ev}_\alpha B$ to take $\alpha : \Gamma \to \mathbf{grpd}_\bullet$ and $B : \Gamma \cdot U \circ \alpha \to \mathbf{grpd}$ and return $\mathsf{ev}_\alpha B : \Gamma \to \mathbf{grpd}$, described below.



where we write $A := U \circ \alpha$ and treat a map $\Gamma \to \mathbf{grpd}$ as the same as a map $\Gamma \to \mathsf{Ty}$.

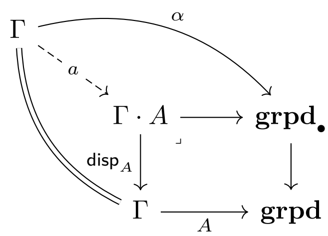
More concisely, evaluation is a natural transformation $\mathsf{ev} : R \to \mathsf{Ty}$, given by

$$\mathsf{ev} = \pi_{\mathsf{Ty}} \circ \mathsf{counit}$$

Lemma 4.4.5. *The functor* $\mathsf{ev}_\alpha B : \Gamma \to \mathbf{grpd}$ *can be computed as*

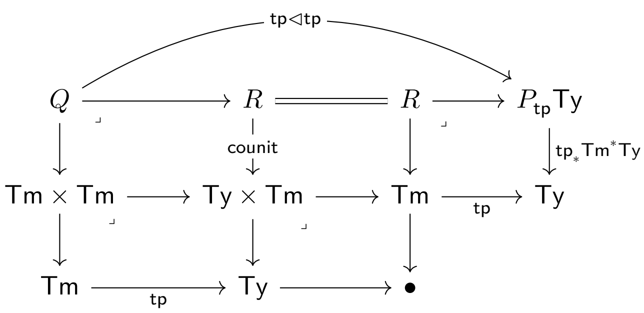
$$\mathsf{ev}_\alpha B = B \circ a$$

where

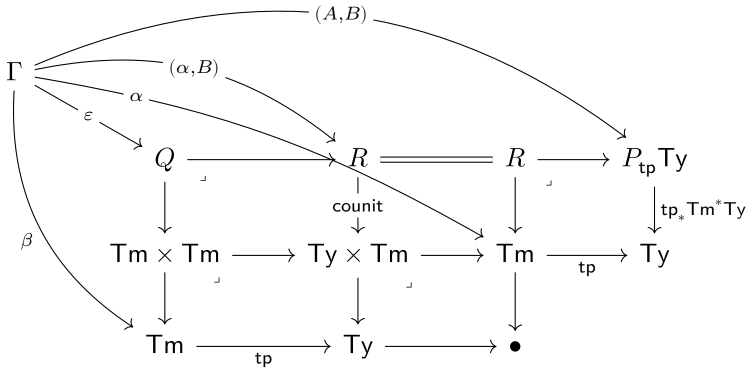


Proof. This is a specialization of 5.0.5 with liberal applications of Yoneda. □

Definition 4.4.6 (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 $\varepsilon : \Gamma \to Q$ corresponds to the data of a triple of maps $\alpha, \beta : \Gamma \to \mathsf{Tm}$ and $(A, B) : \Gamma \to P_{\mathsf{tp}}\mathsf{Ty}$ such that $\mathsf{tp} \circ \beta = \pi_{\mathsf{Ty}} \circ \mathsf{counit} \circ (\alpha, B)$ and $A = \mathsf{tp} \circ \alpha$.

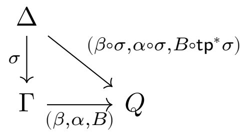


This in turn corresponds to three functors $\alpha, \beta : \Gamma \to \mathbf{grpd}_\bullet$ and $B : \Gamma{\cdot}U{\circ}\alpha \to \mathbf{grpd}$, such that $U \circ \beta = \mathsf{ev}_\alpha\, B$. So we will write

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

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

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



Definition 4.4.7 (Interpretation of Σ)**.** We define the natural transformation

$$\Sigma : P_{\mathsf{tp}}\mathsf{Ty} \to \mathsf{Ty}$$

as that which is induced (4.4.1) by the Σ-former operation (4.2.8).

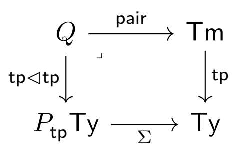
To define $\mathsf{pair} : Q \to \mathsf{Tm}$, let Γ be a groupoid and $(\beta, \alpha, B) : \Gamma \to Q$ (such that $U \circ \beta = \mathsf{ev}_\alpha\, \beta$). We define a functor $\mathsf{pair}_\Gamma(\beta, \alpha, B) : \Gamma \to \mathbf{grpd}_\bullet$ such that on objects $x \in \Gamma$, the functor returns $(\Sigma_A B\, x, (a_x, b_{a_x}))$, where (using 4.4.5 $U \circ \beta x = \mathsf{ev}_\alpha\, Bx = B(x, a_x)$)

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

and on morphisms $f : x \to y$, the functor returns $(\Sigma_A B\, f, (\phi_f, \psi_f))$, where (using 4.4.5 $U \circ \beta f = \mathsf{ev}_\alpha\, Bf = B(f, \phi_f)$)

$$\alpha\, f = (A\, f, \phi_f \colon A\, f\, a_x \to a_y) \quad \text{and} \quad \beta\, f = (B(f, \phi_f), \psi_f \colon B(f, \phi_f)\, b_{a_x} \to b_{a_y})$$

Σ and pair combine to give us a pullback square



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

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

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

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

where

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

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,

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

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

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

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

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

Indeed if we write

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

this uniquely determines α and β as

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

□

4.5 Identity types

Definition 4.5.1 (Identity formation and introduction)**.** To define the commutative square in **Psh**(**grpd**)

$$\begin{array}{ccc} \mathsf{Tm} & \xrightarrow{\mathsf{refl}} & \mathsf{Tm} \\ {\scriptstyle\delta}\downarrow & & \downarrow{\scriptstyle\mathsf{tp}} \\ \mathsf{tp} \times_{\mathsf{Ty}} \mathsf{tp} & \xrightarrow[\mathsf{Id}]{} & \mathsf{Ty} \end{array}$$

We first note that both δ and tp in the are in the essential image of the composition from 4.1.2

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

since the composition preserves pullbacks. So we first define in **Cat**

$$\begin{array}{ccc} \mathbf{grpd}_\bullet & \xrightarrow{\mathsf{refl}'} & \mathbf{grpd}_\bullet \\ {\scriptstyle\delta}\downarrow & & \downarrow{\scriptstyle U} \\ U \times_{\mathbf{grpd}} U & \xrightarrow[\mathsf{Id}']{} & \mathbf{grpd} \end{array} \tag{4.5.1}$$

Then obtain Id and refl in **Psh**(**grpd**) by applying $\mathsf{res} \circ \mathsf{y}$ to this diagram.

To this end, let $\mathsf{Id}' : U \times_{\mathbf{grpd}} U \to \mathbf{grpd}$ act on objects by taking the *set* - the discrete groupoid - of isomorphisms

$$(A, a_0, a_1) \mapsto A(a_0, a_1)$$

and on morphisms $(f, \phi_0, \phi_1) : (A, a_0, a_1) \to (B, b_0, b_1)$ by

$$(f : A \to B, \phi_0 : fa_0 \to b_0, \phi_1 : fa_1 \to b_1) \mapsto \phi_1 \circ f(-) \circ \phi_0^{-1}$$

Let $\mathsf{refl}' : \mathbf{grpd}_\bullet \to \mathbf{grpd}_\bullet$ act on objects by

$$(A, a) \mapsto (A(a, a), \mathsf{id}_a)$$

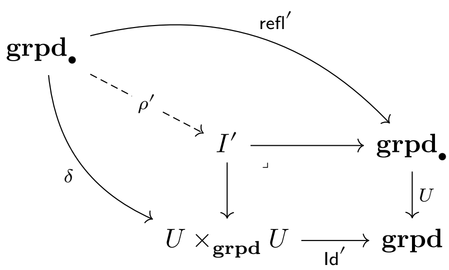
and on morphisms $(f, \phi) : (A, a) \to (B, b)$ by

$$(f : A \to B, \phi : (A, a) \to (B, b)) \mapsto (\phi \circ f(-) \circ \phi^{-1}, \phi \circ f(\mathsf{id}_a) \circ \phi^{-1} = \mathsf{id}_b)$$

where the second component has to be the identity on the object id_d, since $B(b, b)$ is a discrete groupoid. So we need a merely propositional proof that the two maps are equal, which in this case is clear.

Proof. Since $\delta(A, a) = (A, a, a)$, it follows that the square in 4.5.1 commutes. □

Lemma 4.5.2. *We can then construct the pullback I'*



as the groupoid with objects (A, a_0, a_1, h) *where* A *is a groupoid with* $a_0, a_1 \in A$ *and* $h : a_0 \to a_1$*, and morphisms*

$$(f, \phi_0, \phi_1, Ah = k) : (A, a_0, a_1, h : a_0 \to a_1) \to (B, b_0, b_1, k : b_0 \to b_1)$$

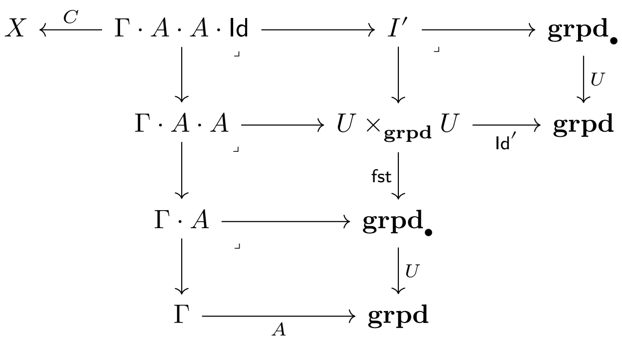
where $f : A \to B$*,* $\phi_i : fa_i \to b_i$ *and* $Ah = k$ *represents a merely propositional proof of equality. Then we can also compute*

$$\rho'(A, a) = (A, a, a, \mathsf{id}_a)$$

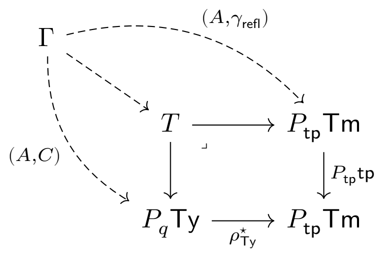
Lemma 4.5.3. *Specialized to* $q : I \to \mathsf{Ty}$ *in* $\mathbf{Psh}(\mathbf{grpd})$*, the characterizing property of polynomial endofunctors 5.0.2 says that a map from a representable* $\varepsilon : \Gamma \to P_q X$ *corresponds to the data of*

$$A : \Gamma \to \mathsf{Ty} \qquad \text{and} \qquad C : \Gamma \cdot A \cdot A \cdot \mathsf{Id} \to X$$

where $A = q \circ \varepsilon$ *and*



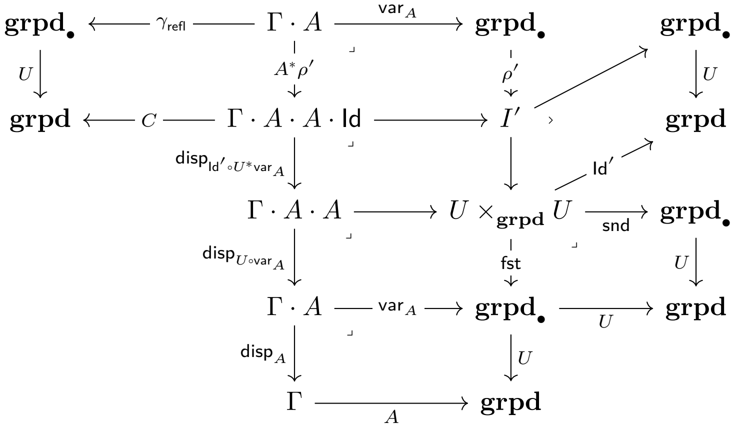
Lemma 4.5.4.



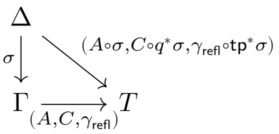
The data of a map $(A, C, \gamma_{\mathsf{refl}}) : \Gamma \to T$ *corresponds to the data of*

$$\begin{aligned} A &: \Gamma \to \mathbf{grpd} \\ C &: \Gamma \cdot A \cdot A \cdot \mathsf{Id} \to \mathbf{grpd} \\ \gamma_{\mathsf{refl}} &: \Gamma \cdot A \to \mathbf{grpd}_\bullet \end{aligned}$$

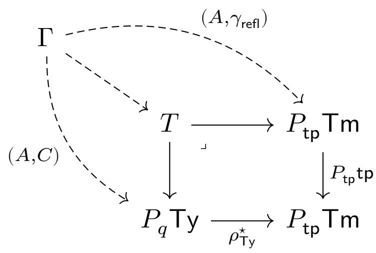
such that $C \circ A^* \rho' = U \circ \gamma_{\mathsf{refl}}$



Then precomposition with $\sigma : \Delta \to \Gamma$ acts on such a triple via



Proof.



By the universal property of pullbacks, The data of a map from a representable $\Gamma \to T$ corresponds to the data of $(A, C) : \Gamma \to P_q\mathsf{Ty}$ and $(A', \gamma_{\mathsf{refl}}) : \Gamma \to P_{\mathsf{tp}}\mathsf{Tm}$ such that

$$\rho^\star_{\mathsf{Ty}} \circ (A, C) = P_{\mathsf{tp}}\mathsf{tp} \circ (A', \gamma_{\mathsf{refl}})$$

By 5.0.8 and 5.0.2 this says

$$(A, C \circ A^* \rho) = (A', \mathsf{tp} \circ \gamma_{\mathsf{refl}})$$

so the above is equivalent to having $A = A', C, \gamma_{\mathsf{refl}}$ such that

$$C \circ A^* \rho = \mathsf{tp} \circ \gamma_{\mathsf{refl}} \text{ in } \mathbf{Psh}(\mathbf{grpd})$$

By Yoneda this is equivalent to requiring

$$C \circ A^* \rho' = U \circ \gamma_{\mathsf{refl}} \text{ in } \mathbf{Cat}$$

□

Proposition 4.5.5. *We can compute $\varepsilon : P_q\mathsf{Tm} \to T$ via*

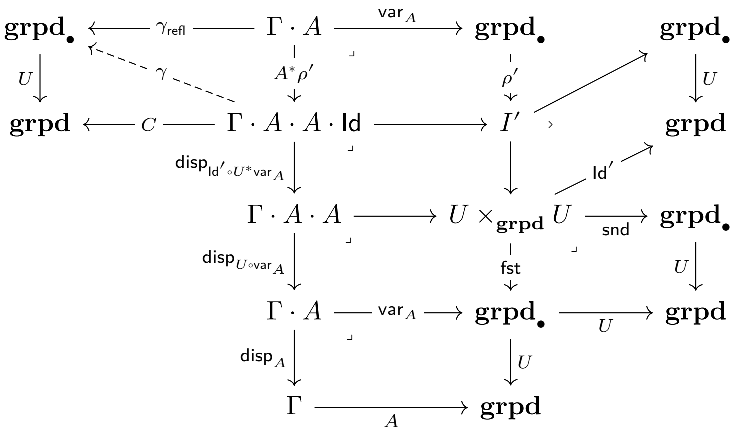
$$\begin{aligned} \varepsilon_\Gamma : \mathbf{Psh}(\mathbf{grpd})(\Gamma, P_q\mathsf{Tm}) &\to \mathbf{Psh}(\mathbf{grpd})(\Gamma, T) \\ (A, \gamma) &\mapsto (A, U \circ \gamma, \gamma \circ A^* \rho') \end{aligned}$$

Proof. This follows from the computation for T 4.5.4, the polynomial action on slice morphisms 5.0.8, and 5.0.2. □

Definition 4.5.6 (Identity elimination)**.** We want to define $J : T \to P_q\mathsf{Tm}$

$$J_\Gamma : \mathbf{Psh}(\mathbf{grpd})(\Gamma, T) \to \mathbf{Psh}(\mathbf{grpd})(\Gamma, P_q\mathsf{Tm})$$
$$(A, C, \gamma_{\mathsf{refl}}) \mapsto (A, \gamma)$$

for some $\gamma : \Gamma \cdot A \cdot A \cdot \mathsf{Id} \to \mathbf{grpd}_\bullet$ which we will define below. We first use T 4.5.4 to describe the given data:



Let us name the fibers over the diagonal

$$C_{\mathsf{refl}} := U \circ \gamma_{\mathsf{refl}} = C \circ A^*\rho' : \Gamma \cdot A \to \mathbf{grpd}$$

and its given points

$$\gamma_{\mathsf{refl}} = (C_{\mathsf{refl}}, c_{\mathsf{refl}})$$

(Note that c_{refl} is not a functor, but will give us an object per object (x, a), and morphism $c_{\mathsf{refl}}(f, \phi) : C_{\mathsf{refl}}(f, \phi)c_{\mathsf{refl}}(x, a) \to c_{\mathsf{refl}}(y, b)$ per morphism (f, ϕ).) Then γ will be defined by using C to lift the path

$$(\mathsf{id}_x, \mathsf{id}_{a_0}, h, \_) : (x, a_0, a_0, \mathsf{id}_a) \to (x, a_0, a_1, h) \in \Gamma \cdot A \cdot A \cdot \mathsf{Id}$$

that starts on the diagonal, to give us a point in any fiber, using c_{refl}. Note that we unfolded $\Gamma \cdot A \cdot A \cdot \mathsf{Id}$ as the domain of the nested display maps so that $x \in \Gamma$, $a_0 \in Ax$,

$$a_1 \in U \circ \mathsf{var}_A(x, a_0) = U(Ax, a_0) = Ax$$

and

$$h \in Id' \circ U^*\mathsf{var}_A(x, a_0, a_1) = \mathsf{Id}'(Ax, a_0, a_1) = Ax(a_0, a_1)$$

We also check $(\mathsf{id}_x, \mathsf{id}_{a_0}, h, \_)$ is a path in $\Gamma \cdot A \cdot A \cdot \mathsf{Id}$ by proving "_", the omitted equality

$$(\mathsf{Id}' \circ U^*\mathsf{var}_A(\mathsf{id}_x, \mathsf{id}_{a_0}, h))\mathsf{id}_{a_0} = (\mathsf{Id}'(A\mathsf{id}_x, \mathsf{id}_{a_0}, h))\mathsf{id}_{a_0} = h \circ A\mathsf{id}_x\mathsf{id}_{a_0} \circ \mathsf{id}_{a_0}^{-1} = h$$

So we define $\gamma : \Gamma \cdot A \cdot A \cdot \mathsf{Id} \to \mathbf{grpd}_\bullet$ on objects by

$$(x, a_0, a_1, h) \mapsto (C(x, a_0, a_1, h), C(\mathsf{id}_x, \mathsf{id}_{a_0}, h, \_)\, c_{\mathsf{refl}}(x, a_0))$$

noting that from the computation of ρ' given in 4.5.2 it follows that

$$c_{\mathsf{refl}}(x, a_0) \in C \circ A^*\rho'(x, a_0) = C(x, a_0, a_1, h)$$

Define γ on morphism $(f, \phi_0, \phi_1, \phi_1 \circ Afh \circ \phi_0^{-1} = k) : (x, a_0, a_1, h) \to (y, b_0, b_1, k)$ by

$$(f, \phi_0, \phi_1, \_) \mapsto (C(f, \phi_0, \phi_1, \_), C(\mathsf{id}_y, \mathsf{id}_{b_0}, k, \_)\, c_{\mathsf{refl}}(f, \phi_0))$$

We type check $C(\mathsf{id}_y, \mathsf{id}_{b_0}, k, \_)\, c_{\mathsf{refl}}(f, \phi_0)$

$$
\begin{aligned}
C(\mathsf{id}_y, \mathsf{id}_{b_0}, k, \_) c_{\mathsf{refl}}(f, \phi_0) \quad : \quad & C(f, \phi_0, \phi_1, \_) \circ C(\mathsf{id}_x, \mathsf{id}_{a_0}, h, \_)\, c_{\mathsf{refl}}(x, a_0) \\
&= C(f, \phi_0, \phi_1 \circ Afh, \_)\, c_{\mathsf{refl}}(x, a_0) \\
&= C(f, \phi_0, k \circ \phi_0, \_)\, c_{\mathsf{refl}}(x, a_0) \\
&= C(\mathsf{id}_y, \mathsf{id}_{b_0}, k, \_) \circ C(f, \phi_0, \phi_0, \_)\, c_{\mathsf{refl}}(x, a_0) \\
&= C(\mathsf{id}_y, \mathsf{id}_{b_0}, k, \_) \circ C_{\mathsf{refl}}(f, \phi_0)\, c_{\mathsf{refl}}(x, a_0) \\
&\to C(\mathsf{id}_y, \mathsf{id}_{b_0}, k, \_)\, c_{\mathsf{refl}}(y, b_0)
\end{aligned}
$$

Proof. Functoriality of γ is routine. We show naturality of J. Suppose $\sigma : \Delta \to \Gamma$ is representable

$$
\begin{array}{ccc}
(A \circ \sigma, C \circ q^*\sigma, \gamma_{\mathsf{refl}} \circ \mathsf{tp}^*\sigma) & \longmapsto & (A \circ \sigma, \gamma_\Delta) \\
 & & \| \\
 & & (A \circ \sigma, \gamma_\Gamma \circ q^*\sigma)
\end{array}
$$

$$
\begin{array}{ccc}
\mathbf{Psh}(\mathbf{grpd})(\Delta, T) & \xrightarrow{J_\Delta} & \mathbf{Psh}(\mathbf{grpd})(\Delta, P_q\mathsf{Tm}) \\
{\scriptstyle - \circ \sigma}\uparrow & & \uparrow{\scriptstyle - \circ \sigma} \\
\mathbf{Psh}(\mathbf{grpd})(\Gamma, T) & \xrightarrow[J_\Gamma]{} & \mathbf{Psh}(\mathbf{grpd})(\Gamma, P_q\mathsf{Tm})
\end{array}
$$

$$
(A, C, \gamma_{\mathsf{refl}}) \longmapsto (A, \gamma_\Gamma)
$$

So we want to show that on objects $(x, a_0, a_1, h) \in \Delta \cdot A \circ \sigma \cdot A \circ \sigma \cdot \mathsf{Id}$

$$
\gamma_\Delta\, (x, a_0, a_1, h) = \gamma_\Gamma \circ q^*\sigma\, (x, a_0, a_1, h)
$$

Let us denote $q^*\sigma(x, a_0, a_1, h) = (\sigma x, a_0', a_1', h')$. Then

$$
\begin{aligned}
& \gamma_\Delta\, (x, a_0, a_1, h) \\
&= (C \circ q^*\sigma\, (x, a_0, a_1, h), (C \circ q^*\sigma\, (\mathsf{id}_x, \mathsf{id}_{a_0}, h, \_))(c_{\mathsf{refl}}(\mathsf{tp}^*\sigma(x, a_0)))) \\
&= (C\, (\sigma x, a_0', a_1', h'), (C\, (\mathsf{id}_{\sigma x}, \mathsf{id}_{a_0'}, h', \_))(c_{\mathsf{refl}}\, (\sigma x, a_0'))) \\
&= \gamma_\Gamma(\sigma x, a_0', a_1', h') \\
&= \gamma_\Gamma \circ q^*\sigma\, (x, a_0, a_1, h)
\end{aligned}
$$

and similarly for morphisms. □

Proposition 4.5.7. *$J : T \to P_q\mathsf{Tm}$, as defined above is a section of ε.*

Proof. Let $(A, C, \gamma_{\mathsf{refl}}) : \Gamma \to T$ be a map from a representable. Then using the definition of J and the computation of ε 4.5.5

$$
\varepsilon_\Gamma \circ J_\Gamma\, (A, C, \gamma_{\mathsf{refl}}) = \varepsilon_\Gamma(A, \gamma) = (A, U \circ \gamma, \gamma \circ A^*\rho')
$$

By definition of γ from J we can see that $U \circ \gamma = C$, so it suffices to show that $\gamma \circ A^*\rho' = \gamma_{\mathsf{refl}}$. On an object (x, a_0)

$$\begin{aligned} &\gamma \circ A^*\rho'(x, a_0) \\ &\qquad = \gamma(x, a_0, a_0, \mathsf{id}_{a_0}) \\ &\qquad = (C(x, a_0, a_0, \mathsf{id}_{a_0}), C(\mathsf{id}_x, \mathsf{id}_{a_0}, \mathsf{id}_{a_0})\, c_{\mathsf{refl}}) \\ &\qquad = (C_{\mathsf{refl}}(x, a_0), c_{\mathsf{refl}}(x, a_0)) \end{aligned}$$

□

4.6 Universe of Discrete Groupoids

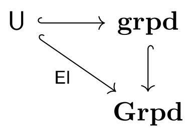
In this section we assume *three* different universe sizes, which we will distinguish by all lowercase (small), capitalized first letter (large), and all-caps (extra large), respectively. For example, the three categories of sets will be nested as follows

$$\mathbf{set} \hookrightarrow \mathbf{Set} \hookrightarrow \mathbf{SET}$$

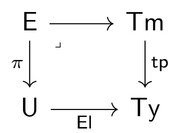
We shift all of our previous work up by one universe level, so that we are working in the category $\mathbf{PSH}(\mathbf{Grpd})$ of extra large presheaves, indexed by the (extra large, locally large) category of large groupoids. We would then have $\mathsf{Ty} = [-, \mathbf{Grpd}]$ and $\mathsf{Tm} = [-, \mathbf{Grpd}_\bullet]$.

Definition 4.6.1 (Universe of discrete groupoids)**.** Let U be the (large) groupoid of small sets, i.e. let U have **set** as its objects and morphisms between two small sets as all the bijections between them. This gives us $\ulcorner \mathsf{U} \urcorner : \bullet \to \mathsf{Ty}$.

Then we define $\mathsf{El} : \mathsf{y}\mathsf{U} \to \mathsf{Ty}$ by defining $\mathsf{El} : \mathsf{U} \to \mathbf{Grpd}$ as the inclusion - any small set can be regarded as a large discrete groupoid.



Then we take $\pi := \mathsf{disp}_{\mathsf{El}}$, giving us



We can compute the groupoid E as that with objects that are pairs (X, x) where $x \in X \in \mathbf{set}$, and morphisms

$$E((X, x), (Y, y)) = \{f : X \to Y \mid f\, x = y\}$$

Then $\pi : E \to U$ is the forgetful functor $(X, x) \mapsto X$.

Showing that this universe is closed under Π, Σ, Id formation depends on how we formalize $\mathbf{set} \hookrightarrow \mathbf{Set}$. In both cases we need to check that discreteness is preserved by the type formers, which is straightforward. If we are working with sets and cardinality, i.e. taking $\mathbf{set} = \mathbf{Set}_{<\lambda} \subset \mathbf{Set}_{<\kappa} = \mathbf{Set}$ for some inaccessible cardinals $\lambda < \kappa$, then it is straightforward to check that the type formers do not make "larger" types. If we are working with type theoretic universes with a lift operation $\mathsf{ULift} : \mathbf{set} \to \mathbf{Set}$ then it may *not* be true that ULift commutes with our type formers.

Chapter 5

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 5.0.1 (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 $t : B \to A$ we have an adjoint triple

$$\begin{array}{c} \mathbb{C}/B \\ t_! \downarrow \;\dashv\; \uparrow t^* \;\dashv\; \downarrow t_* \\ \mathbb{C}/A \end{array}$$

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

Let $t : B \to A$ be a morphism in $\mathbb{C}$. Then define $P_t : \mathbb{C} \to \mathbb{C}$ be the composition

$$P_t := A_! \circ t_* \circ B^*$$

$$\mathbb{C} \xrightarrow{B^*} \mathbb{C}/B \xrightarrow{t_*} \mathbb{C}/A \xrightarrow{A_!} \mathbb{C}$$

Proposition 5.0.2 (Characterising property of Polynomial Endofunctors)**.** *The data of a map into the polynomial applied to an object in* $\mathbb{C}$

$$\Gamma \longrightarrow P_t Y$$

corresponds to a pair of morphisms

$$\alpha : \Gamma \to A \qquad \text{and} \qquad \beta : \Gamma \cdot \alpha \to Y$$

and this correspondance is natural in both Γ *and* Y*.*

Given any such ϕ *we can extract* $\alpha : \Gamma \to A$ *by composition*

$$\begin{array}{ccc} \Gamma & \xrightarrow{\phi} & P_t Y \\ & {\scriptstyle \alpha} \searrow \quad \swarrow {\scriptstyle t_* B^* Y} & \\ & A & \end{array}$$

Applying the adjunction $t^* \dashv t_*$, and viewing $\phi : \alpha \to t_* B^* Y$ as a map in the slice over A, this corresponds to

$$\alpha : \Gamma \to A \qquad \textit{and}$$

$$\begin{tikzcd} B_! t^* \alpha \arrow[rr, dashed, "\tilde{\phi}"] \arrow[dr, "t^*\alpha"'] & & B \times Y \arrow[dl, "B^*Y"] \\ & B & \end{tikzcd}$$

Applying the adjunction $B_! \dashv B^*$, this corresponds to

$$\alpha : \Gamma \to A \qquad \textit{and}$$

$$\Gamma \cdot \alpha := B_! t^* \alpha \overset{\beta}{\dashrightarrow} Y$$

Henceforth we will write

$$(\alpha, \beta) : \Gamma \to P_t Y$$

for this map, since it is uniquely determined by this data.

This is natural in Γ. Precomposition by $\sigma : \Delta \to \Gamma$, acts on such a pair by

$$\begin{tikzcd} \Delta \arrow[d, "\sigma"'] \arrow[dr, "(\alpha\circ\sigma, \beta\circ t^*\sigma)"] & \\ \Gamma \arrow[r, "(\alpha,\beta)"'] & P_t Y \end{tikzcd}$$

It is also natural in $f : X \to Y$, meaning the morphism $P_t f$ acts on such a pair by

$$\begin{tikzcd} \Gamma \arrow[r, "(\alpha,\beta)"] \arrow[dr, "(\alpha, f\circ\beta)"'] & P_t X \arrow[d, "P_t f"] \\ & P_t Y \end{tikzcd}$$

Lemma 5.0.3. *Use R to denote the fiber product*

$$\begin{tikzcd} R \arrow[r, "\rho_{\mathsf{Tm}}"] \arrow[d, "\rho_P"'] \arrow[dr, phantom, "\lrcorner", very near start] & B \arrow[d, "t"] \\ P_t Y \arrow[r, "t_* B^* Y"'] & A \end{tikzcd}$$

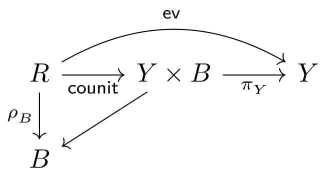
By the universal property of pullbacks and 5.0.2, The data of a map $\Gamma \to R$ corresponds to the data of $\beta : \Gamma \to B$ and $(t \circ \beta, y) : \Gamma \to P_t Y$, or just $\beta : \Gamma \to B$ and $y : \Gamma \cdot t \circ \beta \to Y$

$$\begin{tikzcd} \Gamma \arrow[drr, bend left, "\beta"] \arrow[dr, dashed, "(\beta,y)"] \arrow[ddr, bend right, "(t\circ\beta, y)"'] & & \\ & R \arrow[r, "\rho_B"] \arrow[d, "\rho_P"] \arrow[dr, phantom, "\lrcorner", very near start] & B \arrow[d, "t"] \\ & P_t Y \arrow[r, "t_* B^* Y"] & A \end{tikzcd}$$

By uniqueness in the universal property of pullbacks and 5.0.2, Precomposition by a map $\sigma : \Delta \to \Gamma$ acts on such a pair by

$$\begin{tikzcd} \Delta \arrow[d, "\sigma"'] \arrow[dr, "(\beta\circ\sigma, y\circ t^*\sigma)"] & \\ \Gamma \arrow[r, "(\beta,y)"'] & R \end{tikzcd}$$

Definition 5.0.4 (Evaluation)**.** Let $\mathsf{counit} : \rho_B \to B \to B^*Y$ denote the counit of the adjunction $f^* \dashv f_*$ at the object B^*Y, recalling that $\rho_B = t^*t_*B^*Y$. Then viewing the object B^*Y in the slice as the object $Y \times B$ in the ambient category, we define $\mathsf{ev} : R \to Y$ as the composition



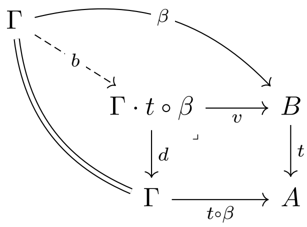
Lemma 5.0.5 (Evaluation Computation)**.** *Suppose* $(\beta, y) : \Gamma \to R$*, as in* 5.0.3

$$\beta : \Gamma \to B \quad \textit{and} \quad y : \Gamma \cdot t \circ \beta \to Y$$

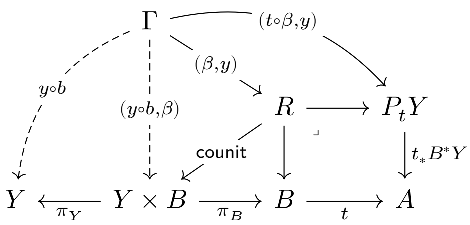
Then the evaluation of y *at* β *can be computed as*

$$\mathsf{ev} \circ (\beta, y) = y \circ b$$

where



and



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

$$
\begin{aligned}
& \mathsf{counit} \circ (\beta, y) & \\
&= \mathsf{counit} \circ (v \circ b, y \circ t^*d \circ t^*b) & 5.1 \\
&= \mathsf{counit} \circ (v, y \circ t^*d) \circ b & 5.0.3, 5.2 \\
&= \mathsf{counit} \circ t^*(t \circ \beta, y) \circ b & 5.3 \\
&= \overline{(t \circ \beta, y)} \circ b & 5.4 \\
&= (y, v) \circ b & 5.5 \\
&= (y \circ b, v \circ b) & \\
&= (y \circ b, \beta) &
\end{aligned}
$$

□

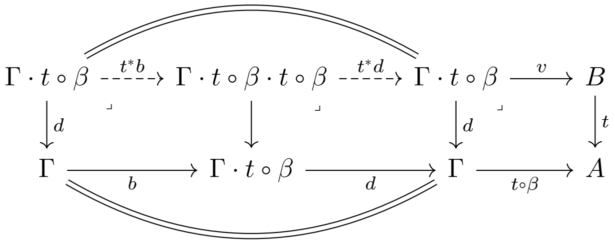


Figure 5.1: $t^*d \circ t^*b = \mathsf{id}_{\Gamma \cdot t \circ \beta}$

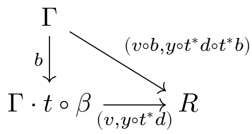
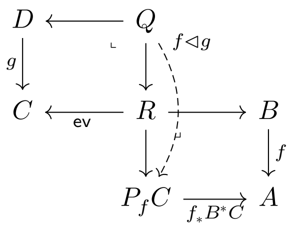


Figure 5.2: $(v, y \circ t^*d) \circ b = (v \circ b, y \circ t^*d \circ t^*b)$

Definition 5.0.6 (Polynomial composition)**.** Let $f : B \to A$ and $g : D \to C$. Define the *polynomial composition* $f \lhd g : Q \to P_f C$ as the composition of the two vertical maps in the following



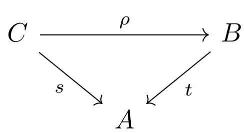
Then the two functors

$$P_{f \lhd g} \cong P_f \circ P_g$$

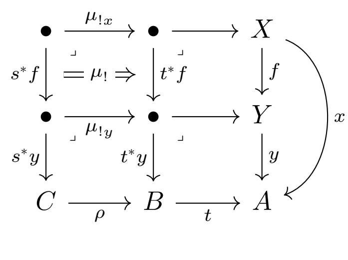
are naturally isomorphic.

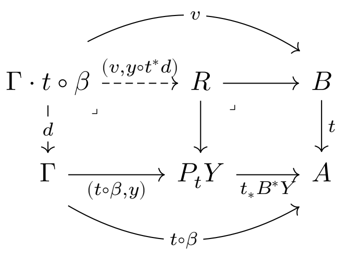
Proof. □

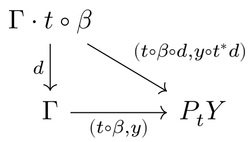
Definition 5.0.7 (Mate)**.** Suppose



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







using 5.0.2, 5.0.3

Figure 5.3: $t^*(t \circ \beta, y) = (v, y \circ t^* d)$

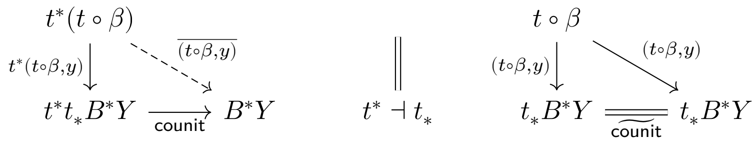
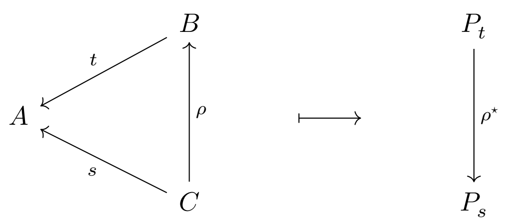


Figure 5.4: $\mathsf{counit} \circ t^*(t \circ \beta, y) = \overline{(t \circ \beta, y)}$

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

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

Definition 5.0.8 (Contravariant action of $P\_$ on a slice)**.** Let $P\_ : (\mathbb{C}/A)^{\mathrm{op}} \to [\mathbb{C}, \mathbb{C}]$ be defined by taking $s \mapsto P_s$ on objects and act on a morphism by



where

$$\rho^\star := A_!(s_* \eta \circ \mu B^*) : P_t \to P_s$$

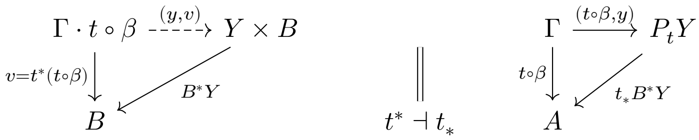
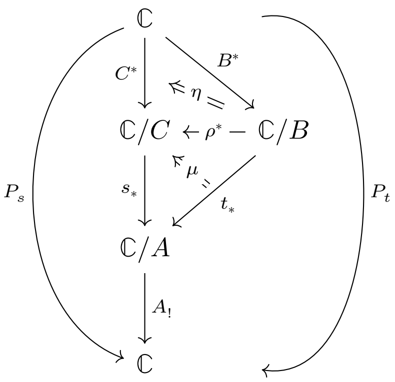
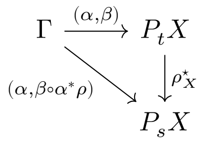


Figure 5.5: $\overline{(t \circ \beta, y)} = (y, v)$

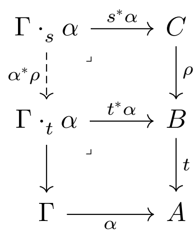


where $\mu = \mu^*$ is the mate from 5.0.7, and η is the natural isomorphism given by pullback pasting.

Pointwise, this natural transformation acts on a pair $(\alpha, \beta) : \Gamma \to P_t X$ by

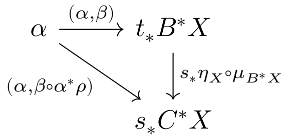


where $\alpha^* \rho$ is defined as

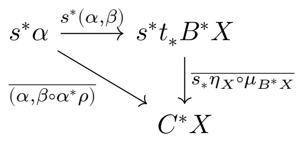


We prove this now.

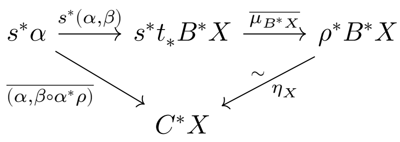
Proof. Firstly $\rho^\star_X = A_!(s_* \eta_X \circ \mu_{B^* X})$, so the first component $\alpha : \Gamma \to A$ is preserved by $\rho^\star_X$ and it suffices to show, in $\mathbb{C}/A$



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



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



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.

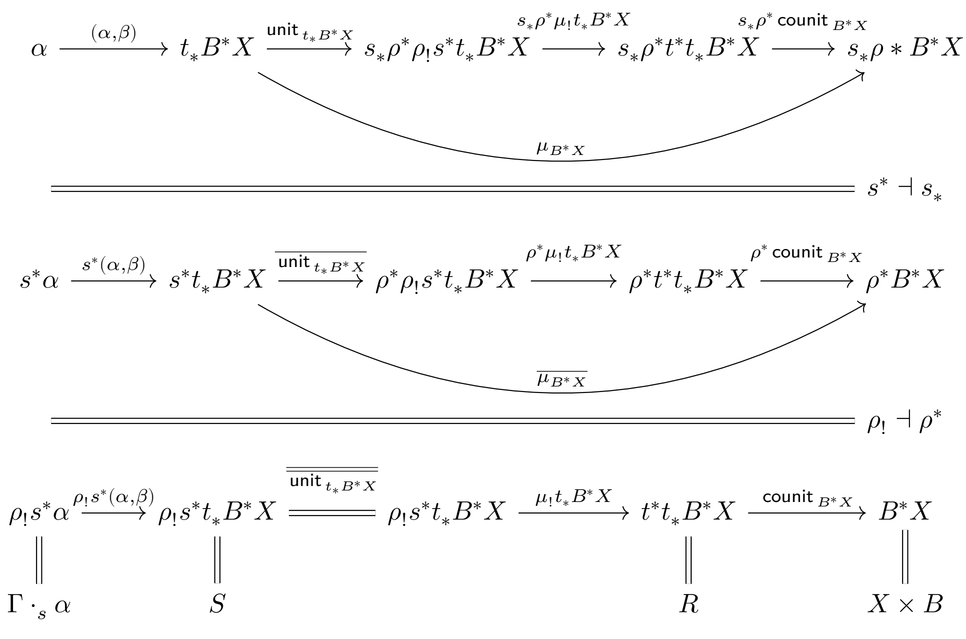
By the characterising property of polynomial endofunctors (5.0.2) we calculate

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

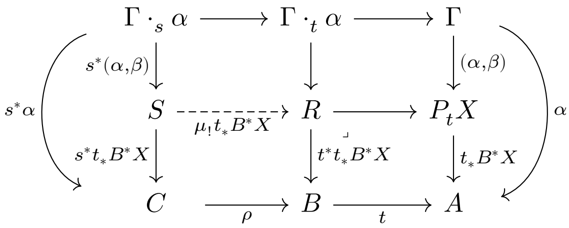
$$\alpha \xrightarrow{(\alpha,\beta\circ\alpha^*\rho)} s_* C^* X \quad \Bigg\| \quad s^*\alpha \xrightarrow[(\beta\circ\alpha^*\rho,\, s^*\alpha)]{\overline{(\alpha,\beta\circ\alpha^*\rho)}} C^* X \quad \Bigg\| \quad C_! s^* \alpha \xrightarrow[\beta\circ\alpha^*\rho]{} X$$

More formally, this means $\beta \circ \alpha^* \rho : C_! s^* \alpha \to X$ and $s^* \alpha : C_! s^* \alpha \to C$ are the two maps that uniquely determine the map $C_! \overline{\alpha, \beta \circ \alpha^* \rho} : C_! s^* \alpha \to X \times C$.

On the other hand,



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



Using the characterization of maps into R from 5.0.3 we can calculate

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

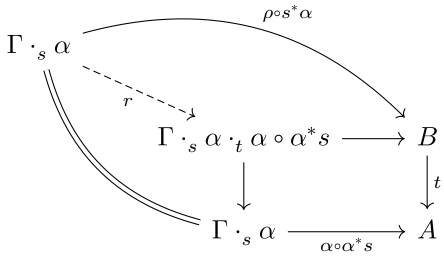
since the first component is simply the map $\Gamma \cdot_s \alpha \to B$ and the second component is the second component of the map

$$(\alpha \circ \alpha^* s, \beta \circ t^* \alpha^* s) = (\alpha, \beta) \circ \alpha^* s : \Gamma \cdot_s \alpha \to P_t X$$

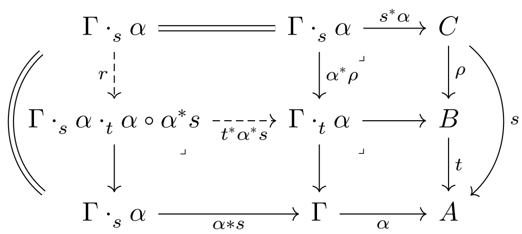
Then using 5.0.5

$$\begin{aligned}
&\overline{\overline{\mu_{B^*X}} \circ s^*(\alpha, \beta)} && (5.0.1)\\
&= \mathsf{counit}_{B^*X} \circ \mu_! t_* B^* X \circ s^*(\alpha, \beta) && (5.0.2)\\
&= \mathsf{counit}_{B^*X} \circ (\rho \circ s^*\alpha, \beta \circ t^*\alpha^* s) && (5.0.3)\\
&= (\beta \circ t^*\alpha^* s \circ r, \rho \circ s^*\alpha) && (5.0.4)\\
&= (\beta \circ \alpha^*\rho, \rho \circ s^*\alpha) && (5.0.5)\\
&: \Gamma \cdot_s \alpha \to X \times B && (5.0.6)
\end{aligned}$$

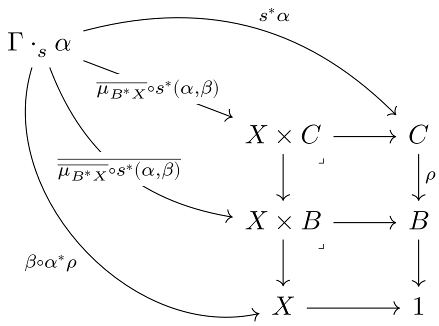
where



and



Moving back along the adjunction $\rho_! \dashv \rho^*$ 5.0.1 tells us that

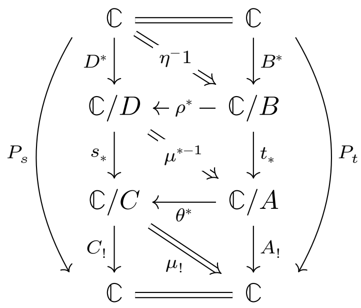


So that, as required, $\overline{\mu_{B^*X}} \circ s^*(\alpha, \beta)$ and $\overline{(\alpha, \beta \circ \alpha^* \rho)}$ are uniquely determined by the same two maps into X and C. $\square$

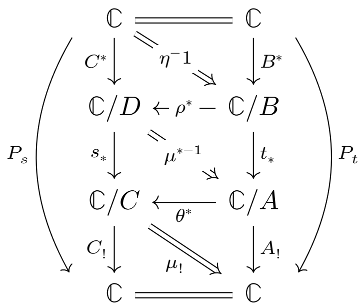
Definition 5.0.9 (Covariant action of $P\_$ on a cartesian square)**.** We can also view taking polynomial endofunctors as a covariant functor on the category of arrows with cartesian squares as morphisms

$$P\_ : \mathsf{CartArr}(\mathbb{C}) \to [\mathbb{C}, \mathbb{C}]$$

where the action on a cartesian square is



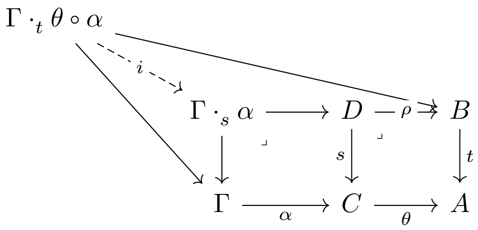
given by the whiskered natural transformations

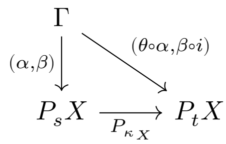


Furthermore, the natural transformation P_κ is cartesian. meaning each naturality square is a pullback square.

$$\begin{array}{ccc} P_s X & \xrightarrow{P_{\kappa_Y}} & P_t X \\ {\scriptstyle P_s f}\downarrow & \lrcorner & \downarrow{\scriptstyle P_s f} \\ P_s Y & \xrightarrow[P_{\kappa_Y}]{} & P_t Y \end{array}$$

The natural transformation P_κ computes in the following way

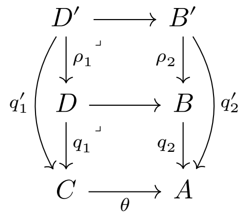




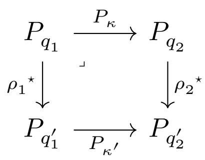
using the fact that $\Gamma \cdot_s \alpha$ and $\Gamma \cdot_t \theta \circ \alpha$ are limits of the same diagram.

Proof. We can use the computation of P_{κ_X} and $P_s f$ to show that the natural transformation P_κ is cartesian. Essentially, the first component of a map $\Gamma \to P_s X$ is determined by its composition with $P_s f$ and its second component is determined by its composition with P_{κ_X}. □

Corollary 5.0.10. *If we have*



then the two possible ways of obtaining composing the covariant and contravariant actions of P_ form a (strictly commuting) pullback square in $[\mathbb{C}, \mathbb{C}]$.



Proof. To check that it commutes and is a pullback, it suffices to do this pointwise, for some $X \in \mathbb{C}$. Then we simply unfold the computation for each of P_κ and $\rho^\star$. □

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