

Groupoid 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 locally 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 (large) 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

Definition 0.1.2. We will use $P_{\mathbf{tp}}$ to denote the polynomial endofunctor (0.3.1) associated with our presentable map \mathbf{tp} . Then an interpretation of Π types consists of a pullback square

$$\begin{array}{ccc} P_{\mathbf{tp}} \mathbf{Tm} & \xrightarrow{\lambda} & \mathbf{Tm} \\ P_{\mathbf{tp}} \downarrow & \lrcorner & \downarrow \mathbf{tp} \\ P_{\mathbf{tp}} \mathbf{Ty} & \xrightarrow{\Pi} & \mathbf{Ty} \end{array} \quad (0.1.1)$$

0.1.3 Sigma types

Definition 0.1.3.

An interpretation of Σ types consists of a pullback square

$$\begin{array}{ccc} Q & \xrightarrow{\text{pair}} & \mathbf{Tm} \\ \mathbf{tp} \triangleleft \mathbf{tp} \downarrow & \lrcorner & \downarrow \mathbf{tp} \\ P_{\mathbf{tp}} \mathbf{Ty} & \xrightarrow{\Sigma} & \mathbf{Ty} \end{array} \quad (0.1.2)$$

where the composition of polynomials $\mathbf{tp} \triangleleft \mathbf{tp} : Q \rightarrow P_{\mathbf{tp}} \mathbf{Ty}$ is given by

$$\begin{array}{ccccccc} & & & \mathbf{tp} \triangleleft \mathbf{tp} & & & \\ & & \curvearrowright & & \curvearrowleft & & \\ Q & \xrightarrow{\quad} & R & \xlongequal{\quad} & R & \xrightarrow{\quad} & P_{\mathbf{tp}} \mathbf{Ty} \\ \downarrow \lrcorner & & \downarrow \text{counit} & & \downarrow \lrcorner & & \downarrow \mathbf{tp}_* \mathbf{Tm}^* \mathbf{Ty} \\ \mathbf{Tm} \times \mathbf{Tm} & \longrightarrow & \mathbf{Ty} \times \mathbf{Tm} & \longrightarrow & \mathbf{Tm} & \xrightarrow{\mathbf{tp}} & \mathbf{Ty} \\ \downarrow \lrcorner & & \downarrow \lrcorner & & \downarrow \lrcorner & & \\ \mathbf{Tm} & \xrightarrow{\mathbf{tp}} & \mathbf{Ty} & \longrightarrow & \bullet & & \end{array}$$

Here, $\text{counit} : \mathbf{tp}^* \mathbf{tp}_* \mathbf{Tm}^* \mathbf{Ty} \rightarrow \mathbf{Tm}^* \mathbf{Ty}$ is the counit of the adjunction $\mathbf{tp}^* \dashv \mathbf{tp}_*$ at $\mathbf{Tm}^* \mathbf{Ty} \in \mathbf{Psh}(\mathbf{grpd})/\mathbf{Tm}$.

0.1.4 Identity types

Definition 0.1.4. To interpret the formation and introduction rules for identity types we require a commutative square (this need not be pullback)

$$\begin{array}{ccc}
 \mathsf{Tm} & \xrightarrow{\text{refl}} & \mathsf{Tm} \\
 \delta \downarrow & & \downarrow \text{tp} \\
 \text{tp} \times_{\mathsf{Ty}} \text{tp} & \xrightarrow{\text{id}} & \mathsf{Ty}
 \end{array} \tag{0.1.3}$$

where δ is the diagonal:

$$\begin{array}{ccc}
 \mathsf{Tm} & \xrightarrow{\text{refl}} & \mathsf{Tm} \\
 \delta \searrow & & \downarrow \text{tp} \\
 \text{tp} \times_{\mathsf{Ty}} \text{tp} & \xrightarrow{\text{id}} & \mathsf{Ty} \\
 \downarrow & \lrcorner & \downarrow \text{tp} \\
 \mathsf{Tm} & \xrightarrow{\text{tp}} & \mathsf{Ty}
 \end{array}$$

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

$$\begin{array}{ccc}
 \mathsf{Tm} & \xrightarrow{\text{refl}} & \mathsf{Tm} \\
 \rho \dashrightarrow & & \downarrow \text{tp} \\
 I & \xrightarrow{\text{id}} & \mathsf{Tm} \\
 \delta \searrow & \lrcorner & \downarrow \text{tp} \\
 \text{tp} \times_{\mathsf{Ty}} \text{tp} & \xrightarrow{\text{id}} & \mathsf{Ty}
 \end{array}$$

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

$$\begin{array}{ccc}
 \mathsf{Tm} & \xrightarrow{\text{refl}} & \mathsf{Tm} \\
 \rho \dashrightarrow & & \downarrow \text{tp} \\
 I & \xrightarrow{\text{id}} & \mathsf{Tm} \\
 \delta \searrow & \lrcorner & \downarrow \text{tp} \\
 \text{tp} \times_{\mathsf{Ty}} \text{tp} & \xrightarrow{\text{id}} & \mathsf{Ty} \\
 \text{fst} \downarrow & & \downarrow \text{tp} \\
 \mathsf{Tm} & \xrightarrow{\text{tp}} & \mathsf{Ty}
 \end{array}$$

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

$$\begin{array}{ccc}
 P_q \mathsf{Tm} & \xrightarrow{\rho_{\mathsf{Tm}}^*} & P_{\text{tp}} \mathsf{Tm} \\
 P_q \text{tp} \downarrow & & \downarrow P_{\text{tp}} \text{tp} \\
 P_q \mathsf{Ty} & \xrightarrow{\rho_{\mathsf{Ty}}^*} & P_{\text{tp}} \mathsf{Tm}
 \end{array} \tag{0.1.4}$$

Taking the pullback T and the comparison map ε we have

$$\begin{array}{ccc}
 P_q \mathsf{Tm} & \xrightarrow{\rho_{\mathsf{Tm}}^*} & P_{\mathsf{tp}} \mathsf{Tm} \\
 \downarrow P_q \mathsf{tp} & \searrow \varepsilon & \downarrow P_{\mathsf{tp}} \mathsf{tp} \\
 T & \xrightarrow{J} & P_{\mathsf{tp}} \mathsf{Tm} \\
 \downarrow & & \downarrow \\
 P_q \mathsf{Ty} & \xrightarrow{\rho_{\mathsf{Ty}}^*} & P_{\mathsf{tp}} \mathsf{Ty}
 \end{array} \quad (0.1.5)$$

Finally, we require a section $J : T \rightarrow P_q \mathsf{Tm}$ 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

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

Definition 0.1.5. In the Natural Model, a universe U is postulated by a map

$$\pi : \mathsf{E} \rightarrow \mathsf{U}$$

In the Natural Model:

- There is a pullback diagram of the form

$$\begin{array}{ccc}
 \mathsf{U} & \longrightarrow & \mathsf{Tm} \\
 \downarrow & & \downarrow \\
 1 & \xrightarrow{\ulcorner \mathsf{U} \urcorner} & \mathsf{Ty}
 \end{array} \quad (0.1.6)$$

- There is an inclusion of U into Ty

$$\mathsf{El} : \mathsf{U} \rightarrow \mathsf{Ty}$$

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

$$\begin{array}{ccc}
 \mathsf{E} & \longrightarrow & \mathsf{Tm} \\
 \downarrow & & \downarrow \\
 \mathsf{U} & \xrightarrow{\mathsf{El}} & \mathsf{Ty}
 \end{array} \quad (0.1.7)$$

With the notation above, we get

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

Both squares above are pullback squares.

0.1.6 Stability of the universe under type formers

Take the pullback diagram 0.1.7. That is a morphism in the category of polynomials. By 0.3.7 we have a cartesian natural transformation $P_\pi \rightarrow P_{\text{tp}}$ induced by the pullback 0.1.7. This cartesian natural transformation induces the cube diagram below; all of the squares in the cube are pullback squares.

$$\begin{array}{ccccc}
 & P_\pi E & \xrightarrow{\quad} & P_{\text{tp}} E & \\
 & \swarrow & & \swarrow & \\
 P_\pi \mathsf{Tm} & \xrightarrow{\quad} & P_{\text{tp}} \mathsf{Tm} & & \\
 \downarrow & & \downarrow & & \downarrow \\
 & P_\pi U & \xrightarrow{\quad} & P_{\text{tp}} U & \\
 & \swarrow & & \swarrow & \\
 P_\pi \mathsf{Ty} & \xrightarrow{\quad} & P_{\text{tp}} \mathsf{Ty} & &
 \end{array} \tag{0.1.8}$$

We will use the compositions $P_\pi U \rightarrow P_{\text{tp}} \mathsf{Ty}$ and $P_\pi E \rightarrow P_{\text{tp}} \mathsf{Tm}$ below.

Definition 0.1.6. We will say that universe U is closed under formation of Π -types when we have some map $\Pi_U : P_\pi U \rightarrow U$ making the following square commute

$$\begin{array}{ccc}
 P_\pi U & \xrightarrow{\quad} & P_{\text{tp}} \mathsf{Ty} \\
 \Pi_U \downarrow & & \downarrow \Pi \\
 U & \xrightarrow{\quad \text{El} \quad} & \mathsf{Ty}
 \end{array} \tag{0.1.9}$$

Note that this is merely propositional when El is a monomorphism.

From the universal property of pullbacks we can define $\lambda_U P_\pi E \rightarrow E$.

$$\begin{array}{ccccc}
 & P_{\text{tp}} E & \xrightarrow{\quad \lambda_U \quad} & E & \\
 & \swarrow & & \swarrow & \\
 P_{\text{tp}} \mathsf{Tm} & \xrightarrow{\quad \lambda \quad} & \mathsf{Tm} & & \\
 \downarrow & & \downarrow & & \downarrow \\
 & P_\pi U & \xrightarrow{\quad \Pi_U \quad} & U & \\
 & \swarrow & & \swarrow & \\
 P_{\text{tp}} \mathsf{Ty} & \xrightarrow{\quad \Pi \quad} & \mathsf{Ty} & &
 \end{array}$$

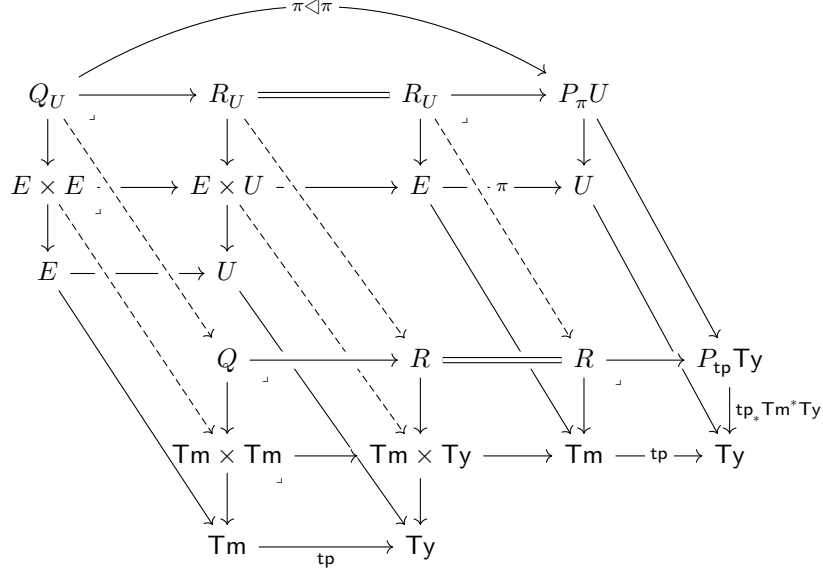
The top and bottom squares in the cube above are not pullbacks, but we know three of the vertical faces are pullback squares. By the pullback pasting lemma it follows that the back square involving Π_U and λ_U is also a pullback square. This concludes the construction of the Π type former for the universe U . The only data we needed to supply was the lift Π_U of $\Pi : P_{\text{tp}} \mathsf{Ty} \rightarrow \mathsf{Ty}$ to the universe U .

Definition 0.1.7. We will say that universe U is closed under formation of Σ -types when we have some map $\Sigma_U : P_\pi U \rightarrow U$ making the following square commute

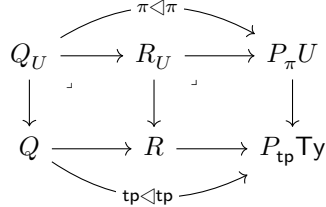
$$\begin{array}{ccc}
 P_\pi U & \xrightarrow{\quad} & P_{\text{tp}} \mathsf{Ty} \\
 \Sigma_U \downarrow & & \downarrow \Sigma \\
 U & \xrightarrow{\quad \text{El} \quad} & \mathsf{Ty}
 \end{array} \tag{0.1.10}$$

Again, this is merely propositional when El is a monomorphism.

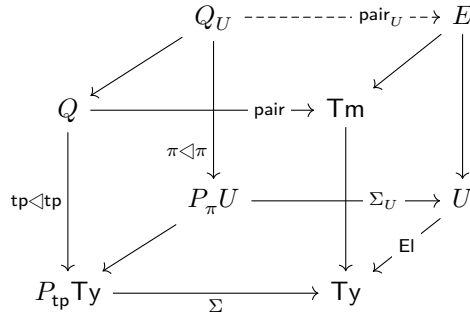
Now consider the polynomial composition $\pi \triangleleft \pi$.



Using pullback pasting, we see that the horizontal faces of the left cuboid and the right cube are all pullbacks. Hence we have a pullback



which is the left side of the following cube



As was the case for Π , pullback pasting along the vertical faces shows that the back face involving Σ_U and pair_U is also a pullback square. This concludes the construction of the Σ type former for the universe U . Again, the only data we needed to supply was the lift Σ_U of $\Sigma: P_{\text{tp}} \text{Ty} \rightarrow \text{Ty}$ to the universe U .

$$\begin{array}{ccccc}
& & \pi \times_U \pi & \xrightarrow{\quad} & E \\
& \swarrow \text{dashed} & \downarrow & \lrcorner & \downarrow \\
\text{tp} \times_{T_y} \text{tp} & \xrightarrow{\quad} & Tm & & U \\
\downarrow & & \downarrow & \lrcorner & \downarrow \\
& & E & \xrightarrow{\quad} & U \\
& \swarrow & \downarrow & \lrcorner & \downarrow \\
Tm & \xrightarrow{\quad} & Ty & &
\end{array}$$

Definition 0.1.8. We will say that universe U is closed under formation of Id -types when we have some map $\text{Id}_U : \pi \times_U \pi \rightarrow U$ making the following square commute

$$\begin{array}{ccc}
\pi \times_U \pi & \xrightarrow{\quad} & \text{tp} \times_{T_y} \text{tp} \\
\text{Id}_U \downarrow \text{dashed} & & \downarrow \text{Id} \\
U & \xrightarrow{\quad \text{El} \quad} & Ty
\end{array}$$

Again, this is merely propositional when El is a monomorphism.

From this we can obtain refl_U since E is a pulback.

$$\begin{array}{ccccc}
& & E & \xrightarrow{\quad \text{refl}_U \quad} & E \\
& \swarrow & \downarrow \delta_U & \lrcorner & \downarrow \\
Tm & \xrightarrow{\quad \text{refl} \quad} & Tm & & U \\
\downarrow \delta & & \downarrow & \lrcorner & \downarrow \\
& & \pi \times_U \pi & \xrightarrow{\quad \text{Id}_U \quad} & U \\
& \swarrow & \downarrow & \lrcorner & \downarrow \\
\text{tp} \times_{T_y} \text{tp} & \xrightarrow{\quad \text{Id} \quad} & Ty & &
\end{array}$$

We must ensure that the left face commutes - which we can prove using the universal property of $\text{tp} \times_{T_y} \text{tp}$. It remains to construct J_U , a section of ε_U , given below

$$\begin{array}{c}
\begin{array}{ccccc}
& & \text{refl}_U & \xrightarrow{\quad} & \\
E & \xrightarrow{\quad \rho_U \quad} & I_U & \xrightarrow{\quad} & E \\
& \searrow \delta & \downarrow & \lrcorner & \downarrow \pi \\
& & \pi \times_U \pi & \xrightarrow{\quad \text{Id}_U \quad} & U
\end{array} \\
\\
\begin{array}{ccccc}
& & (\rho_U^*)_E & \xrightarrow{\quad} & \\
P_{q_U} E & \xrightarrow{\quad \varepsilon_U \quad} & T_U & \xrightarrow{\quad} & P_\pi E \\
& \searrow P_{q_U} \text{tp} & \downarrow & \lrcorner & \downarrow P_\pi \pi \\
& & P_{q_U} U & \xrightarrow{\quad (\rho_U^*)_U \quad} & P_\pi U
\end{array} \\
\\
\begin{array}{ccccc}
& & I_U & \xrightarrow{\quad} & E \\
& \swarrow & \downarrow & \lrcorner & \downarrow \\
& & \pi \times_U \pi & \xrightarrow{\quad} & \text{tp} \times_{T_y} \text{tp} \\
& \swarrow & \downarrow & \lrcorner & \downarrow \\
& & E & \xrightarrow{\quad} & Tm \\
& \swarrow & \downarrow & \lrcorner & \downarrow \\
& & U & \xrightarrow{\quad} & Ty
\end{array}
\end{array}
\tag{0.1.11}$$

Now the above give us the following pullback factorization of 0.1.7

$$\pi \xRightarrow{\kappa} \text{tp}$$

$$\begin{array}{ccc} E & \xrightarrow{\quad} & \text{Tm} \\ \downarrow \rho_U & \lrcorner & \downarrow \rho \\ \pi \left(\begin{array}{ccc} I_U & \xrightarrow{\quad} & I \end{array} \right) & \xrightarrow{\quad} & \text{tp} \\ \downarrow q_U & \lrcorner & \downarrow q \\ U & \xrightarrow{\text{El}} & \text{Ty} \end{array}$$

If we apply 0.3.7 to the lower pullback square, i.e. κ_q then we will get a cartesian natural tranformation $P_{\kappa_U} : P_{q_U} \rightarrow P_q$. Like in 0.1.8, evaluating this at the pullback square 0.1.7 induces the cube below with pullbacks on every face.

$$\begin{array}{ccccc} & P_{q_U} E & \xrightarrow{\quad} & P_q E & \\ & \swarrow & & \swarrow & \\ P_{q_U} \text{Tm} & \xrightarrow{\quad} & P_q \text{Tm} & & \\ & \downarrow & & \downarrow & \\ & P_{q_U} U & \xrightarrow{\quad} & P_q U & \\ & \swarrow & & \swarrow & \\ P_{q_U} \text{Ty} & \xrightarrow{\quad} & P_q \text{Ty} & & \end{array} \quad (0.1.12)$$

Now we consider the diagrams for both ε and ε_U

$$\begin{array}{ccccccc} & P_{q_U} E & \xrightarrow{\varepsilon_U} & T_U & \xrightarrow{\quad} & P_{\pi} E & \\ & \downarrow & & \downarrow & \lrcorner & \downarrow & \\ & P_{q_U} U & \xrightarrow{\quad} & P_{\pi} U & & & \\ & \swarrow & & \swarrow & & \swarrow & \\ P_q \text{Tm} & \xrightarrow{\varepsilon} & T & \xrightarrow{\quad} & P_{\text{tp}} \text{Tm} & & \\ & \downarrow & & \downarrow & & \downarrow & \\ P_q \text{Ty} & \xrightarrow{\quad} & P_{\text{tp}} \text{Ty} & & & & \end{array}$$

The right face is the composed diagonal pullback square from 0.1.8. The left face of the outer cube is the composed diagonal pullback square from 0.1.12. The front face of the outer cube is the naturality square for ρ^* from 0.1.5 and similarly the back face is the naturality square for ρ_U^* from 0.1.11.

Since the left face is a pullback square, to make $J_U : T_U \rightarrow P_{q_U} E$ it suffices to consider

$$\begin{array}{ccc} T_U & \xrightarrow{d} & T \\ \downarrow J_U & & \downarrow J \\ P_{q_U} E & \xrightarrow{\quad} & P_q \text{Tm} \\ \downarrow & \lrcorner & \downarrow \\ P_{q_U} U & \xrightarrow{\quad} & P_q \text{Ty} \end{array}$$

It follows from uniqueness of maps into pullbacks that J_U so defined is a section of ε_U . This concludes the construction of the Id type former for the universe \mathbf{U} . Again, the only data we needed to supply was the lift Id_U of Id to the universe \mathbf{U} .

0.1.7 Binary products and Exponentials

It is convenient to specialize Σ and Π types to their non-dependent counterparts. In the natural model we can construct these by considering first the map

$$(\text{fst}, \text{snd}) : \text{Ty} \times \text{Ty} \rightarrow P_{\text{tp}} \text{Ty}$$

which we can visualize in

$$\begin{array}{ccc} \text{Ty} \leftarrow \text{snd} - \text{Tm} \times \text{Ty} & \longrightarrow & \text{Tm} \\ \text{fst}^* \text{tp} \downarrow & \lrcorner & \downarrow \text{tp} \\ \text{Ty} \times \text{Ty} & \xrightarrow{\text{fst}} & \text{Ty} \end{array}$$

Then, respectively, the pullback of the diagrams 0.1.1 and 0.1.2 for interpreting Π and Σ rules along this map give us pullback diagrams for interpreting function types and product types.

$$\begin{array}{ccccc} & & \lambda & & \\ & \nearrow & & \searrow & \\ F & \xrightarrow{(\text{dom}, \text{fun})} & P_{\text{tp}} \text{Tm} & \xrightarrow{\lambda} & \text{Tm} \\ (\text{dom}, \text{cod}) \downarrow & \lrcorner & P_{\text{tp}} \text{tp} \downarrow & \lrcorner & \downarrow \text{tp} \\ \text{Ty} \times \text{Ty} & \xrightarrow{(\text{fst}, \text{snd})} & P_{\text{tp}} \text{Ty} & \xrightarrow{\Pi} & \text{Ty} \\ & \searrow & & \nearrow & \\ & & \text{Exp} & & \end{array}$$

$$\begin{array}{ccccc} & & \text{pair} & & \\ & \nearrow & & \searrow & \\ \text{Tm} \times \text{Tm} & \xrightarrow{(\text{snd}, \text{fst}, \text{tp} \circ \text{snd})} & Q & \xrightarrow{\text{pair}} & \text{Tm} \\ \text{tp} \times \text{tp} \downarrow & \lrcorner & \text{tp} \triangleleft \text{tp} \downarrow & \lrcorner & \downarrow \text{tp} \\ \text{Ty} \times \text{Ty} & \xrightarrow{(\text{fst}, \text{snd})} & P_{\text{tp}} \text{Ty} & \xrightarrow{\Sigma} & \text{Ty} \\ & \searrow & & \nearrow & \\ & & \times & & \end{array}$$

By the universal property of pullbacks and 0.3.2 We can write a map $\Gamma \rightarrow F$ as a triple (A, B, f) such that $A, B : \Gamma \rightarrow \text{Ty}$ and

$$\begin{array}{ccc} \Gamma \cdot A & \xrightarrow{f} & \text{Tm} \\ \text{disp}_A \downarrow & & \downarrow \text{tp} \\ \Gamma & \xrightarrow{B} & \text{Ty} \end{array}$$

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

$$\begin{array}{ccc}
\Gamma \cdot A & \xrightarrow{f} & \mathsf{Tm} \\
\downarrow \text{disp}_A & \searrow (\text{disp}_A, f) & \downarrow \text{disp}_B \\
\Gamma \cdot B & \xrightarrow{\quad} & \mathsf{Tm} \\
\downarrow \text{disp}_B & \searrow & \downarrow \\
\Gamma & \xrightarrow{B} & \mathsf{Ty}
\end{array}$$

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 0.3.2 to classify a map into the pullback (whatever it may be) as a pair (α, β) , where $\alpha, \beta : \Gamma \rightarrow \mathsf{Tm}$. This could then be adapted to a proof that the pullback is what the diagram claims it to be.

Naturally, there are the same constructions bounded by the universe, which will exist when Π_U and Σ_U exist.

$$\begin{array}{ccc}
\mathsf{U} \times \mathsf{U} & \xrightarrow{\text{Exp}_U} & \mathsf{U} \\
\text{El} \times \text{El} \downarrow & & \downarrow \text{El} \\
\mathsf{Ty} \times \mathsf{Ty} & \xrightarrow{\text{Exp}} & \mathsf{Ty}
\end{array}
\qquad
\begin{array}{ccc}
\mathsf{U} \times \mathsf{U} & \xrightarrow{\times_U} & \mathsf{U} \\
\text{El} \times \text{El} \downarrow & & \downarrow \text{El} \\
\mathsf{Ty} \times \mathsf{Ty} & \xrightarrow{\times} & \mathsf{Ty}
\end{array}$$

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

$$\begin{array}{ccc}
\Gamma \cdot A & \xrightarrow{\text{var}_A} & \mathsf{Tm} \\
\downarrow \text{disp}_A & \searrow & \downarrow \text{tp} \\
\Gamma & \xrightarrow{A} & \mathsf{Ty}
\end{array}
\qquad
\begin{array}{ccc}
\Gamma & \xrightarrow{\text{id}_A} & \mathsf{Tm} \\
\downarrow (A, A) & \searrow (A, A, \text{var}_A) & \downarrow \text{tp} \\
\mathsf{Ty} \times \mathsf{Ty} & \xrightarrow{\text{Exp}} & \mathsf{Ty}
\end{array}$$

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

$$\begin{array}{ccc}
\Gamma \cdot A & \xrightarrow{\text{var}_A} & \mathsf{Tm} \\
\downarrow \text{disp}_A & \searrow & \downarrow \text{tp} \\
\Gamma & \xrightarrow{A} & \mathsf{Ty}
\end{array}$$

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

0.1.8 Univalence

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

$$f \sim g := \Pi_{a:A} \text{ld}(f a, g a)$$

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

$$\text{BigLinv } f := \Sigma_{g:B \rightarrow A} g \circ f \sim \text{id}_A$$

$$\text{BigRinv } f := \Sigma_{g:B \rightarrow A} f \circ g \sim \text{id}_B$$

and the property of being an equivalence

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

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

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

$$\text{Equiv } A \ B := \Sigma_{f:A \rightarrow B} \text{IsEquiv } f$$

Again, internally we can define a function

$$\text{IdToEquiv } A \ B : \text{Id}(A, B) \rightarrow \text{Equiv } A \ B$$

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

Definition 0.1.9. Univalence for universe \mathbb{U} states that IdToEquiv itself is an equivalence

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

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

$$\begin{array}{ccc} \mathbb{U} \cdot \mathbb{U} \cdot \text{Id} & \xrightarrow{\text{IdToEquiv}} & \mathbb{U} \cdot \mathbb{U} \cdot \text{Equiv} \\ & \searrow & \swarrow \\ & \mathbb{U} \cdot \mathbb{U} & \end{array}$$

0.1.9 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. 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 $\text{Id}(a, b)$ then we have that definitionally $a \equiv b$, i.e. they are equal morphisms in the natural model. This amounts to requiring that 0.1.3 is a pullback, i.e. ρ is an isomorphism

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

Note that this means ρ^* is an isomorphism, from which it follows that 0.1.4 is also a pullback, i.e. ε is an isomorphism.

$$\begin{array}{ccc} P_q \text{Tm} & \xrightarrow{\rho_{\text{Tm}}^*} & P_{\text{tp}} \text{Tm} \\ P_q \text{tp} \downarrow & \lrcorner & \downarrow P_{\text{tp}} \text{tp} \\ P_q \text{Ty} & \xrightarrow{\rho_{\text{Ty}}^*} & P_{\text{tp}} \text{Tm} \end{array}$$

If we were to only require UIP then this is asking that $I \rightarrow \mathbf{tp} \times_{\mathbf{Ty}} \mathbf{tp}$ is a strict proposition, meaning for any $(a, b) : \Gamma \rightarrow \mathbf{tp} \times_{\mathbf{Ty}} \mathbf{tp}$ there is at most one lift

$$\begin{array}{ccc} & & I \\ & \nearrow \text{!} & \downarrow \\ \Gamma & \xrightarrow{(a,b)} & \mathbf{tp} \times_{\mathbf{Ty}} \mathbf{tp} \end{array}$$

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 is 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 is just the extensional case again.

0.2 The Groupoid Model

In this section we construct a natural model in $\mathbf{Psh}(\mathbf{grpd})$ the presheaf category indexed by the category \mathbf{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 \mathbf{grpd} - which comes from restricting the “classical Quillen model structure” on \mathbf{cat} [Joy] to \mathbf{grpd} .

0.2.1 Classifying display maps

Notation. We denote the category of small categories as \mathbf{cat} and the large categories as \mathbf{Cat} . We denote the category of small groupoids as \mathbf{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

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

In this section, \mathbf{Tm} and \mathbf{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 \mathbf{cat}_\bullet to have objects as pairs $(\mathbb{C} \in \mathbf{cat}, c \in \mathbb{C})$ and morphisms as pairs

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

Then the category of pointed small groupoids \mathbf{grpd}_\bullet 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 $\mathbf{Psh}(\mathbf{grpd})$

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

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 $i: \mathbf{grpd} \hookrightarrow \mathbf{Cat}$, we can restrict \mathbf{Cat} indexed presheaves to be \mathbf{grpd} indexed presheaves (this the nerve in $i_! \dashv \text{res}$). We define $\mathbf{tp}: \mathbf{Tm} \rightarrow \mathbf{Ty}$ as the image of $U \circ$ under this restriction.

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

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

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 $(f: c \rightarrow d, \phi: Ff \cdot x \rightarrow y)$. This makes the following pullback in \mathbf{Cat}

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

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 $y\mathbf{disp}_A$.*

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

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

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

The Yoneda embedding $y : \mathbf{Cat} \rightarrow \mathbf{Psh}(\mathbf{Cat})$ preserves pullbacks, as does \mathbf{res} since it is a right adjoint (with left Kan extension $\iota_! \dashv \mathbf{res}_!$). \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 $\mathbf{lift} a f$ 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 $\mathbf{lift} a f : a \rightarrow b$ in \mathbb{C}_1 such that $p(\mathbf{lift} a f) = f$ and moreover $\mathbf{lift} a g \circ f = \mathbf{lift} b g \circ \mathbf{lift} a f$

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

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*

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

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 **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 $p \in \text{Fib}_\Gamma$ 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*

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

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).

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

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 $(\text{id}_x, f) : (x, a_0) \rightarrow (x, a_1)$

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

$\Sigma_A B$ 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.*

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

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

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

$$\begin{array}{ccccccc}
& & & & & & (\sigma x)_A \\
& & & & & & \curvearrowright \\
A(\sigma x) & \xrightarrow{x_{A\sigma}} & \Delta \cdot A\sigma & \xrightarrow{\sigma_A} & \Gamma \cdot A & \xrightarrow{B} & \mathbf{grpd} \\
\downarrow \scriptstyle \downarrow & \downarrow \scriptstyle \downarrow & \downarrow \scriptstyle \downarrow & \downarrow \scriptstyle \downarrow & \downarrow \scriptstyle \downarrow & \downarrow \scriptstyle \downarrow & \\
\bullet & \xrightarrow{x} & \Delta & \xrightarrow{\sigma} & \Gamma & \xrightarrow{A} & \mathbf{grpd}
\end{array}$$

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

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

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

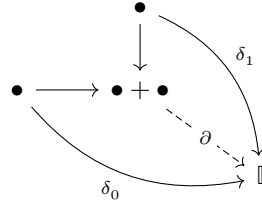
$$\begin{array}{ccccc}
 \Delta \cdot A\sigma \cdot B \circ \sigma_A & \xrightarrow{\sigma_{A \cdot B}} & \Gamma \cdot A \cdot B \\
 \downarrow \text{disp}_{B \circ \sigma_A} & & \downarrow \text{disp}_B \\
 \Delta \cdot A\sigma & \xrightarrow{\sigma_A} & \Gamma \cdot A & \xrightarrow{B} & \mathbf{grpd}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

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

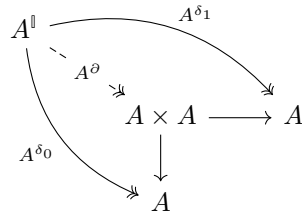
Proposition 0.2.17 (All objects are fibrant). *Let \bullet denote the terminal groupoid, namely that with a single object and morphism. Then the unique map $\Gamma \rightarrow \bullet$ is a fibration.*

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 A be a small groupoid. Recall that \mathbf{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 $A^! : A \rightarrow A^!$.

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

$$\begin{array}{ccccc}
A & \xrightarrow{\cong} & \bullet \cdot A & \xrightarrow{\text{var}_A} & \mathbf{grpd}_\bullet \\
\downarrow & & \downarrow A^* \rho' & \downarrow \rho' & \nearrow \\
A^\parallel & \xrightarrow{\cong} & \bullet \cdot A \cdot A \cdot \text{ld} & \longrightarrow & I' \\
\downarrow A^\partial & & \downarrow \text{disp}_{\text{ld}' \circ U^* \text{var}_A} & \downarrow & \nearrow \text{ld}' \\
A \times A & \xrightarrow{\cong} & \bullet \cdot A \cdot A & \longrightarrow & U \times \mathbf{grpd} \quad U \xrightarrow{\text{snd}} \mathbf{grpd}_\bullet \\
\downarrow \text{fst} & & \downarrow \text{disp}_{U \circ \text{var}_A} & \downarrow \text{fst} & \downarrow U \\
A & \xrightarrow{\cong} & \bullet \cdot A & \xrightarrow{\text{var}_A} & \mathbf{grpd}_\bullet \xrightarrow{U} \mathbf{grpd} \\
& & \downarrow \text{disp}_A & \downarrow U & \\
& & \bullet & \xrightarrow{A} & \mathbf{grpd}
\end{array}$$

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.

0.2.3 Classifying type dependency

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

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

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

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

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

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

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

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

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 $\tilde{F} : P_{\mathbf{tp}}X \rightarrow X$ pointwise as

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

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 0.2.20

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

□

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

Then we define the natural transformation $\lambda : P_{\mathbf{tp}}\mathbf{Ty} \rightarrow \mathbf{Ty}$ 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

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

These combine to give us a pullback square

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

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

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

where we have used 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 $(A, B) : \Gamma \rightarrow P_{\mathbf{tp}} \mathbf{Tm}$ such that $U \circ f = \Pi_A B$, there exists a unique $(A, \beta) : \Gamma \rightarrow P_{\mathbf{tp}} \mathbf{Tm}$ 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 0.3.3. Use R to denote the fiber product*

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

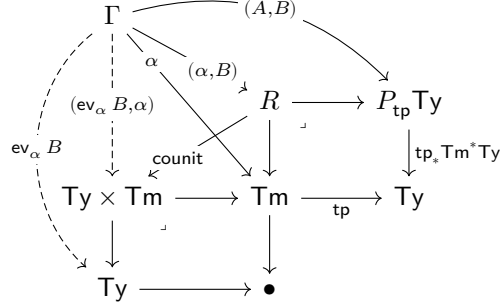
By the universal property of pullbacks, The data of a map from a representable $\varepsilon : \Gamma \rightarrow R$ corresponds to the data of $\alpha : \Gamma \rightarrow \mathbf{Tm}$ and $(U \circ \alpha, B) : \Gamma \rightarrow P_{\mathbf{tp}} \mathbf{Tm}$. Then by 0.2.20 this corresponds to the data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

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

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

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

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.



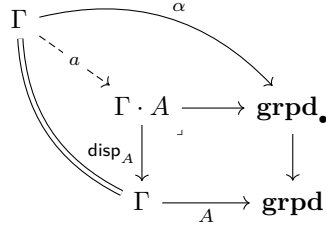
where we write $A := U \circ \alpha$ and treat a map $\Gamma \rightarrow \mathbf{grpd}$ as the same as a map $\Gamma \rightarrow \mathbf{Ty}$. More concisely, evaluation is a natural transformation $\text{ev} : R \rightarrow \mathbf{Ty}$, given by

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

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

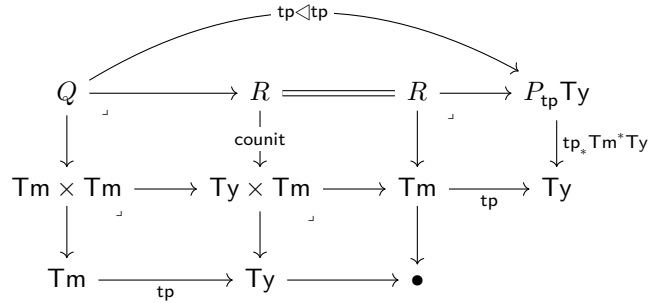
$$\text{ev}_\alpha B = B \circ a$$

where



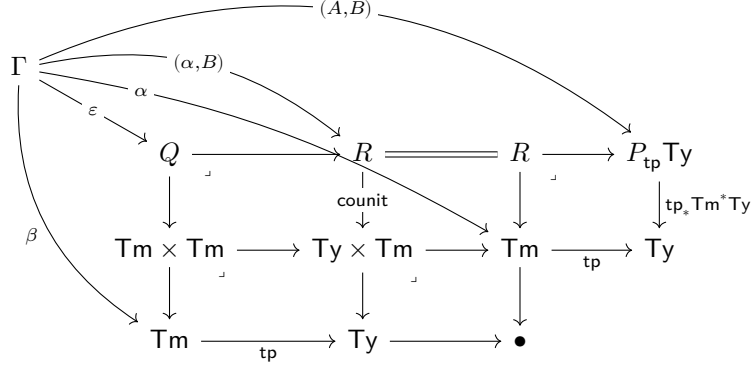
Proof. This is a specialization of 0.3.4 with liberal applications of Yoneda. \square

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 $(A, B) :$

$\Gamma \rightarrow P_{\text{tp}} \text{Ty}$ 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

$$\Sigma : P_{\text{tp}} \text{Ty} \rightarrow \text{Ty}$$

as that which is induced (0.2.21) by the Σ -former operation (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 $U \circ \beta = \text{ev}_\alpha B$). 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 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 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

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

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 ,

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

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

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

this uniquely determines α and β as

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

□

0.2.5 Identity types

Definition 0.2.28 (Identity formation and introduction). To define the commutative square in $\mathbf{Psh}(\mathbf{grpd})$

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

We first note that both δ and tp in the are in the essential image of the composition from 0.2.2

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

since the composition preserves pullbacks. So we first define in \mathbf{Cat}

$$\begin{array}{ccc} \mathbf{grpd}_\bullet & \xrightarrow{\text{refl}'} & \mathbf{grpd}_\bullet \\ \delta \downarrow & & \downarrow U \\ U \times_{\mathbf{grpd}} U & \xrightarrow{\text{Id}'} & \mathbf{grpd} \end{array} \quad (0.2.1)$$

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

To this end, let $\text{Id}' : U \times_{\mathbf{grpd}} U \rightarrow \mathbf{grpd}$ 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 $(f, \phi_0, \phi_1) : (A, a_0, a_1) \rightarrow (B, b_0, b_1)$ by

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

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

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

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

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

where the second component has to be the identity on the object id_a , 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 0.2.1 commutes. \square

Lemma 0.2.29. *We can then construct the pullback I'*

$$\begin{array}{ccccc} & & \text{refl}' & & \\ & & \curvearrowright & & \\ \mathbf{grpd}_\bullet & & & & \mathbf{grpd}_\bullet \\ & \searrow \rho' & \xrightarrow{\quad} & & \downarrow U \\ & I' & & & \mathbf{grpd} \\ & \downarrow \text{Id}' & & & \\ & U \times_{\mathbf{grpd}} U & \xrightarrow{\quad \text{Id}' \quad} & & \mathbf{grpd} \\ & \uparrow \delta & & & \\ & & & & \end{array}$$

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

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

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

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

Lemma 0.2.30. *Specialized to $q : I \rightarrow \mathbf{Ty}$ in $\mathbf{Psh}(\mathbf{grpd})$, the characterizing property of polynomial endofunctors 0.3.2 says that a map from a representable $\varepsilon : \Gamma \rightarrow P_q X$ corresponds to the data of*

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

where $A = q \circ \varepsilon$ and

$$\begin{array}{ccccc} X & \xleftarrow{C} & \Gamma \cdot A \cdot A \cdot \text{ld} & \longrightarrow & I' & \longrightarrow & \mathbf{grpd}_\bullet \\ & & \downarrow & & \downarrow & & \downarrow U \\ & & \Gamma \cdot A \cdot A & \longrightarrow & U \times_{\mathbf{grpd}} U & \xrightarrow{\text{ld}'} & \mathbf{grpd} \\ & & \downarrow & & \text{fst} \downarrow & & \\ & & \Gamma \cdot A & \longrightarrow & \mathbf{grpd}_\bullet & & \\ & & \downarrow & & \downarrow U & & \\ & & \Gamma & \xrightarrow{A} & \mathbf{grpd} & & \end{array}$$

Lemma 0.2.31.

$$\begin{array}{ccccc} & & & (A, \gamma_{\text{refl}}) & \\ & & \Gamma & \xrightarrow{\quad} & \\ & \searrow & & & \\ & & T & \longrightarrow & P_{\text{tp}} \mathbf{Tm} \\ & \downarrow & \downarrow & & \downarrow P_{\text{tp}} \text{tp} \\ (A, C) & \searrow & P_q \mathbf{Ty} & \xrightarrow{\rho_{\mathbf{Ty}}^*} & P_{\text{tp}} \mathbf{Tm} \end{array}$$

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

$$\begin{aligned} A &: \Gamma \rightarrow \mathbf{grpd} \\ C &: \Gamma \cdot A \cdot A \cdot \text{ld} \rightarrow \mathbf{grpd} \\ \gamma_{\text{refl}} &: \Gamma \cdot A \rightarrow \mathbf{grpd}_\bullet \\ \text{such that } C \circ A^* \rho' &= U \circ \gamma_{\text{refl}} \end{aligned}$$

$$\begin{array}{ccccc}
\mathbf{grpd}_\bullet & \xleftarrow{\gamma_{\text{refl}}} & \Gamma \cdot A & \xrightarrow{\text{var}_A} & \mathbf{grpd}_\bullet \\
\downarrow U & & \downarrow A^* \rho' & \downarrow \rho' & \downarrow U \\
\mathbf{grpd} & \xleftarrow{C} & \Gamma \cdot A \cdot A \cdot \text{ld} & \xrightarrow{\quad} & I' \\
& & \downarrow \text{disp}_{\text{ld}' \circ U^* \text{var}_A} & \downarrow \text{ld}' & \downarrow U \\
& & \Gamma \cdot A \cdot A & \xrightarrow{\quad} & U \times \mathbf{grpd} \\
& & \downarrow \text{disp}_{U \circ \text{var}_A} & \downarrow \text{fst} & \downarrow \text{snd} \\
& & \Gamma \cdot A & \xrightarrow{\text{var}_A} & \mathbf{grpd} \\
& & \downarrow \text{disp}_A & \downarrow U & \downarrow U \\
& & \Gamma & \xrightarrow{A} & \mathbf{grpd}
\end{array}$$

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

$$\begin{array}{ccc}
\Delta & & \\
\sigma \downarrow & \searrow (A \circ \sigma, C \circ q^* \sigma, \gamma_{\text{refl}} \circ \text{tp}^* \sigma) & \\
\Gamma & \xrightarrow{(A, C, \gamma_{\text{refl}})} & T
\end{array}$$

Proof.

$$\begin{array}{ccccc}
\Gamma & \xrightarrow{(A, \gamma_{\text{refl}})} & & & \\
\downarrow (A, C) & \searrow & T & \xrightarrow{\quad} & P_{\text{tp}} \mathbf{Tm} \\
& & \downarrow & \downarrow P_{\text{tp}} \text{tp} & \\
& & P_q \mathbf{T}_y & \xrightarrow{\rho_{\mathbf{T}_y}^*} & P_{\text{tp}} \mathbf{Tm}
\end{array}$$

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

$$\rho_{\mathbf{T}_y}^* \circ (A, C) = P_{\text{tp}} \text{tp} \circ (A', \gamma_{\text{refl}})$$

By 0.3.6 and 0.3.2 this says

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

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

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

By Yoneda this is equivalent to requiring

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

□

Proposition 0.2.32. We can compute $\varepsilon : P_q \mathbf{Tm} \rightarrow T$ via

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

Proof. This follows from the computation for T 0.2.31, the polynomial action on slice morphisms 0.3.6, and 0.3.2. □

Definition 0.2.33 (Identity elimination). We want to define $J : T \rightarrow P_q \mathsf{Tm}$

$$\begin{aligned} J_\Gamma : \mathbf{Psh}(\mathbf{grpd})(\Gamma, T) &\rightarrow \mathbf{Psh}(\mathbf{grpd})(\Gamma, P_q \mathsf{Tm}) \\ (A, C, \gamma_{\text{refl}}) &\mapsto (A, \gamma) \end{aligned}$$

for some $\gamma : \Gamma \cdot A \cdot A \cdot \text{Id} \rightarrow \mathbf{grpd}_\bullet$ which we will define below. We first use [T 0.2.31](#) to describe the given data:

$$\begin{array}{ccccc} \mathbf{grpd}_\bullet & \xleftarrow{\gamma_{\text{refl}}} & \Gamma \cdot A & \xrightarrow{\text{var}_A} & \mathbf{grpd}_\bullet \\ \downarrow U & \swarrow \gamma & \downarrow A^* \rho' & \downarrow \rho' & \downarrow U \\ \mathbf{grpd} & \xleftarrow{C} & \Gamma \cdot A \cdot A \cdot \text{Id} & \xrightarrow{\quad} & I' \\ \downarrow \text{disp}_{\text{Id}' \circ U^* \text{var}_A} & & \downarrow \text{Id}' & \downarrow \text{fst} & \downarrow U \\ & & \Gamma \cdot A \cdot A & \xrightarrow{\quad} & U \times_{\mathbf{grpd}} U \\ \downarrow \text{disp}_{U \circ \text{var}_A} & & \downarrow \text{var}_A & \downarrow U & \downarrow \text{snd} \\ & & \Gamma \cdot A & \xrightarrow{\quad} & \mathbf{grpd}_\bullet \\ \downarrow \text{disp}_A & & \downarrow A & \downarrow U & \downarrow U \\ & & \Gamma & \xrightarrow{\quad} & \mathbf{grpd} \end{array}$$

Let us name the fibers over the diagonal

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

and its given points

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

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

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

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

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

and

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

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

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

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

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

noting that from the computation of ρ' given in [0.2.29](#) it follows that

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

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

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

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

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

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

$$\begin{array}{ccc}
(A \circ \sigma, C \circ q^* \sigma, \gamma_{\text{refl}} \circ \text{tp}^* \sigma) & \xrightarrow{\quad} & (A \circ \sigma, \gamma_\Delta) \\
& & \text{\scriptsize $\begin{smallmatrix} \Downarrow \\ \Downarrow \\ \Downarrow \\ \Downarrow \end{smallmatrix}$} \\
& & (A \circ \sigma, \gamma_\Gamma \circ q^* \sigma)
\end{array}$$

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

$$(A, C, \gamma_{\text{refl}}) \xrightarrow{\quad} (A, \gamma_\Gamma)$$

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

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

Let us denote $q^* \sigma(x, a_0, a_1, h) = (\sigma x, a'_0, a'_1, h')$. Then

$$\begin{aligned}
& \gamma_\Delta(x, a_0, a_1, h) \\
& = (C \circ q^* \sigma(x, a_0, a_1, h), (C \circ q^* \sigma(\text{id}_x, \text{id}_{a_0}, h, _))(c_{\text{refl}}(\text{tp}^* \sigma(x, a_0)))) \\
& = (C(\sigma x, a'_0, a'_1, h'), (C(\text{id}_{\sigma x}, \text{id}_{a'_0}, h', _))(c_{\text{refl}}(\sigma x, a'_0))) \\
& = \gamma_\Gamma(\sigma x, a'_0, a'_1, h') \\
& = \gamma_\Gamma \circ q^* \sigma(x, a_0, a_1, h)
\end{aligned}$$

and similarly for morphisms. □

Proposition 0.2.34. $J : T \rightarrow P_q \mathbf{Tm}$, as defined above is a section of ε .

Proof. Let $(A, C, \gamma_{\text{refl}}) : \Gamma \rightarrow T$ be a map from a representable. Then using the definition of J and the computation of ε [0.2.32](#)

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

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

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

□

0.2.6 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 $\mathbf{Ty} = [-, \mathbf{Grpd}]$ and $\mathbf{Tm} = [-, \mathbf{Grpd}_*]$.

Definition 0.2.35 (Universe of discrete groupoids). Let \mathbf{U} be the (large) groupoid of small sets, i.e. let \mathbf{U} have \mathbf{set} as its objects and morphisms between two small sets as all the bijections between them. This gives us $\lceil \mathbf{U} \rceil : \bullet \rightarrow \mathbf{Ty}$.

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

$$\begin{array}{ccc} \mathbf{U} & \hookrightarrow & \mathbf{grpd} \\ & \searrow \text{El} & \downarrow \\ & & \mathbf{Grpd} \end{array}$$

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

$$\begin{array}{ccc} \mathbf{E} & \longrightarrow & \mathbf{Tm} \\ \pi \downarrow & \lrcorner & \downarrow \text{tp} \\ \mathbf{U} & \xrightarrow{\text{El}} & \mathbf{Ty} \end{array}$$

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

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

Then $\pi : \mathbf{E} \rightarrow \mathbf{U}$ 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 $\mathbf{ULift} : \mathbf{set} \rightarrow \mathbf{Set}$ then it may *not* be true that \mathbf{ULift} commutes with our type formers.

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

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

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

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

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

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

$$\Gamma \longrightarrow P_t Y$$

corresponds to

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

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

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

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

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

and given a morphism $f : X \rightarrow Y$, the morphism $P_t f$ acts on such a pair by

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

Lemma 0.3.3. Use R to denote the fiber product

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

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

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

By uniqueness in the universal property of pullbacks and 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 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

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

and

$$\begin{array}{ccccccc} & & \Gamma & & & & \\ & & \downarrow (\beta, y) & & \downarrow (\beta, y) & & \\ & & R & \xrightarrow{\rho_P} & P_t Y & & \\ & & \downarrow \text{counit} & \lrcorner & \downarrow t_* B^* Y & & \\ Y & \xleftarrow{\pi_Y} & Y \times B & \xrightarrow{\pi_B} & B & \xrightarrow{t} & A \end{array}$$

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

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

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

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

$$\begin{array}{ccc}
\Gamma & & \\
\downarrow b & \searrow (v \circ b, y \circ t^* d \circ t^* b) & \\
\Gamma \cdot t \circ \beta & \xrightarrow{(v, y \circ t^* d)} & R
\end{array}$$

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

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

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

□

Definition 0.3.5. Suppose

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

$$\begin{array}{ccccc}
t^*(t \circ \beta) & & & & t \circ \beta \\
\downarrow t^*(t \circ \beta, y) & \searrow \overline{(t \circ \beta, y)} & & & \downarrow (t \circ \beta, y) \quad \searrow (t \circ \beta, y) \\
t^*t_*B^*Y & \xrightarrow{\text{counit}} & B^*Y & \quad t^* \dashv t_* \quad & t_*B^*Y \xrightarrow[\text{counit}]{=} t_*B^*Y
\end{array}$$

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

$$\begin{array}{ccccc}
\Gamma \cdot t \circ \beta & \xrightarrow{(y, v)} & Y \times B & & \Gamma \xrightarrow{(t \circ \beta, y)} P_t Y \\
\downarrow v = t^*(t \circ \beta) & \swarrow B^*Y & & & \downarrow t \circ \beta \quad \swarrow t_*B^*Y \\
B & & & t^* \dashv t_* & A
\end{array}$$

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

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

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

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 (Contravariant of P_- on a slice). Let $P_- : (\mathbb{C}/A)^{\text{op}} \rightarrow [\mathbb{C}, \mathbb{C}]$ be defined by taking $s \mapsto P_s$ on objects and act on a morphism by

$$\begin{array}{ccc}
\begin{array}{ccc} & B & \\ & \uparrow \rho & \\ A & \xleftarrow{t} & C \\ & \nwarrow s & \end{array} & \longmapsto & \begin{array}{c} P_t \\ \downarrow \rho^* \\ P_s \end{array}
\end{array}$$

where

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

$$\begin{array}{ccc}
& \mathbb{C} & \\
P_s \swarrow & \downarrow C^* & \searrow B^* \\
& \mathbb{C}/C \leftarrow \rho^* - \mathbb{C}/B & \\
& \downarrow s_* & \swarrow \mu^* \searrow t_* \\
& \mathbb{C}/A & \\
& \downarrow A_! & \\
& \mathbb{C} & \\
& \nwarrow & \nearrow P_t
\end{array}$$

where $\mu = \mu^*$ is the mate from 3.5, and η is the natural isomorphism given by pullback pasting.

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

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

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

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

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

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

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

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

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

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

Then using 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

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

and

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

Moving back along the adjunction $\rho_{!} \dashv \rho^*$ 0.3.1 tells us that

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

$\beta \circ \alpha^* \rho$

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 0.3.7 (Covariant 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

$$P_- : \text{CartArr}(\mathbb{C}) \rightarrow [\mathbb{C}, \mathbb{C}]$$

where the action on a cartesian square is

$$\begin{array}{ccc}
 C & \xleftarrow{s} & D \\
 \theta \downarrow & \lrcorner & \downarrow \rho \\
 A & \xleftarrow{t} & B
 \end{array}
 \quad \xrightarrow{\quad} \quad
 \begin{array}{c}
 P_s \\
 \downarrow P_\kappa \\
 P_t
 \end{array}$$

given by the whiskered natural transformations

$$\begin{array}{c}
 \mathbb{C} \xlongequal{\quad} \mathbb{C} \\
 \left(\begin{array}{ccc}
 C^* \downarrow & \xRightarrow{\eta^{-1}} & \downarrow B^* \\
 \mathbb{C}/D \xleftarrow{\rho^*} & \mathbb{C}/B \\
 s_* \downarrow & \xRightarrow{\mu^{*-1}} & \downarrow t_* \\
 \mathbb{C}/C \xleftarrow{\theta^*} & \mathbb{C}/A \\
 C_! \downarrow & \xRightarrow{\mu_!} & \downarrow A_! \\
 \mathbb{C} \xlongequal{\quad} & \mathbb{C}
 \end{array} \right)
 \begin{array}{c}
 P_s \\
 \downarrow \\
 P_t
 \end{array}
 \end{array}$$

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

$$\begin{array}{ccc}
 P_s X & \xrightarrow{P_{\kappa Y}} & P_t X \\
 P_s f \downarrow & \lrcorner & \downarrow P_s f \\
 P_s Y & \xrightarrow{P_{\kappa Y}} & P_t Y
 \end{array}$$

The natural transformation P_κ computes in the following way

$$\begin{array}{ccc}
 \Gamma \cdot_t \theta \circ \alpha & & \\
 \swarrow \text{dashed } i & \searrow & \\
 \Gamma \cdot_s \alpha & \xrightarrow{\quad} & D \xrightarrow{\rho} B \\
 \downarrow & \lrcorner & \downarrow s \\
 \Gamma & \xrightarrow{\alpha} & C \xrightarrow{\theta} A
 \end{array}
 \quad
 \begin{array}{ccc}
 \Gamma & & \\
 (\alpha, \beta) \downarrow & \searrow (\theta \circ \alpha, \beta \circ i) & \\
 P_s X & \xrightarrow{P_{\kappa X}} & P_t X
 \end{array}$$

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 $P_{\kappa X}$ and $P_s f$ to show that the natural transformation P_κ is cartesian. Essentially, the first component of a map $\Gamma \rightarrow P_s X$ is determined by its composition with $P_s f$ and its second component is determined by its composition with $P_{\kappa X}$. \square

Corollary 0.3.8. *If we have*

$$\begin{array}{ccc}
 D' & \longrightarrow & B' \\
 \left(\begin{array}{ccc}
 \downarrow \rho_1 & & \downarrow \rho_2 \\
 D & \longrightarrow & B \\
 \downarrow q_1 & & \downarrow q_2 \\
 C & \xrightarrow{\theta} & A
 \end{array} \right)
 \begin{array}{c}
 q'_1 \\
 \downarrow \\
 q'_2
 \end{array}
 \end{array}$$

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

$$\begin{array}{ccc} P_{q_1} & \xrightarrow{P_\kappa} & P_{q_2} \\ \rho_1^* \downarrow & \lrcorner & \downarrow \rho_2^* \\ P_{q'_1} & \xrightarrow{P_{\kappa'}} & P_{q'_2} \end{array}$$

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 ρ^* . \square

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