

The Clowder Project

2017–2024



The Clowder Project Authors

Version 01f3714, compiled on Apr 04, 2024.

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Part I

Sets

Chapter 1

Sets

0000 This chapter (will eventually) contain material on axiomatic set theory, as well as a couple other things.

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0001 1.1 Sets and Functions

0002 1.1.1 Functions

0003 **Definition 1.1.1.1.1.** A **function** is a functional and total relation.

0004 **Notation 1.1.1.1.2.** Throughout this work, we will sometimes denote a function $f: X \rightarrow Y$ by

$$f \stackrel{\text{def}}{=} \llbracket x \mapsto f(x) \rrbracket.$$

1. For example, given a function

$$\Phi: \text{Hom}_{\text{Sets}}(X, Y) \rightarrow K$$

taking values on a set of functions such as $\text{Hom}_{\text{Sets}}(X, Y)$, we will sometimes also write

$$\Phi(f) \stackrel{\text{def}}{=} \Phi(\llbracket x \mapsto f(x) \rrbracket).$$

2. This notational choice is based on the lambda notation

$$f \stackrel{\text{def}}{=} (\lambda x. f(x)),$$

but uses a “ \mapsto ” symbol for better spacing and double brackets instead of either:

- (a) Square brackets $[x \mapsto f(x)]$;
- (b) Parentheses $(x \mapsto f(x))$;

hoping to improve readability when dealing with e.g.:

- (a) Equivalence classes, cf.:
 - i. $\llbracket [x] \mapsto f([x]) \rrbracket$
 - ii. $\llbracket [x] \mapsto f([x]) \rrbracket$
 - iii. $(\lambda [x]. f([x]))$
- (b) Function evaluations, cf.:
 - i. $\Phi(\llbracket x \mapsto f(x) \rrbracket)$
 - ii. $\Phi((x \mapsto f(x)))$
 - iii. $\Phi((\lambda x. f(x)))$

3. We will also sometimes write $-_1, -_2$, etc. for the arguments of a function. Some examples include:

- (a) Writing $f(-_1)$ for a function $f: A \rightarrow B$.
- (b) Writing $f(-_1, -_2)$ for a function $f: A \times B \rightarrow C$.
- (c) Given a function $f: A \times B \rightarrow C$, writing

$$f(a, -): B \rightarrow C$$

for the function $\llbracket b \mapsto f(a, b) \rrbracket$.

(d) Denoting a composition of the form

$$A \times B \xrightarrow{\phi \times \text{id}_B} A' \times B \xrightarrow{f} C$$

by $f(\phi(-_1), -_2)$.

4. Finally, given a function $f : A \rightarrow B$, we write

$$\text{ev}_a(f) \stackrel{\text{def}}{=} f(a)$$

for the value of f at some $a \in A$.

For an example of the above notations being used in practice, see the proof of the adjunction

$$(A \times - \dashv \text{Hom}_{\text{Sets}}(A, -)) : \text{Sets} \begin{array}{c} \xrightarrow{A \times -} \\ \perp \\ \xleftarrow{\text{Hom}_{\text{Sets}}(A, -)} \end{array} \text{Sets},$$

stated in [Item 2](#) of [Proposition 2.1.3.1.2](#).

0005 1.2 The Enrichment of Sets in Classical Truth Values

0006 1.2.1 (-2) -Categories

0007 **Definition 1.2.1.1.1.** A (-2) -category is the “necessarily true” truth value.^{1,2,3}

0008 1.2.2 (-1) -Categories

0009 **Definition 1.2.2.1.1.** A (-1) -category is a classical truth value.

000A **Remark 1.2.2.1.2.** ⁴ (-1) -categories should be thought of as being “categories enriched in (-2) -categories”, having a collection of objects and, for each pair of objects, a Hom-object $\text{Hom}(x, y)$ that is a (-2) -category (i.e. trivial).

Therefore, a (-1) -category C is either ([\[BS10, pp. 33–34\]](#)):

1. *Empty*, having no objects;
2. *Contractible*, having a collection of objects $\{a, b, c, \dots\}$, but with $\text{Hom}_C(a, b)$ being a (-2) -category (i.e. trivial) for all $a, b \in \text{Obj}(C)$, forcing all objects of C to be uniquely isomorphic to each other.

As such, there are only two (-1) -categories, up to equivalence:

- The (-1) -category false (the empty one);

¹Thus, there is only one (-2) -category.

²A $(-n)$ -category for $n = 3, 4, \dots$ is also the “necessarily true” truth value, coinciding with a (-2) -category.

³For motivation, see [\[BS10, p. 13\]](#).

⁴For more motivation, see [\[BS10, p. 13\]](#).

- The (-1) -category **true** (the contractible one).

000B Definition 1.2.2.1.3. The **poset of truth values**⁵ is the poset $(\{\text{true}, \text{false}\}, \preceq)$ consisting of

- *The Underlying Set.* The set $\{\text{true}, \text{false}\}$ whose elements are the truth values true and false.
- *The Partial Order.* The partial order

$$\preceq: \{\text{true}, \text{false}\} \times \{\text{true}, \text{false}\} \rightarrow \{\text{true}, \text{false}\}$$

on $\{\text{true}, \text{false}\}$ defined by⁶

$$\begin{aligned} \text{false} \preceq \text{false} &\stackrel{\text{def}}{=} \text{true}, \\ \text{true} \preceq \text{false} &\stackrel{\text{def}}{=} \text{false}, \\ \text{false} \preceq \text{true} &\stackrel{\text{def}}{=} \text{true}, \\ \text{true} \preceq \text{true} &\stackrel{\text{def}}{=} \text{true}. \end{aligned}$$

000C Notation 1.2.2.1.4. We also write $\{t, f\}$ for the poset $\{\text{true}, \text{false}\}$.

000D Proposition 1.2.2.1.5. The poset of truth values $\{t, f\}$ is Cartesian closed with product given by⁷

$$\begin{aligned} t \times t &= t, \\ t \times f &= f, \\ f \times t &= f, \\ f \times f &= f, \end{aligned}$$

and internal Hom $\mathbf{Hom}_{\{t,f\}}$ given by the partial order of $\{t, f\}$, i.e. by

$$\begin{aligned} \mathbf{Hom}_{\{t,f\}}(t, t) &= t, \\ \mathbf{Hom}_{\{t,f\}}(t, f) &= f, \\ \mathbf{Hom}_{\{t,f\}}(f, t) &= t, \\ \mathbf{Hom}_{\{t,f\}}(f, f) &= t. \end{aligned}$$

Proof. Existence of Products: We claim that the products $t \times t$, $t \times f$, $f \times t$, and $f \times f$ satisfy the universal property of the product in $\{t, f\}$. Indeed, consider

⁵*Further Terminology:* Also called the **poset of (-1) -categories**.

⁶This partial order coincides with logical implication.

⁷Note that \times coincides with the “and” operator, while $\mathbf{Hom}_{\{t,f\}}$ coincides with the logical implication operator.

the diagrams

$$\begin{array}{cccc}
 \begin{array}{ccc} p_1^1 & P_1 & p_2^1 \\ & \downarrow \exists! & \\ t & \underbrace{t \times t}_{=t} & t \\ \leftarrow \text{pr}_1 & & \text{pr}_2 \rightarrow \end{array} &
 \begin{array}{ccc} p_1^2 & P_2 & p_2^2 \\ & \downarrow \exists! & \\ t & \underbrace{t \times f}_{=f} & f \\ \leftarrow \text{pr}_1 & & \text{pr}_2 \rightarrow \end{array} &
 \begin{array}{ccc} p_1^3 & P_3 & p_2^3 \\ & \downarrow \exists! & \\ f & \underbrace{f \times t}_{=f} & t \\ \leftarrow \text{pr}_1 & & \text{pr}_2 \rightarrow \end{array} &
 \begin{array}{ccc} p_1^4 & P_4 & p_2^4 \\ & \downarrow \exists! & \\ f & \underbrace{f \times f}_{=f} & f \\ \leftarrow \text{pr}_1 & & \text{pr}_2 \rightarrow \end{array}
 \end{array}$$

Here:

1. If $P_1 = t$, then $p_1^1 = p_2^1 = \text{id}_t$, and there's indeed a unique morphism from P_1 to t making the diagram commute, namely id_t ;
2. If $P_1 = f$, then $p_1^1 = p_2^1$ are given by the unique morphism from f to t , and there's indeed a unique morphism from P_1 to t making the diagram commute, namely the unique morphism from f to t ;
3. If $P_2 = t$, then there is no morphism p_2^2 .
4. If $P_2 = f$, then p_1^2 is the unique morphism from f to t while $p_2^2 = \text{id}_f$, and there's indeed a unique morphism from P_2 to f making the diagram commute, namely id_f ;
5. The proof for P_3 is similar to the one for P_2 ;
6. If $P_4 = t$, then there is no morphism p_1^4 or p_2^4 .
7. If $P_4 = f$, then $p_1^4 = p_2^4 = \text{id}_f$, and there's indeed a unique morphism from P_4 to f making the diagram commute, namely id_f .

Cartesian Closedness: We claim there's a bijection

$$\text{Hom}_{\{t,f\}}(A \times B, C) \cong \text{Hom}_{\{t,f\}}(A, \mathbf{Hom}_{\{t,f\}}(B, C))$$

natural in $A, B, C \in \{t, f\}$. Indeed:

- For $(A, B, C) = (t, t, t)$, we have

$$\begin{aligned}
 \text{Hom}_{\{t,f\}}(t \times t, t) &\cong \text{Hom}_{\{t,f\}}(t, t) \\
 &= \{\text{id}_{\text{true}}\} \\
 &\cong \text{Hom}_{\{t,f\}}(t, t) \\
 &\cong \text{Hom}_{\{t,f\}}(t, \mathbf{Hom}_{\{t,f\}}(t, t)).
 \end{aligned}$$

- For $(A, B, C) = (t, t, f)$, we have

$$\begin{aligned}
 \text{Hom}_{\{t,f\}}(t \times t, f) &\cong \text{Hom}_{\{t,f\}}(t, f) \\
 &= \emptyset \\
 &\cong \text{Hom}_{\{t,f\}}(t, f) \\
 &\cong \text{Hom}_{\{t,f\}}(t, \mathbf{Hom}_{\{t,f\}}(t, f)).
 \end{aligned}$$

- For $(A, B, C) = (t, f, t)$, we have

$$\begin{aligned} \text{Hom}_{\{t,f\}}(t \times f, t) &\cong \text{Hom}_{\{t,f\}}(f, t) \\ &\cong \text{pt} \\ &\cong \text{Hom}_{\{t,f\}}(f, t) \\ &\cong \text{Hom}_{\{t,f\}}(f, \mathbf{Hom}_{\{t,f\}}(f, t)). \end{aligned}$$

- For $(A, B, C) = (t, f, f)$, we have

$$\begin{aligned} \text{Hom}_{\{t,f\}}(t \times f, f) &\cong \text{Hom}_{\{t,f\}}(f, f) \\ &\cong \{\text{id}_{\text{false}}\} \\ &\cong \text{Hom}_{\{t,f\}}(f, f) \\ &\cong \text{Hom}_{\{t,f\}}(t, \mathbf{Hom}_{\{t,f\}}(f, f)). \end{aligned}$$

- For $(A, B, C) = (f, t, t)$, we have

$$\begin{aligned} \text{Hom}_{\{t,f\}}(f \times t, t) &\cong \text{Hom}_{\{t,f\}}(f, t) \\ &\cong \text{pt} \\ &\cong \text{Hom}_{\{t,f\}}(f, t) \\ &\cong \text{Hom}_{\{t,f\}}(f, \mathbf{Hom}_{\{t,f\}}(t, t)). \end{aligned}$$

- For $(A, B, C) = (f, t, f)$, we have

$$\begin{aligned} \text{Hom}_{\{t,f\}}(f \times t, f) &\cong \text{Hom}_{\{t,f\}}(f, f) \\ &\cong \{\text{id}_{\text{false}}\} \\ &\cong \text{Hom}_{\{t,f\}}(f, f) \\ &\cong \text{Hom}_{\{t,f\}}(f, \mathbf{Hom}_{\{t,f\}}(t, f)). \end{aligned}$$

- For $(A, B, C) = (f, f, t)$, we have

$$\begin{aligned} \text{Hom}_{\{t,f\}}(f \times f, t) &\cong \text{Hom}_{\{t,f\}}(f, t) \\ &\cong \text{pt} \\ &\cong \text{Hom}_{\{t,f\}}(f, t) \\ &\cong \text{Hom}_{\{t,f\}}(f, \mathbf{Hom}_{\{t,f\}}(f, t)). \end{aligned}$$

- For $(A, B, C) = (f, f, f)$, we have

$$\begin{aligned} \text{Hom}_{\{t,f\}}(f \times f, f) &\cong \text{Hom}_{\{t,f\}}(f, f) \\ &= \{\text{id}_{\text{false}}\} \\ &\cong \text{Hom}_{\{t,f\}}(f, f) \\ &\cong \text{Hom}_{\{t,f\}}(f, \mathbf{Hom}_{\{t,f\}}(f, f)). \end{aligned}$$

The proof of naturality is omitted.

□

000E 1.2.3 0-Categories**000F Definition 1.2.3.1.1.** A **0-category** is a poset.⁸**000G Definition 1.2.3.1.2.** A **0-groupoid** is a 0-category in which every morphism is invertible.⁹**000H 1.2.4 Tables of Analogies Between Set Theory and Category Theory**

Here we record some analogies between notions in set theory and category theory. Note that the analogies relating to presheaves relate equally well to copresheaves, as the opposite X^{op} of a set X is just X again.

Basics:

SET THEORY	CATEGORY THEORY
Enrichment in $\{\text{true}, \text{false}\}$	Enrichment in Sets
Set X	Category \mathcal{C}
Element $x \in X$	Object $X \in \text{Obj}(\mathcal{C})$
Function	Functor
Function $X \rightarrow \{\text{true}, \text{false}\}$	Functor $\mathcal{C} \rightarrow \text{Sets}$
Function $X \rightarrow \{\text{true}, \text{false}\}$	Presheaf $\mathcal{C}^{\text{op}} \rightarrow \text{Sets}$

Powersets and categories of presheaves:

⁸*Motivation:* A 0-category is precisely a category enriched in the poset of (-1) -categories.

⁹That is, a *set*.

SET THEORY	CATEGORY THEORY
Powerset $\mathcal{P}(X)$	Presheaf category $\text{PSh}(C)$
Characteristic function $\chi_{\{x\}}$	Representable presheaf h_X
Characteristic embedding $\chi_{(-)} : X \hookrightarrow \mathcal{P}(X)$	Yoneda embedding $\mathcal{J} : C^{\text{op}} \hookrightarrow \text{PSh}(C)$
Characteristic relation $\chi_X(-1, -2)$	Hom profunctor $\text{Hom}_C(-1, -2)$
The Yoneda lemma for sets $\text{Hom}_{\mathcal{P}(X)}(\chi_x, \chi_U) = \chi_U(x)$	The Yoneda lemma for categories $\text{Nat}(h_X, \mathcal{F}) \cong \mathcal{F}(X)$
The characteristic embedding is fully faithful, $\text{Hom}_{\mathcal{P}(X)}(\chi_x, \chi_y) = \chi_X(x, y)$	The Yoneda embedding is fully faithful, $\text{Nat}(h_X, h_Y) \cong \text{Hom}_C(X, Y)$
Subsets are unions of their elements $U = \bigcup_{x \in U} \{x\}$ or $\chi_U = \text{colim}_{\chi_x \in \text{Sets}(U, \{t, f\})} (\chi_x)$	Presheaves are colimits of representables, $\mathcal{F} \cong \text{colim}_{h_X \in \int_C \mathcal{F}} (h_X)$

Categories of elements:

SET THEORY	CATEGORY THEORY
Assignment $U \mapsto \chi_U$	Assignment $\mathcal{F} \mapsto \int_C \mathcal{F}$ (the category of elements)
Assignment $U \mapsto \chi_U$ giving an isomorphism $\mathcal{P}(X) \cong \text{Sets}(X, \{t, f\})$	Assignment $\mathcal{F} \mapsto \int_C \mathcal{F}$ giving an equivalence $\text{PSh}(C) \cong^{\text{eq.}} \text{DFib}(C)$

Functions between powersets and functors between presheaf categories:

SET THEORY	CATEGORY THEORY
Direct image function $f_* : \mathcal{P}(X) \rightarrow \mathcal{P}(Y)$	Inverse image functor $f^{-1} : \text{PSh}(C) \rightarrow \text{PSh}(D)$
Inverse image function $f^{-1} : \mathcal{P}(Y) \rightarrow \mathcal{P}(X)$	Direct image functor $f_* : \text{PSh}(D) \rightarrow \text{PSh}(C)$
Direct image with compact support function $f_! : \mathcal{P}(X) \rightarrow \mathcal{P}(Y)$	Direct image with compact support functor $f_! : \text{PSh}(C) \rightarrow \text{PSh}(D)$

Relations and profunctors:

SET THEORY	CATEGORY THEORY
Relation $R: X \times Y \rightarrow \{t, f\}$	Profunctor $\mathfrak{p}: \mathcal{D}^{\text{op}} \times \mathcal{C} \rightarrow \text{Sets}$
Relation $R: X \rightarrow \mathcal{P}(Y)$	Profunctor $\mathfrak{p}: \mathcal{C} \rightarrow \text{PSh}(\mathcal{D})$
Relation as a cocontinuous morphism of posets $R: (\mathcal{P}(X), \subset) \rightarrow (\mathcal{P}(Y), \subset)$	Profunctor as a colimit-preserving functor $\mathfrak{p}: \text{PSh}(\mathcal{C}) \rightarrow \text{PSh}(\mathcal{D})$

Appendices

1.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets

Relations

5. Relations

6. Constructions With Relations

7. Equivalence Relations and Apartness Relations

Category Theory

8. Categories

Bicategories

9. Types of Morphisms in Bicategories

Chapter 2

Constructions With Sets

000J This chapter develops some material relating to constructions with sets with an eye towards its categorical and higher-categorical counterparts to be introduced later in this work. In particular, it contains:

1. Explicit descriptions of the major types of co/limits in Sets, including in particular explicit descriptions of pushouts and coequalisers (see [Definitions 2.2.4.1.1](#) and [2.2.5.1.1](#) and [Remarks 2.2.4.1.2](#) and [2.2.5.1.2](#)).
2. A discussion of powersets as decategorifications of categories of presheaves ([Remarks 2.4.1.1.2](#) and [2.4.3.1.2](#)), including a (-1) -categorical analogue of un/straightening, described in [Items 1](#) and [2](#) of [Proposition 2.4.3.1.6](#) and [Remark 2.4.3.1.7](#).
3. A lengthy discussion of the adjoint triple

$$f_* \dashv f^{-1} \dashv f_! : \mathcal{P}(A) \xrightarrow{\cong} \mathcal{P}(B)$$

of functors (morphisms of posets) between $\mathcal{P}(A)$ and $\mathcal{P}(B)$ induced by a map of sets $f: A \rightarrow B$, along with a discussion of the properties of f_* , f^{-1} , and $f_!$.

In line with the categorical viewpoint developed here, this adjoint triple may be described in terms of Kan extensions, and, as it turns out, it also shows up in some definitions and results in point-set topology, such as in e.g. notions of continuity for functions (??).

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000K 2.1 Limits of Sets

000L 2.1.1 The Terminal Set

000M **Definition 2.1.1.1.1.** The **terminal set** is the pair $(pt, \{!_A\}_{A \in \text{Obj}(\text{Sets})})$

consisting of:

- *The Limit.* The punctual set $\text{pt} \stackrel{\text{def}}{=} \{\star\}$.
- *The Cone.* The collection of maps

$$\{!_A: A \rightarrow \text{pt}\}_{A \in \text{Obj}(\text{Sets})}$$

defined by

$$!_A(a) \stackrel{\text{def}}{=} \star$$

for each $a \in A$ and each $A \in \text{Obj}(\text{Sets})$.

Proof. We claim that pt is the terminal object of Sets . Indeed, suppose we have a diagram of the form

$$A \quad \text{pt}$$

in Sets . Then there exists a unique map $\phi: A \rightarrow \text{pt}$ making the diagram

$$A \xrightarrow[\exists!]{\phi} \text{pt}$$

commute, namely $!_A$. □

000N 2.1.2 Products of Families of Sets

Let $\{A_i\}_{i \in I}$ be a family of sets.

000P **Definition 2.1.2.1.1.** The **product**¹ of $\{A_i\}_{i \in I}$ is the pair $(\prod_{i \in I} A_i, \{\text{pr}_i\}_{i \in I})$ consisting of:

- *The Limit.* The set $\prod_{i \in I} A_i$ defined by²

$$\prod_{i \in I} A_i \stackrel{\text{def}}{=} \left\{ f \in \text{Sets} \left(I, \bigcup_{i \in I} A_i \right) \mid \begin{array}{l} \text{for each } i \in I, \text{ we} \\ \text{have } f(i) \in A_i \end{array} \right\}.$$

¹Further Terminology: Also called the **Cartesian product** of $\{A_i\}_{i \in I}$.

²Less formally, $\prod_{i \in I} A_i$ is the set whose elements are I -indexed collections $(a_i)_{i \in I}$ with $a_i \in A_i$ for each $i \in I$. The projection maps

$$\left\{ \text{pr}_i: \prod_{i \in I} A_i \rightarrow A_i \right\}_{i \in I}$$

are then given by

$$\text{pr}_i \left((a_j)_{j \in I} \right) \stackrel{\text{def}}{=} a_i$$

for each $(a_j)_{j \in I} \in \prod_{i \in I} A_i$ and each $i \in I$.

- *The Cone.* The collection

$$\left\{ \text{pr}_i: \prod_{i \in I} A_i \rightarrow A_i \right\}_{i \in I}$$

of maps given by

$$\text{pr}_i(f) \stackrel{\text{def}}{=} f(i)$$

for each $f \in \prod_{i \in I} A_i$ and each $i \in I$.

Proof. We claim that $\prod_{i \in I} A_i$ is the categorical product of $\{A_i\}_{i \in I}$ in Sets. Indeed, suppose we have, for each $i \in I$, a diagram of the form

$$\begin{array}{ccc} P & & \\ & \searrow^{p_i} & \\ \prod_{i \in I} A_i & \xrightarrow{\text{pr}_i} & A_i \end{array}$$

in Sets. Then there exists a unique map $\phi: P \rightarrow \prod_{i \in I} A_i$ making the diagram

$$\begin{array}{ccc} P & & \\ \downarrow \phi \exists! & \searrow^{p_i} & \\ \prod_{i \in I} A_i & \xrightarrow{\text{pr}_i} & A_i \end{array}$$

commute, being uniquely determined by the condition $\text{pr}_i \circ \phi = p_i$ for each $i \in I$ via

$$\phi(x) = (p_i(x))_{i \in I}$$

for each $x \in P$. □

000Q Proposition 2.1.2.1.2. Let $\{A_i\}_{i \in I}$ be a family of sets.

000R 1. *Functoriality.* The assignment $\{A_i\}_{i \in I} \mapsto \prod_{i \in I} A_i$ defines a functor

$$\prod_{i \in I}: \text{Fun}(I_{\text{disc}}, \text{Sets}) \rightarrow \text{Sets}$$

where

- *Action on Objects.* For each $(A_i)_{i \in I} \in \text{Obj}(\text{Fun}(I_{\text{disc}}, \text{Sets}))$, we have

$$\left[\prod_{i \in I} \right] ((A_i)_{i \in I}) \stackrel{\text{def}}{=} \prod_{i \in I} A_i$$

- *Action on Morphisms.* For each $(A_i)_{i \in I}, (B_i)_{i \in I} \in \text{Obj}(\text{Fun}(I_{\text{disc}}, \text{Sets}))$, the action on Hom-sets

$$\left(\prod_{i \in I} \right)_{(A_i)_{i \in I}, (B_i)_{i \in I}} : \text{Nat}((A_i)_{i \in I}, (B_i)_{i \in I}) \rightarrow \text{Sets} \left(\prod_{i \in I} A_i, \prod_{i \in I} B_i \right)$$

of $\prod_{i \in I}$ at $((A_i)_{i \in I}, (B_i)_{i \in I})$ is defined by sending a map

$$\{f_i : A_i \rightarrow B_i\}_{i \in I}$$

in $\text{Nat}((A_i)_{i \in I}, (B_i)_{i \in I})$ to the map of sets

$$\prod_{i \in I} f_i : \prod_{i \in I} A_i \rightarrow \prod_{i \in I} B_i$$

defined by

$$\left[\prod_{i \in I} f_i \right] ((a_i)_{i \in I}) \stackrel{\text{def}}{=} (f_i(a_i))_{i \in I}$$

for each $(a_i)_{i \in I} \in \prod_{i \in I} A_i$.

Proof. Item 1, Functoriality: This follows from ?? of ??.

□

000S 2.1.3 Binary Products of Sets

Let A and B be sets.

000T **Definition 2.1.3.1.1.** The **product**³ of A and B is the pair $(A \times B, \{\text{pr}_1, \text{pr}_2\})$ consisting of:

- *The Limit.* The set $A \times B$ defined by⁴

$$\begin{aligned} A \times B &\stackrel{\text{def}}{=} \prod_{z \in \{A, B\}} z \\ &\stackrel{\text{def}}{=} \{f \in \text{Sets}(\{0, 1\}, A \cup B) \mid \text{we have } f(0) \in A \text{ and } f(1) \in B\} \\ &\cong \{\{\{a\}, \{a, b\}\} \in \mathcal{P}(\mathcal{P}(A \cup B)) \mid \text{we have } a \in A \text{ and } b \in B\}. \end{aligned}$$

³*Further Terminology:* Also called the **Cartesian product of A and B** or the **binary Cartesian product of A and B** , for emphasis.

This can also be thought of as the $(\mathbb{E}_{-1}, \mathbb{E}_{-1})$ -**tensor product of A and B** .

⁴In other words, $A \times B$ is the set whose elements are ordered pairs (a, b) with $a \in A$ and $b \in B$ as in [Definition 2.3.4.1.1](#)

- *The Cone.* The maps

$$\begin{aligned} \text{pr}_1 &: A \times B \rightarrow A, \\ \text{pr}_2 &: A \times B \rightarrow B \end{aligned}$$

defined by

$$\begin{aligned} \text{pr}_1(a, b) &\stackrel{\text{def}}{=} a, \\ \text{pr}_2(a, b) &\stackrel{\text{def}}{=} b \end{aligned}$$

for each $(a, b) \in A \times B$.

Proof. We claim that $A \times B$ is the categorical product of A and B in Sets. Indeed, suppose we have a diagram of the form

$$\begin{array}{ccc} & P & \\ p_1 \swarrow & & \searrow p_2 \\ A & \xleftarrow{\text{pr}_1} & A \times B \xrightarrow{\text{pr}_2} B \end{array}$$

in Sets. Then there exists a unique map $\phi: P \rightarrow A \times B$ making the diagram

$$\begin{array}{ccc} & P & \\ p_1 \swarrow & \downarrow \phi \exists! & \searrow p_2 \\ A & \xleftarrow{\text{pr}_1} & A \times B \xrightarrow{\text{pr}_2} B \end{array}$$

commute, being uniquely determined by the conditions

$$\begin{aligned} \text{pr}_1 \circ \phi &= p_1, \\ \text{pr}_2 \circ \phi &= p_2 \end{aligned}$$

via

$$\phi(x) = (p_1(x), p_2(x))$$

for each $x \in P$. □

000U Proposition 2.1.3.1.2. Let A, B, C , and X be sets.

000V 1. *Functoriality.* The assignments $A, B, (A, B) \mapsto A \times B$ define functors

$$\begin{aligned} A \times -: \text{Sets} &\rightarrow \text{Sets}, \\ - \times B: \text{Sets} &\rightarrow \text{Sets}, \\ -_1 \times -_2: \text{Sets} \times \text{Sets} &\rightarrow \text{Sets}, \end{aligned}$$

where $-_1 \times -_2$ is the functor where

- *Action on Objects.* For each $(A, B) \in \text{Obj}(\text{Sets} \times \text{Sets})$, we have

$$[-_1 \times -_2](A, B) \stackrel{\text{def}}{=} A \times B.$$

- *Action on Morphisms.* For each $(A, B), (X, Y) \in \text{Obj}(\text{Sets})$, the action on Hom-sets

$$\times_{(A,B),(X,Y)} : \text{Sets}(A, X) \times \text{Sets}(B, Y) \rightarrow \text{Sets}(A \times B, X \times Y)$$

of \times at $((A, B), (X, Y))$ is defined by sending (f, g) to the function

$$f \times g : A \times B \rightarrow X \times Y$$

defined by

$$[f \times g](a, b) \stackrel{\text{def}}{=} (f(a), g(b))$$

for each $(a, b) \in A \times B$.

and where $A \times -$ and $- \times B$ are the partial functors of $-_1 \times -_2$ at $A, B \in \text{Obj}(\text{Sets})$.

- 000W 2. *Adjointness.* We have adjunctions

$$(A \times - \dashv \text{Hom}_{\text{Sets}}(A, -)) : \text{Sets} \begin{array}{c} \xrightarrow{A \times -} \\ \perp \\ \xleftarrow{\text{Hom}_{\text{Sets}}(A, -)} \end{array} \text{Sets},$$

$$(- \times B \dashv \text{Hom}_{\text{Sets}}(B, -)) : \text{Sets} \begin{array}{c} \xrightarrow{- \times B} \\ \perp \\ \xleftarrow{\text{Hom}_{\text{Sets}}(B, -)} \end{array} \text{Sets},$$

witnessed by bijections

$$\begin{aligned} \text{Hom}_{\text{Sets}}(A \times B, C) &\cong \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C)), \\ \text{Hom}_{\text{Sets}}(A \times B, C) &\cong \text{Hom}_{\text{Sets}}(B, \text{Hom}_{\text{Sets}}(A, C)), \end{aligned}$$

natural in $A, B, C \in \text{Obj}(\text{Sets})$.

- 000X 3. *Associativity.* We have an isomorphism of sets

$$(A \times B) \times C \cong A \times (B \times C),$$

natural in $A, B, C \in \text{Obj}(\text{Sets})$.

- 000Y 4. *Unitality.* We have isomorphisms of sets

$$\begin{aligned}\text{pt} \times A &\cong A, \\ A \times \text{pt} &\cong A,\end{aligned}$$

natural in $A \in \text{Obj}(\text{Sets})$.

- 000Z 5. *Commutativity.* We have an isomorphism of sets

$$A \times B \cong B \times A,$$

natural in $A, B \in \text{Obj}(\text{Sets})$.

- 0010 6. *Annihilation With the Empty Set.* We have isomorphisms of sets

$$\begin{aligned}A \times \emptyset &\cong \emptyset, \\ \emptyset \times A &\cong \emptyset,\end{aligned}$$

natural in $A \in \text{Obj}(\text{Sets})$.

- 0011 7. *Distributivity Over Unions.* We have isomorphisms of sets

$$\begin{aligned}A \times (B \cup C) &= (A \times B) \cup (A \times C), \\ (A \cup B) \times C &= (A \times C) \cup (B \times C).\end{aligned}$$

- 0012 8. *Distributivity Over Intersections.* We have isomorphisms of sets

$$\begin{aligned}A \times (B \cap C) &= (A \times B) \cap (A \times C), \\ (A \cap B) \times C &= (A \times C) \cap (B \times C).\end{aligned}$$

- 0013 9. *Middle-Four Exchange with Respect to Intersections.* We have an isomorphism of sets

$$(A \times B) \cap (C \times D) \cong (A \cap B) \times (C \cap D).$$

- 0014 10. *Distributivity Over Differences.* We have isomorphisms of sets

$$\begin{aligned}A \times (B \setminus C) &= (A \times B) \setminus (A \times C), \\ (A \setminus B) \times C &= (A \times C) \setminus (B \times C),\end{aligned}$$

natural in $A, B, C \in \text{Obj}(\text{Sets})$.

- 0015 11. *Distributivity Over Symmetric Differences.* We have isomorphisms of

sets

$$\begin{aligned} A \times (B \triangle C) &= (A \times B) \triangle (A \times C), \\ (A \triangle B) \times C &= (A \times C) \triangle (B \times C), \end{aligned}$$

natural in $A, B, C \in \text{Obj}(\text{Sets})$.

- 0016** 12. *Symmetric Monoidality.* The triple $(\text{Sets}, \times, \text{pt})$ is a symmetric monoidal category.
- 0017** 13. *Symmetric Bimonoidality.* The quintuple $(\text{Sets}, \llbracket _ \rrbracket, \emptyset, \times, \text{pt})$ is a symmetric bimonoidal category.

Proof. Item 1, Functoriality: This follows from ?? of ??.

Item 2, Adjointness: We prove only that there's an adjunction $- \times B \dashv \text{Hom}_{\text{Sets}}(B, -)$, witnessed by a bijection

$$\text{Hom}_{\text{Sets}}(A \times B, C) \cong \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C)),$$

natural in $B, C \in \text{Obj}(\text{Sets})$, as the proof of the existence of the adjunction $A \times - \dashv \text{Hom}_{\text{Sets}}(A, -)$ follows almost exactly in the same way.

- *Map I.* We define a map

$$\Phi_{B,C}: \text{Hom}_{\text{Sets}}(A \times B, C) \rightarrow \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C)),$$

by sending a function

$$\xi: A \times B \rightarrow C$$

to the function

$$\begin{aligned} \xi^\dagger: A &\rightarrow \text{Hom}_{\text{Sets}}(B, C), \\ a &\mapsto \left(\xi_a^\dagger: B \rightarrow C \right), \end{aligned}$$

where we define

$$\xi_a^\dagger(b) \stackrel{\text{def}}{=} \xi(a, b)$$

for each $b \in B$. In terms of the $\llbracket a \mapsto f(a) \rrbracket$ notation of **Notation 1.1.1.1.2**, we have

$$\xi^\dagger \stackrel{\text{def}}{=} \llbracket a \mapsto \llbracket b \mapsto \xi(a, b) \rrbracket \rrbracket.$$

- *Map II.* We define a map

$$\Psi_{B,C}: \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C)), \rightarrow \text{Hom}_{\text{Sets}}(A \times B, C)$$

given by sending a function

$$\begin{aligned} \xi: A &\rightarrow \text{Hom}_{\text{Sets}}(B, C), \\ a &\mapsto (\xi_a: B \rightarrow C), \end{aligned}$$

to the function

$$\xi^\dagger: A \times B \rightarrow C$$

defined by

$$\begin{aligned} \xi^\dagger(a, b) &\stackrel{\text{def}}{=} \text{ev}_b(\text{ev}_a(\xi)) \\ &\stackrel{\text{def}}{=} \text{ev}_b(\xi_a) \\ &\stackrel{\text{def}}{=} \xi_a(b) \end{aligned}$$

for each $(a, b) \in A \times B$.

- *Invertibility I.* We claim that

$$\Psi_{A,B} \circ \Phi_{A,B} = \text{id}_{\text{Hom}_{\text{Sets}}(A \times B, C)}.$$

Indeed, given a function $\xi: A \times B \rightarrow C$, we have

$$\begin{aligned} [\Psi_{A,B} \circ \Phi_{A,B}](\xi) &= \Psi_{A,B}(\Phi_{A,B}(\xi)) \\ &= \Psi_{A,B}(\Phi_{A,B}([(a, b) \mapsto \xi(a, b)])) \\ &= \Psi_{A,B}([a \mapsto [b \mapsto \xi(a, b)]]) \\ &= \Psi_{A,B}([a' \mapsto [b' \mapsto \xi(a', b')]]) \\ &= [(a, b) \mapsto \text{ev}_b(\text{ev}_a([a' \mapsto [b' \mapsto \xi(a', b')]]))] \\ &= [(a, b) \mapsto \text{ev}_b([b' \mapsto \xi(a, b')])] \\ &= [(a, b) \mapsto \xi(a, b)] \\ &= \xi. \end{aligned}$$

- *Invertibility II.* We claim that

$$\Phi_{A,B} \circ \Psi_{A,B} = \text{id}_{\text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C))}.$$

Indeed, given a function

$$\begin{aligned} \xi: A &\rightarrow \text{Hom}_{\text{Sets}}(B, C), \\ a &\mapsto (\xi_a: B \rightarrow C), \end{aligned}$$

we have

$$\begin{aligned}
[\Phi_{A,B} \circ \Psi_{A,B}](\xi) &\stackrel{\text{def}}{=} \Phi_{A,B}(\Psi_{A,B}(\xi)) \\
&\stackrel{\text{def}}{=} \Phi_{A,B}(\llbracket (a, b) \mapsto \xi_a(b) \rrbracket) \\
&\stackrel{\text{def}}{=} \Phi_{A,B}(\llbracket (a', b') \mapsto \xi_{a'}(b') \rrbracket) \\
&\stackrel{\text{def}}{=} \llbracket a \mapsto \llbracket b \mapsto \text{ev}_{(a,b)}(\llbracket (a', b') \mapsto \xi_{a'}(b') \rrbracket) \rrbracket \rrbracket \\
&\stackrel{\text{def}}{=} \llbracket a \mapsto \llbracket b \mapsto \xi_a(b) \rrbracket \rrbracket \\
&\stackrel{\text{def}}{=} \llbracket a \mapsto \xi_a \rrbracket \\
&\stackrel{\text{def}}{=} \xi.
\end{aligned}$$

- *Naturality for Φ , Part I.* We need to show that, given a function $g: B \rightarrow B'$, the diagram

$$\begin{array}{ccc}
\text{Hom}_{\text{Sets}}(A \times B', C) & \xrightarrow{\Phi_{B',C}} & \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B', C)), \\
\text{id}_A \times g^* \downarrow & & \downarrow (g^*)_* \\
\text{Hom}_{\text{Sets}}(A \times B, C) & \xrightarrow{\Phi_{B,C}} & \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C))
\end{array}$$

commutes. Indeed, given a function

$$\xi: A \times B' \rightarrow C,$$

we have

$$\begin{aligned}
[\Phi_{B,C} \circ (\text{id}_A \times g^*)](\xi) &= \Phi_{B,C}([\text{id}_A \times g^*](\xi)) \\
&= \Phi_{B,C}(\xi(-1, g(-2))) \\
&= [\xi(-1, g(-2))]^\dagger \\
&= \xi_{-1}^\dagger(g(-2)) \\
&= (g^*)_* \left(\xi^\dagger \right) \\
&= (g^*)_* (\Phi_{B',C}(\xi)) \\
&= [(g^*)_* \circ \Phi_{B',C}](\xi).
\end{aligned}$$

Alternatively, using the $\llbracket a \mapsto f(a) \rrbracket$ notation of [Notation 1.1.1.1.2](#),

we have

$$\begin{aligned}
[\Phi_{B,C} \circ (\text{id}_A \times g^*)](\xi) &= \Phi_{B,C}([\text{id}_A \times g^*](\xi)) \\
&= \Phi_{B,C}([\text{id}_A \times g^*](\llbracket (a, b') \mapsto \xi(a, b') \rrbracket)) \\
&= \Phi_{B,C}(\llbracket (a, b) \mapsto \xi(a, g(b)) \rrbracket) \\
&= \llbracket a \mapsto \llbracket b \mapsto \xi(a, g(b)) \rrbracket \rrbracket \\
&= \llbracket a \mapsto g^*(\llbracket b' \mapsto \xi(a, b') \rrbracket) \rrbracket \\
&= (g^*)_* (\llbracket a \mapsto \llbracket b' \mapsto \xi(a, b') \rrbracket \rrbracket) \\
&= (g^*)_* (\Phi_{B',C}(\llbracket (a, b') \mapsto \xi(a, b') \rrbracket)) \\
&= (g^*)_* (\Phi_{B',C}(\xi)) \\
&= [(g^*)_* \circ \Phi_{B',C}](\xi).
\end{aligned}$$

- *Naturality for Φ , Part II.* We need to show that, given a function $h: C \rightarrow C'$, the diagram

$$\begin{array}{ccc}
\text{Hom}_{\text{Sets}}(A \times B, C) & \xrightarrow{\Phi_{B,C}} & \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C)), \\
\downarrow h_* & & \downarrow (h_*)_* \\
\text{Hom}_{\text{Sets}}(A \times B, C') & \xrightarrow{\Phi_{B,C'}} & \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, C'))
\end{array}$$

commutes. Indeed, given a function

$$\xi: A \times B \rightarrow C,$$

we have

$$\begin{aligned}
[\Phi_{B,C} \circ h_*](\xi) &= \Phi_{B,C}(h_*(\xi)) \\
&= \Phi_{B,C}(h_*(\llbracket (a, b) \mapsto \xi(a, b) \rrbracket)) \\
&= \Phi_{B,C}(\llbracket (a, b) \mapsto h(\xi(a, b)) \rrbracket) \\
&= \llbracket a \mapsto \llbracket b \mapsto h(\xi(a, b)) \rrbracket \rrbracket \\
&= \llbracket a \mapsto h_* (\llbracket b \mapsto \xi(a, b) \rrbracket) \rrbracket \\
&= (h_*)_* (\llbracket a \mapsto \llbracket b \mapsto \xi(a, b) \rrbracket \rrbracket) \\
&= (h_*)_* (\Phi_{B,C}(\llbracket (a, b) \mapsto \xi(a, b) \rrbracket)) \\
&= (h_*)_* (\Phi_{B,C}(\xi)) \\
&= [(h_*)_* \circ \Phi_{B,C}](\xi).
\end{aligned}$$

- *Naturality for Ψ .* Since Φ is natural in each argument and Φ is a componentwise inverse to Ψ in each argument, it follows from [Item 2 of Proposition 8.8.6.1.2](#) that Ψ is also natural in each argument.

Item 3, Associativity: See [Pro24a].

Item 4, Unitality: Clear.

Item 5, Commutativity: See [Pro24b].

Item 6, Annihilation With the Empty Set: See [Pro24f].

Item 7, Distributivity Over Unions: See [Pro24e].

Item 8, Distributivity Over Intersections: See [Pro24g, Corollary 1].

Item 9, Middle-Four Exchange With Respect to Intersections: See [Pro24g, Corollary 1].

Item 10, Distributivity Over Differences: See [Pro24c].

Item 11, Distributivity Over Symmetric Differences: See [Pro24d].

Item 12, Symmetric Monoidality: See [MO 382264].

Item 13, Symmetric Bimonoidality: Omitted. \square

0018 2.1.4 Pullbacks

Let A , B , and C be sets and let $f: A \rightarrow C$ and $g: B \rightarrow C$ be functions.

0019 **Definition 2.1.4.1.1.** The **pullback of A and B over C along f and g** ⁵ is the pair⁶ $(A \times_C B, \{\text{pr}_1, \text{pr}_2\})$ consisting of:

- *The Limit.* The set $A \times_C B$ defined by

$$A \times_C B \stackrel{\text{def}}{=} \{(a, b) \in A \times B \mid f(a) = g(b)\}.$$

- *The Cone.* The maps

$$\text{pr}_1: A \times_C B \rightarrow A,$$

$$\text{pr}_2: A \times_C B \rightarrow B$$

defined by

$$\text{pr}_1(a, b) \stackrel{\text{def}}{=} a,$$

$$\text{pr}_2(a, b) \stackrel{\text{def}}{=} b$$

for each $(a, b) \in A \times_C B$.

Proof. We claim that $A \times_C B$ is the categorical pullback of A and B over C with respect to (f, g) in Sets. First we need to check that the relevant pullback

⁵*Further Terminology:* Also called the **fibre product of A and B over C along f and g** .

⁶*Further Notation:* Also written $A \times_{f,C,g} B$.

diagram commutes, i.e. that we have

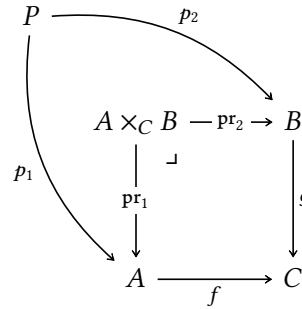
$$f \circ \text{pr}_1 = g \circ \text{pr}_2,$$

$$\begin{array}{ccc} A \times_C B & \xrightarrow{\text{pr}_2} & B \\ \text{pr}_1 \downarrow & & \downarrow g \\ A & \xrightarrow{f} & C. \end{array}$$

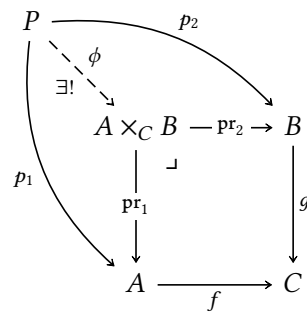
Indeed, given $(a, b) \in A \times_C B$, we have

$$\begin{aligned} [f \circ \text{pr}_1](a, b) &= f(\text{pr}_1(a, b)) \\ &= f(a) \\ &= g(b) \\ &= g(\text{pr}_2(a, b)) \\ &= [g \circ \text{pr}_2](a, b), \end{aligned}$$

where $f(a) = g(b)$ since $(a, b) \in A \times_C B$. Next, we prove that $A \times_C B$ satisfies the universal property of the pullback. Suppose we have a diagram of the form



in Sets. Then there exists a unique map $\phi: P \rightarrow A \times_C B$ making the diagram



commute, being uniquely determined by the conditions

$$\begin{aligned} \text{pr}_1 \circ \phi &= p_1, \\ \text{pr}_2 \circ \phi &= p_2 \end{aligned}$$

via

$$\phi(x) = (p_1(x), p_2(x))$$

for each $x \in P$, where we note that $(p_1(x), p_2(x)) \in A \times B$ indeed lies in $A \times_C B$ by the condition

$$f \circ p_1 = g \circ p_2,$$

which gives

$$f(p_1(x)) = g(p_2(x))$$

for each $x \in P$, so that $(p_1(x), p_2(x)) \in A \times_C B$. □

001A Example 2.1.4.1.2. Here are some examples of pullbacks of sets.

001B 1. *Unions via Intersections.* Let $A, B \subset X$. We have a bijection of sets

$$A \cap B \cong A \times_{A \cup B} B,$$

$$\begin{array}{ccc} A \cap B & \longrightarrow & B \\ \downarrow & \lrcorner & \downarrow i_B \\ A & \xrightarrow{i_A} & A \cup B. \end{array}$$

Proof. Item 1, Unions via Intersections: Indeed, we have

$$\begin{aligned} A \times_{A \cup B} B &\cong \{(x, y) \in A \times B \mid x = y\} \\ &\cong A \cap B. \end{aligned}$$

This finishes the proof. □

001C Proposition 2.1.4.1.3. Let A, B, C , and X be sets.

001D 1. *Functoriality.* The assignment $(A, B, C, f, g) \mapsto A \times_{f, C, g} B$ defines a functor

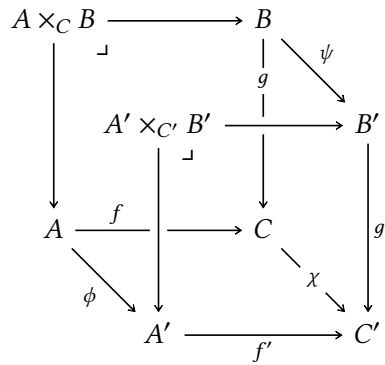
$$-_1 \times_{-3} -_1: \text{Fun}(\mathcal{P}, \text{Sets}) \rightarrow \text{Sets},$$

where \mathcal{P} is the category that looks like this:

$$\begin{array}{ccc} & & \bullet \\ & & \downarrow \\ \bullet & \longrightarrow & \bullet \end{array}$$

In particular, the action on morphisms of $-_1 \times_{-3} -_1$ is given by sending

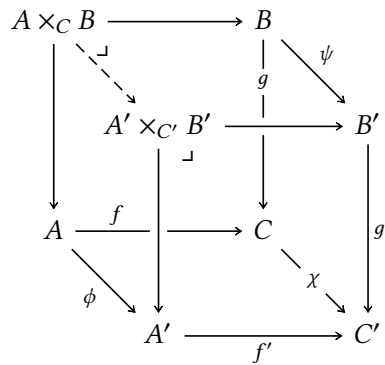
a morphism



in $\text{Fun}(\mathcal{P}, \text{Sets})$ to the map $\xi: A \times_C B \xrightarrow{\exists!} A' \times_{C'} B'$ given by

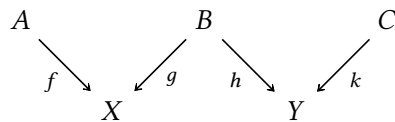
$$\xi(a, b) \stackrel{\text{def}}{=} (\phi(a), \psi(b))$$

for each $(a, b) \in A \times_C B$, which is the unique map making the diagram



commute.

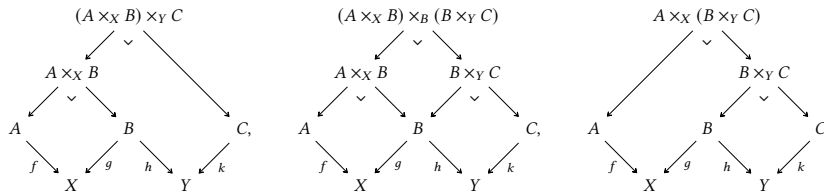
001E 2. *Associativity.* Given a diagram



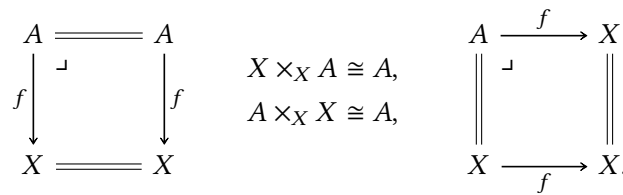
in Sets , we have isomorphisms of sets

$$(A \times_X B) \times_Y C \cong (A \times_X B) \times_B (B \times_Y C) \cong A \times_X (B \times_Y C),$$

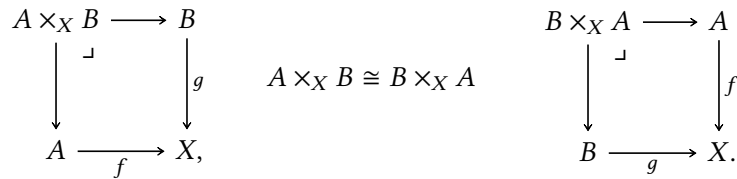
where these pullbacks are built as in the diagrams



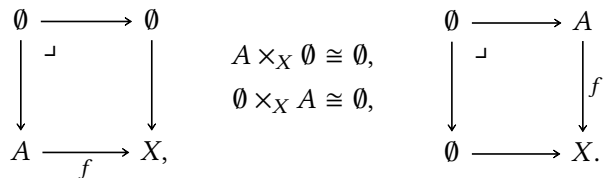
001F 3. *Unitality.* We have isomorphisms of sets



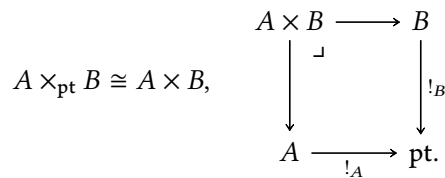
001G 4. *Commutativity.* We have an isomorphism of sets



001H 5. *Annihilation With the Empty Set.* We have isomorphisms of sets



001J 6. *Interaction With Products.* We have an isomorphism of sets



001K 7. *Symmetric Monoidality.* The triple $(\text{Sets}, \times_X, X)$ is a symmetric monoidal category.

Proof. Item 1, Functoriality: This is a special case of functoriality of co/limits, ?? of ??, with the explicit expression for ξ following from the commutativity of the cube pullback diagram.

Item 2, Associativity: Indeed, we have

$$\begin{aligned} (A \times_X B) \times_Y C &\cong \{(a, b), c\} \in (A \times_X B) \times C \mid h(b) = k(c)\} \\ &\cong \{(a, b), c\} \in (A \times B) \times C \mid f(a) = g(b) \text{ and } h(b) = k(c)\} \\ &\cong \{(a, (b, c))\} \in A \times (B \times C) \mid f(a) = g(b) \text{ and } h(b) = k(c)\} \\ &\cong \{(a, (b, c))\} \in A \times (B \times_Y C) \mid f(a) = g(b)\} \\ &\cong A \times_X (B \times_Y C) \end{aligned}$$

and

$$\begin{aligned} (A \times_X B) \times_B (B \times_Y C) &\cong \{(a, b), (b', c)\} \in (A \times_X B) \times (B \times_Y C) \mid b = b'\} \\ &\cong \left\{ \{(a, b), (b', c)\} \in (A \times B) \times (B \times C) \mid \begin{array}{l} f(a) = g(b), b = b', \\ \text{and } h(b') = k(c) \end{array} \right\} \\ &\cong \left\{ \{(a, (b, (b', c)))\} \in A \times (B \times (B \times C)) \mid \begin{array}{l} f(a) = g(b), b = b', \\ \text{and } h(b') = k(c) \end{array} \right\} \\ &\cong \left\{ \{(a, ((b, b'), c))\} \in A \times ((B \times B) \times C) \mid \begin{array}{l} f(a) = g(b), b = b', \\ \text{and } h(b') = k(c) \end{array} \right\} \\ &\cong \left\{ \{(a, ((b, b'), c))\} \in A \times ((B \times_B B) \times C) \mid \begin{array}{l} f(a) = g(b) \text{ and} \\ h(b') = k(c) \end{array} \right\} \\ &\cong \{(a, (b, c))\} \in A \times (B \times C) \mid f(a) = g(b) \text{ and } h(b) = k(c)\} \\ &\cong A \times_X (B \times_Y C), \end{aligned}$$

where we have used **Item 3** for the isomorphism $B \times_B B \cong B$.

Item 3, Unitality: Indeed, we have

$$\begin{aligned} X \times_X A &\cong \{(x, a) \in X \times A \mid f(a) = x\}, \\ A \times_X X &\cong \{(a, x) \in X \times A \mid f(a) = x\}, \end{aligned}$$

which are isomorphic to A via the maps $(x, a) \mapsto a$ and $(a, x) \mapsto a$.

Item 4, Commutativity: Clear.

Item 5, Annihilation With the Empty Set: Clear.

Item 6, Interaction With Products: Clear.

Item 7, Symmetric Monoidality: Omitted. □

001L 2.1.5 Equalisers

Let A and B be sets and let $f, g: A \rightrightarrows B$ be functions.

001M Definition 2.1.5.1.1. The **equaliser of f and g** is the pair $(\text{Eq}(f, g), \text{eq}(f, g))$ consisting of:

- *The Limit.* The set $\text{Eq}(f, g)$ defined by

$$\text{Eq}(f, g) \stackrel{\text{def}}{=} \{a \in A \mid f(a) = g(a)\}.$$

- *The Cone.* The inclusion map

$$\text{eq}(f, g): \text{Eq}(f, g) \hookrightarrow A.$$

Proof. We claim that $\text{Eq}(f, g)$ is the categorical equaliser of f and g in Sets. First we need to check that the relevant equaliser diagram commutes, i.e. that we have

$$f \circ \text{eq}(f, g) = g \circ \text{eq}(f, g),$$

which indeed holds by the definition of the set $\text{Eq}(f, g)$. Next, we prove that $\text{Eq}(f, g)$ satisfies the universal property of the equaliser. Suppose we have a diagram of the form

$$\begin{array}{ccc} \text{Eq}(f, g) & \xrightarrow{\text{eq}(f, g)} & A \xrightarrow[\quad g]{\quad f} B \\ & \nearrow e & \\ E & & \end{array}$$

in Sets. Then there exists a unique map $\phi: E \rightarrow \text{Eq}(f, g)$ making the diagram

$$\begin{array}{ccc} \text{Eq}(f, g) & \xrightarrow{\text{eq}(f, g)} & A \xrightarrow[\quad g]{\quad f} B \\ \uparrow \phi \exists! & \nearrow e & \\ E & & \end{array}$$

commute, being uniquely determined by the condition

$$\text{eq}(f, g) \circ \phi = e$$

via

$$\phi(x) = e(x)$$

for each $x \in E$, where we note that $e(x) \in A$ indeed lies in $\text{Eq}(f, g)$ by the condition

$$f \circ e = g \circ e,$$

which gives

$$f(e(x)) = g(e(x))$$

for each $x \in E$, so that $e(x) \in \text{Eq}(f, g)$. \square

001N Proposition 2.1.5.1.2. Let A , B , and C be sets.

001P 1. *Associativity.* We have isomorphisms of sets⁷

$$\underbrace{\text{Eq}(f \circ \text{eq}(g, h), g \circ \text{eq}(g, h))}_{=\text{Eq}(f \circ \text{eq}(g, h), h \circ \text{eq}(g, h))} \cong \text{Eq}(f, g, h) \cong \underbrace{\text{Eq}(f \circ \text{eq}(f, g), h \circ \text{eq}(f, g))}_{=\text{Eq}(g \circ \text{eq}(f, g), h \circ \text{eq}(f, g))},$$

where $\text{Eq}(f, g, h)$ is the limit of the diagram

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \\ \xrightarrow{h} \end{array} B$$

⁷That is, the following three ways of forming “the” equaliser of (f, g, h) agree:

1. Take the equaliser of (f, g, h) , i.e. the limit of the diagram

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \\ \xrightarrow{h} \end{array} B$$

in Sets.

2. First take the equaliser of f and g , forming a diagram

$$\text{Eq}(f, g) \begin{array}{c} \xrightarrow{\text{eq}(f, g)} \\ \xrightarrow{f} \\ \xrightarrow{g} \end{array} A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B$$

and then take the equaliser of the composition

$$\text{Eq}(f, g) \begin{array}{c} \xrightarrow{\text{eq}(f, g)} \\ \xrightarrow{f} \\ \xrightarrow{h} \end{array} A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{h} \end{array} B,$$

obtaining a subset

$$\text{Eq}(f \circ \text{eq}(f, g), h \circ \text{eq}(f, g)) = \text{Eq}(g \circ \text{eq}(f, g), h \circ \text{eq}(f, g))$$

of $\text{Eq}(f, g)$.

3. First take the equaliser of g and h , forming a diagram

$$\text{Eq}(g, h) \begin{array}{c} \xrightarrow{\text{eq}(g, h)} \\ \xrightarrow{g} \\ \xrightarrow{h} \end{array} A \begin{array}{c} \xrightarrow{g} \\ \xrightarrow{h} \end{array} B$$

and then take the equaliser of the composition

$$\text{Eq}(g, h) \begin{array}{c} \xrightarrow{\text{eq}(g, h)} \\ \xrightarrow{f} \\ \xrightarrow{g} \end{array} A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B,$$

obtaining a subset

$$\text{Eq}(f \circ \text{eq}(g, h), g \circ \text{eq}(g, h)) = \text{Eq}(f \circ \text{eq}(g, h), h \circ \text{eq}(g, h))$$

of $\text{Eq}(g, h)$.

in Sets, being explicitly given by

$$\text{Eq}(f, g, h) \cong \{a \in A \mid f(a) = g(a) = h(a)\}.$$

001Q 4. *Unitality.* We have an isomorphism of sets

$$\text{Eq}(f, f) \cong A.$$

001R 5. *Commutativity.* We have an isomorphism of sets

$$\text{Eq}(f, g) \cong \text{Eq}(g, f).$$

001S 6. *Interaction With Composition.* Let

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{h} \\ \xrightarrow{k} \end{array} C$$

be functions. We have an inclusion of sets

$$\text{Eq}(h \circ f \circ \text{eq}(f, g), k \circ g \circ \text{eq}(f, g)) \subset \text{Eq}(h \circ f, k \circ g),$$

where $\text{Eq}(h \circ f \circ \text{eq}(f, g), k \circ g \circ \text{eq}(f, g))$ is the equaliser of the composition

$$\text{Eq}(f, g) \xrightarrow{\text{eq}(f, g)} A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{h} \\ \xrightarrow{k} \end{array} C.$$

Proof. Item 1, Associativity: We first prove that $\text{Eq}(f, g, h)$ is indeed given by

$$\text{Eq}(f, g, h) \cong \{a \in A \mid f(a) = g(a) = h(a)\}.$$

Indeed, suppose we have a diagram of the form

$$\begin{array}{ccc} \text{Eq}(f, g, h) & \xrightarrow{\text{eq}(f, g, h)} & A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \\ \xrightarrow{h} \end{array} B \\ & \nearrow e & \\ E & & \end{array}$$

in Sets. Then there exists a unique map $\phi: E \rightarrow \text{Eq}(f, g, h)$, uniquely determined by the condition

$$\text{eq}(f, g) \circ \phi = e$$

being necessarily given by

$$\phi(x) = e(x)$$

for each $x \in E$, where we note that $e(x) \in A$ indeed lies in $\text{Eq}(f, g, h)$ by the condition

$$f \circ e = g \circ e = h \circ e,$$

which gives

$$f(e(x)) = g(e(x)) = h(e(x))$$

for each $x \in E$, so that $e(x) \in \text{Eq}(f, g, h)$.

We now check the equalities

$$\text{Eq}(f \circ \text{eq}(g, h), g \circ \text{eq}(g, h)) \cong \text{Eq}(f, g, h) \cong \text{Eq}(f \circ \text{eq}(f, g), h \circ \text{eq}(f, g)).$$

Indeed, we have

$$\begin{aligned} \text{Eq}(f \circ \text{eq}(g, h), g \circ \text{eq}(g, h)) &\cong \{x \in \text{Eq}(g, h) \mid [f \circ \text{eq}(g, h)](a) = [g \circ \text{eq}(g, h)](a)\} \\ &\cong \{x \in \text{Eq}(g, h) \mid f(a) = g(a)\} \\ &\cong \{x \in A \mid f(a) = g(a) \text{ and } g(a) = h(a)\} \\ &\cong \{x \in A \mid f(a) = g(a) = h(a)\} \\ &\cong \text{Eq}(f, g, h). \end{aligned}$$

Similarly, we have

$$\begin{aligned} \text{Eq}(f \circ \text{eq}(f, g), h \circ \text{eq}(f, g)) &\cong \{x \in \text{Eq}(f, g) \mid [f \circ \text{eq}(f, g)](a) = [h \circ \text{eq}(f, g)](a)\} \\ &\cong \{x \in \text{Eq}(f, g) \mid f(a) = h(a)\} \\ &\cong \{x \in A \mid f(a) = h(a) \text{ and } f(a) = g(a)\} \\ &\cong \{x \in A \mid f(a) = g(a) = h(a)\} \\ &\cong \text{Eq}(f, g, h). \end{aligned}$$

Item 4, Unitality: Clear.

Item 5, Commutativity: Clear.

Item 6, Interaction With Composition: Indeed, we have

$$\begin{aligned} \text{Eq}(h \circ f \circ \text{eq}(f, g), k \circ g \circ \text{eq}(f, g)) &\cong \{a \in \text{Eq}(f, g) \mid h(f(a)) = k(g(a))\} \\ &\cong \{a \in A \mid f(a) = g(a) \text{ and } h(f(a)) = k(g(a))\}. \end{aligned}$$

and

$$\text{Eq}(h \circ f, k \circ g) \cong \{a \in A \mid h(f(a)) = k(g(a))\},$$

and thus there's an inclusion from $\text{Eq}(h \circ f \circ \text{eq}(f, g), k \circ g \circ \text{eq}(f, g))$ to $\text{Eq}(h \circ f, k \circ g)$. \square

001T 2.2 Colimits of Sets

001U 2.2.1 The Initial Set

001V Definition 2.2.1.1.1. The **initial set** is the pair $(\emptyset, \{\iota_A\}_{A \in \text{Obj}(\text{Sets})})$ consisting of:

- *The Limit.* The empty set \emptyset of **Definition 2.3.1.1.1**.
- *The Cone.* The collection of maps

$$\{\iota_A: \emptyset \rightarrow A\}_{A \in \text{Obj}(\text{Sets})}$$

given by the inclusion maps from \emptyset to A .

Proof. We claim that \emptyset is the initial object of Sets. Indeed, suppose we have a diagram of the form

$$\emptyset \quad A$$

in Sets. Then there exists a unique map $\phi: \emptyset \rightarrow A$ making the diagram

$$\emptyset \xrightarrow[\exists!]{\phi} A$$

commute, namely the inclusion map ι_A . □

001W 2.2.2 Coproducts of Families of Sets

Let $\{A_i\}_{i \in I}$ be a family of sets.

001X Definition 2.2.2.1.1. The **disjoint union of the family** $\{A_i\}_{i \in I}$ is the pair $(\coprod_{i \in I} A_i, \{\text{inj}_i\}_{i \in I})$ consisting of:

- *The Colimit.* The set $\coprod_{i \in I} A_i$ defined by

$$\coprod_{i \in I} A_i \stackrel{\text{def}}{=} \left\{ (i, x) \in I \times \left(\bigcup_{i \in I} A_i \right) \mid x \in A_i \right\}.$$

- *The Cocone.* The collection

$$\left\{ \text{inj}_i: A_i \rightarrow \coprod_{i \in I} A_i \right\}_{i \in I}$$

of maps given by

$$\text{inj}_i(x) \stackrel{\text{def}}{=} (i, x)$$

for each $x \in A_i$ and each $i \in I$.

Proof. We claim that $\coprod_{i \in I} A_i$ is the categorical coproduct of $\{A_i\}_{i \in I}$ in Sets. Indeed, suppose we have, for each $i \in I$, a diagram of the form

$$\begin{array}{ccc} & & C \\ & \nearrow \iota_i & \\ A_i & \xrightarrow{\text{inj}_i} & \coprod_{i \in I} A_i \end{array}$$

in Sets. Then there exists a unique map $\phi: \coprod_{i \in I} A_i \rightarrow C$ making the diagram

$$\begin{array}{ccc} & & C \\ & \nearrow \iota_i & \uparrow \phi \exists! \\ A_i & \xrightarrow{\text{inj}_i} & \coprod_{i \in I} A_i \end{array}$$

commute, being uniquely determined by the condition $\phi \circ \text{inj}_i = \iota_i$ for each $i \in I$ via

$$\phi((i, x)) = \iota_i(x)$$

for each $(i, x) \in \coprod_{i \in I} A_i$. \square

001Y Proposition 2.2.2.1.2. Let $\{A_i\}_{i \in I}$ be a family of sets.

001Z 1. *Functoriality.* The assignment $\{A_i\}_{i \in I} \mapsto \coprod_{i \in I} A_i$ defines a functor

$$\coprod_{i \in I}: \text{Fun}(I_{\text{disc}}, \text{Sets}) \rightarrow \text{Sets}$$

where

- *Action on Objects.* For each $(A_i)_{i \in I} \in \text{Obj}(\text{Fun}(I_{\text{disc}}, \text{Sets}))$, we have

$$\left[\coprod_{i \in I} \right] ((A_i)_{i \in I}) \stackrel{\text{def}}{=} \coprod_{i \in I} A_i$$

- *Action on Morphisms.* For each $(A_i)_{i \in I}, (B_i)_{i \in I} \in \text{Obj}(\text{Fun}(I_{\text{disc}}, \text{Sets}))$, the action on Hom-sets

$$\left(\coprod_{i \in I} \right)_{(A_i)_{i \in I}, (B_i)_{i \in I}}: \text{Nat}((A_i)_{i \in I}, (B_i)_{i \in I}) \rightarrow \text{Sets} \left(\coprod_{i \in I} A_i, \coprod_{i \in I} B_i \right)$$

of $\coprod_{i \in I}$ at $((A_i)_{i \in I}, (B_i)_{i \in I})$ is defined by sending a map

$$\{f_i: A_i \rightarrow B_i\}_{i \in I}$$

in $\text{Nat}((A_i)_{i \in I}, (B_i)_{i \in I})$ to the map of sets

$$\coprod_{i \in I} f_i: \coprod_{i \in I} A_i \rightarrow \coprod_{i \in I} B_i$$

defined by

$$\left[\coprod_{i \in I} f_i \right] (i, a) \stackrel{\text{def}}{=} f_i(a)$$

for each $(i, a) \in \coprod_{i \in I} A_i$.

Proof. Item 1, Functoriality: This follows from ?? of ??.

□

0020 **2.2.3 Binary Coproducts**

Let A and B be sets.

0021 **Definition 2.2.3.1.1.** The **coproduct**⁸ of A and B is the pair $(A \amalg B, \{\text{inj}_1, \text{inj}_2\})$ consisting of:

- *The Colimit.* The set $A \amalg B$ defined by

$$A \amalg B \stackrel{\text{def}}{=} \coprod_{z \in \{A, B\}} z$$

$$\cong \{(0, a) \mid a \in A\} \cup \{(1, b) \mid b \in B\}.$$

- *The Cocone.* The maps

$$\text{inj}_1: A \rightarrow A \amalg B,$$

$$\text{inj}_2: B \rightarrow A \amalg B,$$

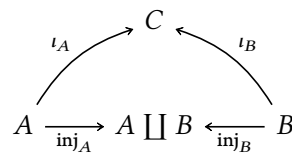
given by

$$\text{inj}_1(a) \stackrel{\text{def}}{=} (0, a),$$

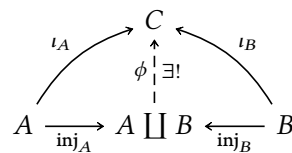
$$\text{inj}_2(b) \stackrel{\text{def}}{=} (1, b),$$

for each $a \in A$ and each $b \in B$.

Proof. We claim that $A \amalg B$ is the categorical coproduct of A and B in Sets. Indeed, suppose we have a diagram of the form



in Sets. Then there exists a unique map $\phi: A \amalg B \rightarrow C$ making the diagram



⁸Further Terminology: Also called the **disjoint union of A and B** , or the **binary disjoint**

commute, being uniquely determined by the conditions

$$\begin{aligned}\phi \circ \text{inj}_A &= \iota_A, \\ \phi \circ \text{inj}_B &= \iota_B\end{aligned}$$

via

$$\phi(x) = \begin{cases} \iota_A(a) & \text{if } x = (0, a), \\ \iota_B(b) & \text{if } x = (1, b) \end{cases}$$

for each $x \in A \amalg B$. \square

0022 Proposition 2.2.3.1.2. Let A, B, C , and X be sets.

0023 1. *Functoriality.* The assignment $A, B, (A, B) \mapsto A \amalg B$ defines functors

$$\begin{aligned}A \amalg -: \text{Sets} &\rightarrow \text{Sets}, \\ - \amalg B: \text{Sets} &\rightarrow \text{Sets}, \\ -_1 \amalg -_2: \text{Sets} \times \text{Sets} &\rightarrow \text{Sets},\end{aligned}$$

where $-_1 \amalg -_2$ is the functor where

- *Action on Objects.* For each $(A, B) \in \text{Obj}(\text{Sets} \times \text{Sets})$, we have

$$[-_1 \amalg -_2](A, B) \stackrel{\text{def}}{=} A \amalg B.$$

- *Action on Morphisms.* For each $(A, B), (X, Y) \in \text{Obj}(\text{Sets})$, the action on Hom-sets

$$\amalg_{(A,B),(X,Y)}: \text{Sets}(A, X) \times \text{Sets}(B, Y) \rightarrow \text{Sets}(A \amalg B, X \amalg Y)$$

of \amalg at $((A, B), (X, Y))$ is defined by sending (f, g) to the function

$$f \amalg g: A \amalg B \rightarrow X \amalg Y$$

defined by

$$[f \amalg g](x) \stackrel{\text{def}}{=} \begin{cases} (0, f(a)) & \text{if } x = (0, a), \\ (1, g(b)) & \text{if } x = (1, b), \end{cases}$$

for each $x \in A \amalg B$.

and where $A \amalg -$ and $- \amalg B$ are the partial functors of $-_1 \amalg -_2$ at $A, B \in \text{Obj}(\text{Sets})$.

0024 2. *Associativity.* We have an isomorphism of sets

$$(A \amalg B) \amalg C \cong A \amalg (B \amalg C),$$

natural in $A, B, C \in \text{Obj}(\text{Sets})$.

0025 3. *Unitality.* We have isomorphisms of sets

$$A \amalg \emptyset \cong A,$$

$$\emptyset \amalg A \cong A,$$

natural in $A \in \text{Obj}(\text{Sets})$.

0026 4. *Commutativity.* We have an isomorphism of sets

$$A \amalg B \cong B \amalg A,$$

natural in $A, B \in \text{Obj}(\text{Sets})$.

0027 5. *Symmetric Monoidality.* The triple $(\text{Sets}, \amalg, \emptyset)$ is a symmetric monoidal category.

Proof. Item 1, Functoriality: This follows from ?? of ??.

Item 2, Associativity: Clear.

Item 3, Unitality: Clear.

Item 4, Commutativity: Clear.

Item 5, Symmetric Monoidality: Omitted. □

0028 2.2.4 Pushouts

Let $A, B,$ and C be sets and let $f: C \rightarrow A$ and $g: C \rightarrow B$ be functions.

0029 **Definition 2.2.4.1.1.** The **pushout of A and B over C along f and g** ⁹ is the pair¹⁰ $(A \amalg_C B, \{\text{inj}_1, \text{inj}_2\})$ consisting of:

- *The Colimit.* The set $A \amalg_C B$ defined by

$$A \amalg_C B \stackrel{\text{def}}{=} A \amalg B / \sim_C,$$

where \sim_C is the equivalence relation on $A \amalg B$ generated by $(0, f(c)) \sim_C (1, g(c))$.

union of A and B , for emphasis.

⁹*Further Terminology:* Also called the **fibre coproduct of A and B over C along f and g** .

¹⁰*Further Notation:* Also written $A \amalg_{f,C,g} B$.

- *The Cocone.* The maps

$$\begin{aligned} \text{inj}_1 &: A \rightarrow A \coprod_C B, \\ \text{inj}_2 &: B \rightarrow A \coprod_C B \end{aligned}$$

given by

$$\begin{aligned} \text{inj}_1(a) &\stackrel{\text{def}}{=} [(0, a)] \\ \text{inj}_2(b) &\stackrel{\text{def}}{=} [(1, b)] \end{aligned}$$

for each $a \in A$ and each $b \in B$.

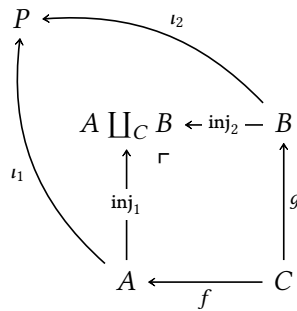
Proof. We claim that $A \coprod_C B$ is the categorical pushout of A and B over C with respect to (f, g) in Sets. First we need to check that the relevant pushout diagram commutes, i.e. that we have

$$\text{inj}_1 \circ f = \text{inj}_2 \circ g,$$

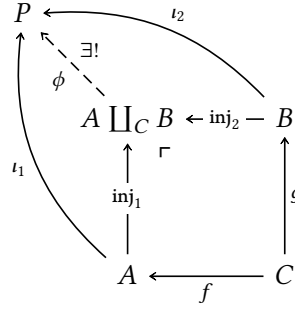
Indeed, given $c \in C$, we have

$$\begin{aligned} [\text{inj}_1 \circ f](c) &= \text{inj}_1(f(c)) \\ &= [(0, f(c))] \\ &= [(1, g(c))] \\ &= \text{inj}_2(g(c)) \\ &= [\text{inj}_2 \circ g](c), \end{aligned}$$

where $[(0, f(c))] = [(1, g(c))]$ by the definition of the relation \sim on $A \coprod B$. Next, we prove that $A \coprod_C B$ satisfies the universal property of the pushout. Suppose we have a diagram of the form



in Sets. Then there exists a unique map $\phi: A \coprod_C B \rightarrow P$ making the diagram



commute, being uniquely determined by the conditions

$$\begin{aligned}\phi \circ \text{inj}_1 &= \iota_1, \\ \phi \circ \text{inj}_2 &= \iota_2\end{aligned}$$

via

$$\phi(x) = \begin{cases} \iota_1(a) & \text{if } x = [(0, a)], \\ \iota_2(b) & \text{if } x = [(1, b)] \end{cases}$$

for each $x \in A \coprod_C B$, where the well-definedness of ϕ is guaranteed by the equality $\iota_1 \circ f = \iota_2 \circ g$ and the definition of the relation \sim on $A \coprod B$ as follows:

1. *Case 1:* Suppose we have $x = [(0, a)] = [(0, a')]$ for some $a, a' \in A$. Then, by [Remark 2.2.4.1.2](#), we have a sequence

$$(0, a) \sim' x_1 \sim' \dots \sim' x_n \sim' (0, a').$$

2. *Case 2:* Suppose we have $x = [(1, b)] = [(1, b')]$ for some $b, b' \in B$. Then, by [Remark 2.2.4.1.2](#), we have a sequence

$$(1, b) \sim' x_1 \sim' \dots \sim' x_n \sim' (1, b').$$

3. *Case 3:* Suppose we have $x = [(0, a)] = [(1, b)]$ for some $a \in A$ and $b \in B$. Then, by [Remark 2.2.4.1.2](#), we have a sequence

$$(0, a) \sim' x_1 \sim' \dots \sim' x_n \sim' (1, b).$$

In all these cases, we declare $x \sim' y$ iff there exists some $c \in C$ such that $x = (0, f(c))$ and $y = (1, g(c))$ or $x = (1, g(c))$ and $y = (0, f(c))$. Then,

the equality $\iota_1 \circ f = \iota_2 \circ g$ gives

$$\begin{aligned}\phi([x]) &= \phi([(0, f(c))]) \\ &\stackrel{\text{def}}{=} \iota_1(f(c)) \\ &= \iota_2(g(c)) \\ &\stackrel{\text{def}}{=} \phi([(1, g(c))]) \\ &= \phi([y]),\end{aligned}$$

with the case where $x = (1, g(c))$ and $y = (0, f(c))$ similarly giving $\phi([x]) = \phi([y])$. Thus, if $x \sim' y$, then $\phi([x]) = \phi([y])$. Applying this equality pairwise to the sequences

$$\begin{aligned}(0, a) &\sim' x_1 \sim' \dots \sim' x_n \sim' (0, a'), \\ (1, b) &\sim' x_1 \sim' \dots \sim' x_n \sim' (1, b'), \\ (0, a) &\sim' x_1 \sim' \dots \sim' x_n \sim' (1, b)\end{aligned}$$

gives

$$\begin{aligned}\phi([(0, a)]) &= \phi([(0, a')]), \\ \phi([(1, b)]) &= \phi([(1, b')]), \\ \phi([(0, a)]) &= \phi([(1, b)]),\end{aligned}$$

showing ϕ to be well-defined. \square

002A Remark 2.2.4.1.2. In detail, by [Construction 7.4.2.1.2](#), the relation \sim of [Definition 2.2.4.1.1](#) is given by declaring $a \sim b$ iff one of the following conditions is satisfied:

- We have $a, b \in A$ and $a = b$;
- We have $a, b \in B$ and $a = b$;
- There exist $x_1, \dots, x_n \in A \amalg B$ such that $a \sim' x_1 \sim' \dots \sim' x_n \sim' b$, where we declare $x \sim' y$ if one of the following conditions is satisfied:
 1. There exists $c \in C$ such that $x = (0, f(c))$ and $y = (1, g(c))$.
 2. There exists $c \in C$ such that $x = (1, g(c))$ and $y = (0, f(c))$.

That is: we require the following condition to be satisfied:

- (\star) There exist $x_1, \dots, x_n \in A \amalg B$ satisfying the following conditions:

1. There exists $c_0 \in C$ satisfying one of the following conditions:
 - (a) We have $a = f(c_0)$ and $x_1 = g(c_0)$.
 - (b) We have $a = g(c_0)$ and $x_1 = f(c_0)$.
2. For each $1 \leq i \leq n - 1$, there exists $c_i \in C$ satisfying one of the following conditions:
 - (a) We have $x_i = f(c_i)$ and $x_{i+1} = g(c_i)$.
 - (b) We have $x_i = g(c_i)$ and $x_{i+1} = f(c_i)$.
3. There exists $c_n \in C$ satisfying one of the following conditions:
 - (a) We have $x_n = f(c_n)$ and $b = g(c_n)$.
 - (b) We have $x_n = g(c_n)$ and $b = f(c_n)$.

002B Example 2.2.4.1.3. Here are some examples of pushouts of sets.

002C 1. *Wedge Sums of Pointed Sets.* The wedge sum of two pointed sets of **Definition 3.3.3.1.1** is an example of a pushout of sets.

002D 2. *Intersections via Unions.* Let $A, B \subset X$. We have a bijection of sets

$$A \cup B \cong A \coprod_{A \cap B} B, \quad \begin{array}{ccc} A \cup B & \longleftarrow & B \\ \uparrow \lrcorner & & \uparrow \\ A & \longleftarrow & A \cap B \end{array}$$

Proof. Item 1, Wedge Sums of Pointed Sets: Follows by definition.

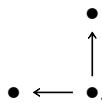
Item 2, Intersections via Unions: Indeed, $A \coprod_{A \cap B} B$ is the quotient of $A \coprod B$ by the equivalence relation obtained by declaring $(0, a) \sim (1, b)$ iff $a = b \in A \cap B$, which is in bijection with $A \cup B$ via the map with $[(0, a)] \mapsto a$ and $[(1, b)] \mapsto b$. □

002E Proposition 2.2.4.1.4. Let A, B, C , and X be sets.

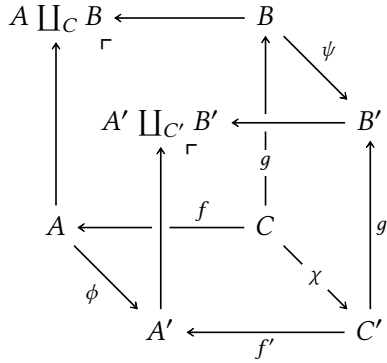
002F 1. *Functoriality.* The assignment $(A, B, C, f, g) \mapsto A \coprod_{f, C, g} B$ defines a functor

$$-_1 \coprod_{-3} -_1 : \text{Fun}(\mathcal{P}, \text{Sets}) \rightarrow \text{Sets},$$

where \mathcal{P} is the category that looks like this:



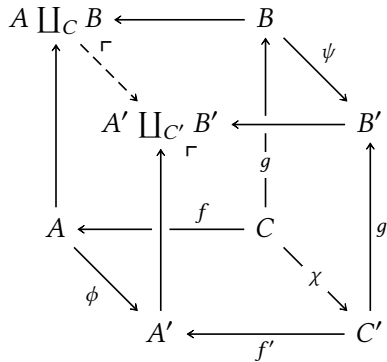
In particular, the action on morphisms of $-1 \coprod_{-3} -1$ is given by sending a morphism



in $\text{Fun}(\mathcal{P}, \text{Sets})$ to the map $\xi: A \coprod_C B \xrightarrow{\exists!} A' \coprod_{C'} B'$ given by

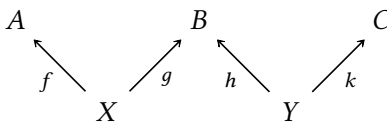
$$\xi(x) \stackrel{\text{def}}{=} \begin{cases} \phi(a) & \text{if } x = [(0, a)], \\ \psi(b) & \text{if } x = [(1, b)] \end{cases}$$

for each $x \in A \coprod_C B$, which is the unique map making the diagram



commute.

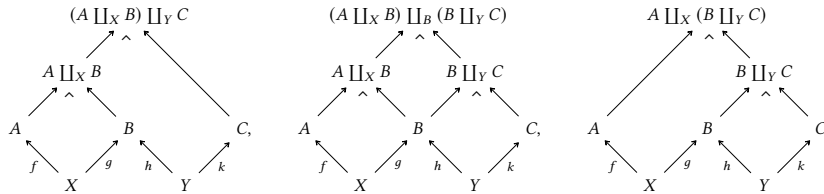
002G 2. *Associativity.* Given a diagram



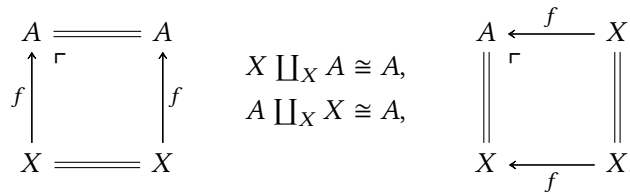
in Sets , we have isomorphisms of sets

$$(A \coprod_X B) \coprod_Y C \cong (A \coprod_X B) \coprod_B (B \coprod_Y C) \cong A \coprod_X (B \coprod_Y C),$$

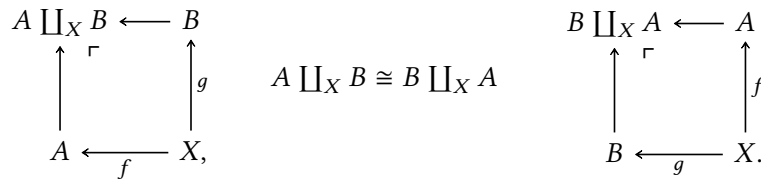
where these pullbacks are built as in the diagrams



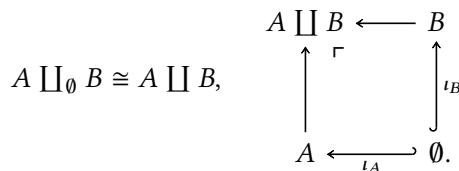
002H 3. *Unitality.* We have isomorphisms of sets



002J 4. *Commutativity.* We have an isomorphism of sets



002K 5. *Interaction With Coproducts.* We have



002L 6. *Symmetric Monoidality.* The triple $(\text{Sets}, \amalg_X, X)$ is a symmetric monoidal category.

Proof. Item 1, Functoriality: This is a special case of functoriality of co/limits, ?? of ??, with the explicit expression for ξ following from the commutativity of the cube pushout diagram.

Item 2, Associativity: Omitted.

Item 3, Unitality: Omitted.

Item 4, Commutativity: Clear.

Item 5, Interaction With Coproducts: Clear.

Item 6, Symmetric Monoidality: Omitted. □

002M 2.2.5 Coequalisers

Let A and B be sets and let $f, g: A \rightrightarrows B$ be functions.

002N Definition 2.2.5.1.1. The **coequaliser of f and g** is the pair $(\text{CoEq}(f, g), \text{coeq}(f, g))$ consisting of:

- *The Colimit.* The set $\text{CoEq}(f, g)$ defined by

$$\text{CoEq}(f, g) \stackrel{\text{def}}{=} B/\sim,$$

where \sim is the equivalence relation on B generated by $f(a) \sim g(a)$.

- *The Cocone.* The map

$$\text{coeq}(f, g): B \rightarrow \text{CoEq}(f, g)$$

given by the quotient map $\pi: B \rightarrow B/\sim$ with respect to the equivalence relation generated by $f(a) \sim g(a)$.

Proof. We claim that $\text{CoEq}(f, g)$ is the categorical coequaliser of f and g in Sets. First we need to check that the relevant coequaliser diagram commutes, i.e. that we have

$$\text{coeq}(f, g) \circ f = \text{coeq}(f, g) \circ g.$$

Indeed, we have

$$\begin{aligned} [\text{coeq}(f, g) \circ f](a) &\stackrel{\text{def}}{=} [\text{coeq}(f, g)](f(a)) \\ &\stackrel{\text{def}}{=} [f(a)] \\ &= [g(a)] \\ &\stackrel{\text{def}}{=} [\text{coeq}(f, g)](g(a)) \\ &\stackrel{\text{def}}{=} [\text{coeq}(f, g) \circ g](a) \end{aligned}$$

for each $a \in A$. Next, we prove that $\text{CoEq}(f, g)$ satisfies the universal property of the coequaliser. Suppose we have a diagram of the form

$$\begin{array}{ccc} A & \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} & B & \xrightarrow{\text{coeq}(f, g)} & \text{CoEq}(f, g) \\ & & & \searrow c & \\ & & & & C \end{array}$$

in Sets. Then, since $c(f(a)) = c(g(a))$ for each $a \in A$, it follows from

Items 4 and 5 of Proposition 7.5.2.1.3 that there exists a unique map $\text{CoEq}(f, g) \xrightarrow{\exists!}$

C making the diagram

$$\begin{array}{ccc}
 A & \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} & B & \begin{array}{c} \xrightarrow{\text{coeq}(f,g)} \\ \searrow c \end{array} & \text{CoEq}(f,g) \\
 & & & & \downarrow \exists! \\
 & & & & C
 \end{array}$$

commute. □

002P Remark 2.2.5.1.2. In detail, by **Construction 7.4.2.1.2**, the relation \sim of **Definition 2.2.5.1.1** is given by declaring $a \sim b$ iff one of the following conditions is satisfied:

- We have $a = b$;
- There exist $x_1, \dots, x_n \in B$ such that $a \sim' x_1 \sim' \dots \sim' x_n \sim' b$, where we declare $x \sim' y$ if one of the following conditions is satisfied:
 1. There exists $z \in A$ such that $x = f(z)$ and $y = g(z)$.
 2. There exists $z \in A$ such that $x = g(z)$ and $y = f(z)$.

That is: we require the following condition to be satisfied:

- (★) There exist $x_1, \dots, x_n \in B$ satisfying the following conditions:
1. There exists $z_0 \in A$ satisfying one of the following conditions:
 - (a) We have $a = f(z_0)$ and $x_1 = g(z_0)$.
 - (b) We have $a = g(z_0)$ and $x_1 = f(z_0)$.
 2. For each $1 \leq i \leq n - 1$, there exists $z_i \in A$ satisfying one of the following conditions:
 - (a) We have $x_i = f(z_i)$ and $x_{i+1} = g(z_i)$.
 - (b) We have $x_i = g(z_i)$ and $x_{i+1} = f(z_i)$.
 3. There exists $z_n \in A$ satisfying one of the following conditions:
 - (a) We have $x_n = f(z_n)$ and $b = g(z_n)$.
 - (b) We have $x_n = g(z_n)$ and $b = f(z_n)$.

002Q Example 2.2.5.1.3. Here are some examples of coequalisers of sets.

002R 1. *Quotients by Equivalence Relations.* Let R be an equivalence relation on a set X . We have a bijection of sets

$$X/\sim_R \cong \text{CoEq}\left(R \hookrightarrow X \times X \begin{array}{c} \xrightarrow{\text{pr}_1} \\ \xrightarrow{\text{pr}_2} \end{array} X\right).$$

Proof. Item 1, Quotients by Equivalence Relations: See [Pro24ad]. \square

002S Proposition 2.2.5.1.4. Let A , B , and C be sets.

002T 1. *Associativity.* We have isomorphisms of sets¹¹

$$\underbrace{\text{CoEq}(\text{coeq}(f, g) \circ f, \text{coeq}(f, g) \circ h)}_{=\text{CoEq}(\text{coeq}(f, g) \circ g, \text{coeq}(f, g) \circ h)} \cong \text{CoEq}(f, g, h) \cong \underbrace{\text{CoEq}(\text{coeq}(g, h) \circ f, \text{coeq}(g, h) \circ g)}_{=\text{CoEq}(\text{coeq}(g, h) \circ f, \text{coeq}(g, h) \circ h)}$$

where $\text{CoEq}(f, g, h)$ is the colimit of the diagram

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \\ \xrightarrow{h} \end{array} B$$

¹¹That is, the following three ways of forming “the” coequaliser of (f, g, h) agree:

1. Take the coequaliser of (f, g, h) , i.e. the colimit of the diagram

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \\ \xrightarrow{h} \end{array} B$$

in Sets.

2. First take the coequaliser of f and g , forming a diagram

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B \xrightarrow{\text{coeq}(f, g)} \text{CoEq}(f, g)$$

and then take the coequaliser of the composition

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{h} \end{array} B \xrightarrow{\text{coeq}(f, g)} \text{CoEq}(f, g),$$

obtaining a quotient

$$\text{CoEq}(\text{coeq}(f, g) \circ f, \text{coeq}(f, g) \circ h) = \text{CoEq}(\text{coeq}(f, g) \circ g, \text{coeq}(f, g) \circ h)$$

of $\text{CoEq}(f, g)$

3. First take the coequaliser of g and h , forming a diagram

$$A \begin{array}{c} \xrightarrow{g} \\ \xrightarrow{h} \end{array} B \xrightarrow{\text{coeq}(g, h)} \text{CoEq}(g, h)$$

and then take the coequaliser of the composition

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B \xrightarrow{\text{coeq}(g, h)} \text{CoEq}(g, h),$$

obtaining a quotient

$$\text{CoEq}(\text{coeq}(g, h) \circ f, \text{coeq}(g, h) \circ g) = \text{CoEq}(\text{coeq}(g, h) \circ f, \text{coeq}(g, h) \circ h)$$

of $\text{CoEq}(g, h)$.

in Sets.

002U 4. *Unitality*. We have an isomorphism of sets

$$\text{CoEq}(f, f) \cong B.$$

002V 5. *Commutativity*. We have an isomorphism of sets

$$\text{CoEq}(f, g) \cong \text{CoEq}(g, f).$$

002W 6. *Interaction With Composition*. Let

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{h} \\ \xrightarrow{k} \end{array} C$$

be functions. We have a surjection

$$\text{CoEq}(h \circ f, k \circ g) \twoheadrightarrow \text{CoEq}(\text{coeq}(h, k) \circ h \circ f, \text{coeq}(h, k) \circ k \circ g)$$

exhibiting $\text{CoEq}(\text{coeq}(h, k) \circ h \circ f, \text{coeq}(h, k) \circ k \circ g)$ as a quotient of $\text{CoEq}(h \circ f, k \circ g)$ by the relation generated by declaring $h(y) \sim k(y)$ for each $y \in B$.

Proof. *Item 1, Associativity*: Omitted.

Item 4, Unitality: Clear.

Item 5, Commutativity: Clear.

Item 6, Interaction With Composition: Omitted. □

002X 2.3 Operations With Sets

002Y 2.3.1 The Empty Set

002Z **Definition 2.3.1.1.1.** The **empty set** is the set \emptyset defined by

$$\emptyset \stackrel{\text{def}}{=} \{x \in X \mid x \neq x\},$$

where A is the set in the set existence axiom, ?? of ??.

0030 2.3.2 Singleton Sets

Let X be a set.

0031 **Definition 2.3.2.1.1.** The **singleton set containing X** is the set $\{X\}$ defined by

$$\{X\} \stackrel{\text{def}}{=} \{X, X\},$$

where $\{X, X\}$ is the pairing of X with itself (**Definition 2.3.3.1.1**).

0032 2.3.3 Pairings of Sets

Let X and Y be sets.

0033 Definition 2.3.3.1.1. The **pairing of X and Y** is the set $\{X, Y\}$ defined by

$$\{X, Y\} \stackrel{\text{def}}{=} \{x \in A \mid x = X \text{ or } x = Y\},$$

where A is the set in the axiom of pairing, ?? of ??.

0034 2.3.4 Ordered Pairs

Let A and B be sets.

0035 Definition 2.3.4.1.1. The **ordered pair associated to A and B** is the set (A, B) defined by

$$(A, B) \stackrel{\text{def}}{=} \{\{A\}, \{A, B\}\}.$$

0036 Proposition 2.3.4.1.2. Let A and B be sets.

0037 1. *Uniqueness.* Let A, B, C , and D be sets. The following conditions are equivalent:

0038 (a) We have $(A, B) = (C, D)$.

0039 (b) We have $A = C$ and $B = D$.

Proof. Item 1, Uniqueness: See [Cie97, Theorem 1.2.3]. □

003A 2.3.5 Sets of Maps

Let A and B be sets.

003B Definition 2.3.5.1.1. The **set of maps from A to B** ¹² is the set $\text{Hom}_{\text{Sets}}(A, B)$ ¹³ whose elements are the functions from A to B .

003C Proposition 2.3.5.1.2. Let A and B be sets.

003D 1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto \text{Hom}_{\text{Sets}}(X, Y)$ define functors

$$\begin{aligned} \text{Hom}_{\text{Sets}}(X, -) &: \text{Sets} \rightarrow \text{Sets}, \\ \text{Hom}_{\text{Sets}}(-, Y) &: \text{Sets}^{\text{op}} \rightarrow \text{Sets}, \\ \text{Hom}_{\text{Sets}}(-, -) &: \text{Sets}^{\text{op}} \times \text{Sets} \rightarrow \text{Sets}. \end{aligned}$$

Proof. Item 1, Functoriality: This follows from **Items 2** and **5** of **Proposition 8.1.6.1.2**. □

¹²*Further Terminology:* Also called the **Hom set from A to B** .

¹³*Further Notation:* Also written $\text{Sets}(A, B)$.

003E 2.3.6 Unions of Families

Let $\{A_i\}_{i \in I}$ be a family of sets.

003F Definition 2.3.6.1.1. The **union of the family** $\{A_i\}_{i \in I}$ is the set $\bigcup_{i \in I} A_i$ defined by

$$\bigcup_{i \in I} A_i \stackrel{\text{def}}{=} \{x \in F \mid \text{there exists some } i \in I \text{ such that } x \in A_i\},$$

where F is the set in the axiom of union, ?? of ??.

003G 2.3.7 Binary Unions

Let A and B be sets.

003H Definition 2.3.7.1.1. The **union**¹⁴ of A and B is the set $A \cup B$ defined by

$$A \cup B \stackrel{\text{def}}{=} \bigcup_{z \in \{A, B\}} z.$$

003J Proposition 2.3.7.1.2. Let X be a set.

003K 1. *Functoriality.* The assignments $U, V, (U, V) \mapsto U \cup V$ define functors

$$\begin{aligned} U \cup -: (\mathcal{P}(X), \subset) &\rightarrow (\mathcal{P}(X), \subset), \\ - \cup V: (\mathcal{P}(X), \subset) &\rightarrow (\mathcal{P}(X), \subset), \\ -_1 \cup -_2: (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \subset) &\rightarrow (\mathcal{P}(X), \subset), \end{aligned}$$

where $-_1 \cup -_2$ is the functor where

- *Action on Objects.* For each $(U, V) \in \mathcal{P}(X) \times \mathcal{P}(X)$, we have

$$[-_1 \cup -_2](U, V) \stackrel{\text{def}}{=} U \cup V.$$

- *Action on Morphisms.* For each pair of morphisms

$$\begin{aligned} \iota_U: U &\hookrightarrow U', \\ \iota_V: V &\hookrightarrow V' \end{aligned}$$

of $\mathcal{P}(X) \times \mathcal{P}(X)$, the image

$$\iota_U \cup \iota_V: U \cup V \hookrightarrow U' \cup V'$$

of (ι_U, ι_V) by \cup is the inclusion

$$U \cup V \subset U' \cup V'$$

i.e. where we have

¹⁴*Further Terminology:* Also called the **binary union** of A and B , for emphasis.

(★) If $U \subset U'$ and $V \subset V'$, then $U \cup V \subset U' \cup V'$.

and where $U \cup -$ and $- \cup V$ are the partial functors of $-_1 \cup -_2$ at $U, V \in \mathcal{P}(X)$.

003L 2. *Via Intersections and Symmetric Differences.* We have an equality of sets

$$U \cup V = (U \Delta V) \Delta (U \cap V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

003M 3. *Associativity.* We have an equality of sets

$$(U \cup V) \cup W = U \cup (V \cup W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

003N 4. *Unitality.* We have equalities of sets

$$U \cup \emptyset = U,$$

$$\emptyset \cup U = U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

003P 5. *Commutativity.* We have an equality of sets

$$U \cup V = V \cup U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

003Q 6. *Idempotency.* We have an equality of sets

$$U \cup U = U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

003R 7. *Distributivity Over Intersections.* We have equalities of sets

$$U \cup (V \cap W) = (U \cup V) \cap (U \cup W),$$

$$(U \cap V) \cup W = (U \cup W) \cap (V \cup W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

003S 8. *Interaction With Characteristic Functions I.* We have

$$\chi_{U \cup V} = \max(\chi_U, \chi_V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

003T 9. *Interaction With Characteristic Functions II.* We have

$$\chi_{U \cup V} = \chi_U + \chi_V - \chi_{U \cap V}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

003U 10. *Interaction With Powersets and Semirings.* The quintuple $(\mathcal{P}(X), \cup, \cap, \emptyset, X)$ is an idempotent commutative semiring.

Proof. Item 1, Functoriality: See [Pro24ar].

Item 2, Via Intersections and Symmetric Differences: See [Pro24bc].

Item 3, Associativity: See [Pro24be].

Item 4, Unitality: This follows from [Pro24bh] and *Item 5*.

Item 5, Commutativity: See [Pro24bf].

Item 6, Idempotency: See [Pro24aq].

Item 7, Distributivity Over Intersections: See [Pro24bd].

Item 8, Interaction With Characteristic Functions I: See [Pro24k].

Item 9, Interaction With Characteristic Functions II: See [Pro24k].

Item 10, Interaction With Powersets and Semirings: This follows from *Items 3 to 6* and *Items 3 to 5, 7 and 8* of *Proposition 2.3.9.1.2*. \square

003V 2.3.8 Intersections of Families

Let \mathcal{F} be a family of sets.

003W **Definition 2.3.8.1.1.** The **intersection of a family \mathcal{F} of sets** is the set $\bigcap_{X \in \mathcal{F}} X$ defined by

$$\bigcap_{X \in \mathcal{F}} X \stackrel{\text{def}}{=} \left\{ z \in \bigcup_{X \in \mathcal{F}} X \mid \text{for each } X \in \mathcal{F}, \text{ we have } z \in X \right\}.$$

003X 2.3.9 Binary Intersections

Let X and Y be sets.

003Y **Definition 2.3.9.1.1.** The **intersection¹⁵ of X and Y** is the set $X \cap Y$ defined by

$$X \cap Y \stackrel{\text{def}}{=} \bigcap_{z \in \{X, Y\}} z.$$

003Z **Proposition 2.3.9.1.2.** Let X be a set.

¹⁵*Further Terminology:* Also called the **binary intersection of X and Y** , for emphasis.

0040 1. *Functoriality.* The assignments $U, V, (U, V) \mapsto U \cap V$ define functors

$$\begin{aligned} U \cap -: (\mathcal{P}(X), \subset) &\rightarrow (\mathcal{P}(X), \subset), \\ - \cap V: (\mathcal{P}(X), \subset) &\rightarrow (\mathcal{P}(X), \subset), \\ -_1 \cap -_2: (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \subset) &\rightarrow (\mathcal{P}(X), \subset), \end{aligned}$$

where $-_1 \cap -_2$ is the functor where

- *Action on Objects.* For each $(U, V) \in \mathcal{P}(X) \times \mathcal{P}(X)$, we have

$$[-_1 \cap -_2](U, V) \stackrel{\text{def}}{=} U \cap V.$$

- *Action on Morphisms.* For each pair of morphisms

$$\begin{aligned} \iota_U: U &\hookrightarrow U', \\ \iota_V: V &\hookrightarrow V' \end{aligned}$$

of $\mathcal{P}(X) \times \mathcal{P}(X)$, the image

$$\iota_U \cap \iota_V: U \cap V \hookrightarrow U' \cap V'$$

of (ι_U, ι_V) by \cap is the inclusion

$$U \cap V \subset U' \cap V'$$

i.e. where we have

$$(\star) \text{ If } U \subset U' \text{ and } V \subset V', \text{ then } U \cap V \subset U' \cap V'.$$

and where $U \cap -$ and $- \cap V$ are the partial functors of $-_1 \cap -_2$ at $U, V \in \mathcal{P}(X)$.

0041 2. *Adjointness.* We have adjunctions

$$\begin{aligned} (U \cap - \dashv \mathbf{Hom}_{\mathcal{P}(X)}(U, -)) &: \mathcal{P}(X) \begin{array}{c} \xrightarrow{U \cap -} \\ \perp \\ \xleftarrow{\mathbf{Hom}_{\mathcal{P}(X)}(U, -)} \end{array} \mathcal{P}(X), \\ (- \cap V \dashv \mathbf{Hom}_{\mathcal{P}(X)}(V, -)) &: \mathcal{P}(X) \begin{array}{c} \xrightarrow{- \cap V} \\ \perp \\ \xleftarrow{\mathbf{Hom}_{\mathcal{P}(X)}(V, -)} \end{array} \mathcal{P}(X), \end{aligned}$$

where

$$\mathbf{Hom}_{\mathcal{P}(X)}(-_1, -_2): \mathcal{P}(X)^{\text{op}} \times \mathcal{P}(X) \rightarrow \mathcal{P}(X)$$

is the bifunctor defined by¹⁶

$$\mathbf{Hom}_{\mathcal{P}(X)}(U, V) \stackrel{\text{def}}{=} (X \setminus U) \cup V$$

witnessed by bijections

$$\mathbf{Hom}_{\mathcal{P}(X)}(U \cap V, W) \cong \mathbf{Hom}_{\mathcal{P}(X)}(U, \mathbf{Hom}_{\mathcal{P}(X)}(V, W)),$$

$$\mathbf{Hom}_{\mathcal{P}(X)}(U \cap V, W) \cong \mathbf{Hom}_{\mathcal{P}(X)}(V, \mathbf{Hom}_{\mathcal{P}(X)}(U, W)),$$

natural in $U, V, W \in \mathcal{P}(X)$, i.e. where:

(a) The following conditions are equivalent:

- i. We have $U \cap V \subset W$.
- ii. We have $U \subset \mathbf{Hom}_{\mathcal{P}(X)}(V, W)$.
- iii. We have $U \subset (X \setminus V) \cup W$.

(b) The following conditions are equivalent:

- i. We have $V \cap U \subset W$.
- ii. We have $V \subset \mathbf{Hom}_{\mathcal{P}(X)}(U, W)$.
- iii. We have $V \subset (X \setminus U) \cup W$.

0042 3. *Associativity.* We have an equality of sets

$$(U \cap V) \cap W = U \cap (V \cap W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

0043 4. *Unitality.* Let X be a set and let $U \in \mathcal{P}(X)$. We have equalities of sets

$$X \cap U = U,$$

$$U \cap X = U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

0044 5. *Commutativity.* We have an equality of sets

$$U \cap V = V \cap U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

0045 6. *Idempotency.* We have an equality of sets

$$U \cap U = U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

¹⁶For intuition regarding the expression defining $\mathbf{Hom}_{\mathcal{P}(X)}(U, V)$, see [Remark 2.3.9.1.3](#).

0046 7. *Distributivity Over Unions.* We have equalities of sets

$$\begin{aligned} U \cap (V \cup W) &= (U \cap V) \cup (U \cap W), \\ (U \cup V) \cap W &= (U \cap W) \cup (V \cap W) \end{aligned}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

0047 8. *Annihilation With the Empty Set.* We have an equality of sets

$$\begin{aligned} \emptyset \cap X &= \emptyset, \\ X \cap \emptyset &= \emptyset \end{aligned}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

0048 9. *Interaction With Characteristic Functions I.* We have

$$\chi_{U \cap V} = \chi_U \chi_V$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

0049 10. *Interaction With Characteristic Functions II.* We have

$$\chi_{U \cap V} = \min(\chi_U, \chi_V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

004A 11. *Interaction With Powersets and Monoids With Zero.* The quadruple $((\mathcal{P}(X), \emptyset), \cap, X)$ is a commutative monoid with zero.

004B 12. *Interaction With Powersets and Semirings.* The quintuple $(\mathcal{P}(X), \cup, \cap, \emptyset, X)$ is an idempotent commutative semiring.

Proof. Item 1, Functoriality: See [Pro24ap].

Item 2, Adjointness: See [MSE 267469].

Item 3, Associativity: See [Pro24v].

Item 4, Unitality: This follows from [Pro24z] and Item 5.

Item 5, Commutativity: See [Pro24w].

Item 6, Idempotency: See [Pro24ao].

Item 7, Distributivity Over Unions: See [Pro24an].

Item 8, Annihilation With the Empty Set: This follows from [Pro24x] and Item 5.

Item 9, Interaction With Characteristic Functions I: See [Pro24h].

Item 10, Interaction With Characteristic Functions II: See [Pro24h].

Item 11, Interaction With Powersets and Monoids With Zero: This follows from Items 3 to 5 and 8.

Item 12, Interaction With Powersets and Semirings: This follows from Items 3 to 6 and Items 3 to 5, 7 and 8 of Proposition 2.3.9.1.2. \square

004C Remark 2.3.9.1.3. Since intersections are the products in $\mathcal{P}(X)$ (Item 1 of Proposition 2.4.3.1.3), the left adjoint $\mathbf{Hom}_{\mathcal{P}(X)}(U, V)$ may be thought of as a function type $[U, V]$.

Then, under the Curry–Howard correspondence, the function type $[U, V]$ corresponds to implication $U \implies V$, which is logically equivalent to the statement $\neg U \vee V$. This in turn corresponds to the set $U^c \vee V = (X \setminus U) \cup V$.

004D 2.3.10 Differences

Let X and Y be sets.

004E Definition 2.3.10.1.1. The **difference of X and Y** is the set $X \setminus Y$ defined by

$$X \setminus Y \stackrel{\text{def}}{=} \{a \in X \mid a \notin Y\}.$$

004F Proposition 2.3.10.1.2. Let X be a set.

004G 1. *Functoriality.* The assignments $U, V, (U, V) \mapsto U \cap V$ define functors

$$\begin{aligned} U \setminus - &: (\mathcal{P}(X), \supset) \rightarrow (\mathcal{P}(X), \subset), \\ - \setminus V &: (\mathcal{P}(X), \subset) \rightarrow (\mathcal{P}(X), \subset), \\ -_1 \setminus -_2 &: (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \supset) \rightarrow (\mathcal{P}(X), \subset), \end{aligned}$$

where $-_1 \setminus -_2$ is the functor where

- *Action on Objects.* For each $(U, V) \in \mathcal{P}(X) \times \mathcal{P}(X)$, we have

$$[-_1 \setminus -_2](U, V) \stackrel{\text{def}}{=} U \setminus V.$$

- *Action on Morphisms.* For each pair of morphisms

$$\begin{aligned} \iota_A &: A \hookrightarrow B, \\ \iota_U &: U \hookrightarrow V \end{aligned}$$

of $\mathcal{P}(X) \times \mathcal{P}(X)$, the image

$$\iota_U \setminus \iota_V: A \setminus V \hookrightarrow B \setminus U$$

of (ι_U, ι_V) by \setminus is the inclusion

$$A \setminus V \subset B \setminus U$$

i.e. where we have

(★) If $A \subset B$ and $U \subset V$, then $A \setminus V \subset B \setminus U$.

and where $U \setminus -$ and $- \setminus V$ are the partial functors of $-_1 \setminus -_2$ at $U, V \in \mathcal{P}(X)$.

004H 2. *De Morgan's Laws.* We have equalities of sets

$$\begin{aligned} X \setminus (U \cup V) &= (X \setminus U) \cap (X \setminus V), \\ X \setminus (U \cap V) &= (X \setminus U) \cup (X \setminus V) \end{aligned}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

004J 3. *Interaction With Unions I.* We have equalities of sets

$$U \setminus (V \cup W) = (U \setminus V) \cap (U \setminus W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

004K 4. *Interaction With Unions II.* We have equalities of sets

$$(U \setminus V) \cup W = (U \cup W) \setminus (V \setminus W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

004L 5. *Interaction With Unions III.* We have equalities of sets

$$\begin{aligned} U \setminus (V \cup W) &= (U \cup W) \setminus (V \cup W) \\ &= (U \setminus V) \setminus W \\ &= (U \setminus W) \setminus V \end{aligned}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

004M 6. *Interaction With Unions IV.* We have equalities of sets

$$(U \cup V) \setminus W = (U \setminus W) \cup (V \setminus W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

004N 7. *Interaction With Intersections.* We have equalities of sets

$$\begin{aligned} (U \setminus V) \cap W &= (U \cap W) \setminus V \\ &= U \cap (W \setminus V) \end{aligned}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

004P 8. *Interaction With Complements.* We have an equality of sets

$$U \setminus V = U \cap V^c$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

004Q 9. *Interaction With Symmetric Differences.* We have an equality of sets

$$U \setminus V = U \Delta (U \cap V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

004R 10. *Triple Differences.* We have

$$U \setminus (V \setminus W) = (U \cap W) \cup (U \setminus V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

004S 11. *Left Annihilation.* We have

$$\emptyset \setminus U = \emptyset$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

004T 12. *Right Unitality.* We have

$$U \setminus \emptyset = U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

004U 13. *Invertibility.* We have

$$U \setminus U = \emptyset$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

004V 14. *Interaction With Containment.* The following conditions are equivalent:

004W (a) We have $V \setminus U \subset W$.

004X (b) We have $V \setminus W \subset U$.

004Y 15. *Interaction With Characteristic Functions.* We have

$$\chi_{U \setminus V} = \chi_U - \chi_{U \cap V}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

Proof. Item 1, Functoriality: See [Pro24ah] and [Pro24al].

Item 2, De Morgan's Laws: See [Pro24p].

Item 3, Interaction With Unions I: See [Pro24q].

Item 4, Interaction With Unions II: Omitted.

Item 5, Interaction With Unions III: See [Pro24am].

Item 6, Interaction With Unions IV: See [Pro24ag].

Item 7, Interaction With Intersections: See [Pro24y].

Item 8, Interaction With Complements: See [Pro24ae].

Item 9, Interaction With Symmetric Differences: See [Pro24af].

Item 10, Triple Differences: See [Pro24ak].

Item 11, Left Annihilation: Clear.

Item 12, Right Unitality: See [Pro24ai].

Item 13, Invertibility: See [Pro24aj].

Item 14, Interaction With Containment: Omitted.

Item 15, Interaction With Characteristic Functions: See [Pro24i]. □

004Z 2.3.11 Complements

Let X be a set and let $U \in \mathcal{P}(X)$.

0050 **Definition 2.3.11.1.1.** The **complement of U** is the set U^c defined by

$$\begin{aligned} U^c &\stackrel{\text{def}}{=} X \setminus U \\ &\stackrel{\text{def}}{=} \{a \in X \mid a \notin U\}. \end{aligned}$$

0051 **Proposition 2.3.11.1.2.** Let X be a set.

0052 1. *Functoriality.* The assignment $U \mapsto U^c$ defines a functor

$$(-)^c: \mathcal{P}(X)^{\text{op}} \rightarrow \mathcal{P}(X),$$

where

- *Action on Objects.* For each $U \in \mathcal{P}(X)$, we have

$$[(-)^c](U) \stackrel{\text{def}}{=} U^c.$$

- *Action on Morphisms.* For each morphism $\iota_U: U \hookrightarrow V$ of $\mathcal{P}(X)$, the image

$$\iota_U^c: V^c \hookrightarrow U^c$$

of ι_U by $(-)^c$ is the inclusion

$$V^c \subset U^c$$

i.e. where we have

- (★) If $U \subset V$, then $V^c \subset U^c$.

0053 2. *De Morgan's Laws.* We have equalities of sets

$$(U \cup V)^c = U^c \cap V^c,$$

$$(U \cap V)^c = U^c \cup V^c$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

0054 3. *Involutority.* We have

$$(U^c)^c = U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

0055 4. *Interaction With Characteristic Functions.* We have

$$\chi_{U^c} = 1 - \chi_U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

Proof. Item 1, Functoriality: This follows from **Item 1** of **Proposition 2.3.10.1.2**.

Item 2, De Morgan's Laws: See [Pro24p].

Item 3, Involutority: See [Pro24l].

Item 4, Interaction With Characteristic Functions: Clear. \square

0056 2.3.12 Symmetric Differences

Let A and B be sets.

0057 **Definition 2.3.12.1.1.** The **symmetric difference of A and B** is the set $A \Delta B$ defined by

$$A \Delta B \stackrel{\text{def}}{=} (A \setminus B) \cup (B \setminus A).$$

0058 **Proposition 2.3.12.1.2.** Let X be a set.

0059 1. *Lack of Functoriality.* The assignment $(U, V) \mapsto U \Delta V$ **need not** define functors

$$U \Delta -: (\mathcal{P}(X), \subset) \rightarrow (\mathcal{P}(X), \subset),$$

$$- \Delta V: (\mathcal{P}(X), \subset) \rightarrow (\mathcal{P}(X), \subset),$$

$$-_1 \Delta -_2: (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \subset) \rightarrow (\mathcal{P}(X), \subset).$$

005A 2. *Via Unions and Intersections.* We have¹⁷

$$U \Delta V = (U \cup V) \setminus (U \cap V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

005B 3. *Associativity.* We have¹⁸

$$(U \Delta V) \Delta W = U \Delta (V \Delta W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

005C 4. *Commutativity.* We have

$$U \Delta V = V \Delta U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

005D 5. *Unitality.* We have

$$U \Delta \emptyset = U,$$

$$\emptyset \Delta U = U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

005E 6. *Invertibility.* We have

$$U \Delta U = \emptyset$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

005F 7. *Interaction With Unions.* We have

$$(U \Delta V) \cup (V \Delta T) = (U \cup V \cup W) \setminus (U \cap V \cap W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

¹⁷Illustration:



¹⁸Illustration:



- 005G 8. *Interaction With Complements I.* We have

$$U \Delta U^c = X$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

- 005H 9. *Interaction With Complements II.* We have

$$U \Delta X = U^c,$$

$$X \Delta U = U^c$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

- 005J 10. *Interaction With Complements III.* We have

$$U^c \Delta V^c = U \Delta V$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

- 005K 11. *“Transitivity”.* We have

$$(U \Delta V) \Delta (V \Delta W) = U \Delta W$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

- 005L 12. *The Triangle Inequality for Symmetric Differences.* We have

$$U \Delta W \subset U \Delta V \cup V \Delta W$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

- 005M 13. *Distributivity Over Intersections.* We have

$$U \cap (V \Delta W) = (U \cap V) \Delta (U \cap W),$$

$$(U \Delta V) \cap W = (U \cap W) \Delta (V \cap W)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V, W \in \mathcal{P}(X)$.

- 005N 14. *Interaction With Characteristic Functions.* We have

$$\chi_{U \Delta V} = \chi_U + \chi_V - 2\chi_{U \cap V}$$

and thus, in particular, we have

$$\chi_{U \Delta V} \equiv \chi_U + \chi_V \pmod{2}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

005P 15. *Bijectivity.* Given $A, B \subset \mathcal{P}(X)$, the maps

$$\begin{aligned} A \Delta - : \mathcal{P}(X) &\rightarrow \mathcal{P}(X), \\ - \Delta B : \mathcal{P}(X) &\rightarrow \mathcal{P}(X) \end{aligned}$$

are bijections with inverses given by

$$\begin{aligned} (A \Delta -)^{-1} &= - \cup (A \cap -), \\ (- \Delta B)^{-1} &= - \cup (B \cap -). \end{aligned}$$

Moreover, the map

$$C \mapsto C \Delta (A \Delta B)$$

is a bijection of $\mathcal{P}(X)$ onto itself sending A to B and B to A .

005Q 16. *Interaction With Powersets and Groups.* Let X be a set.

005R (a) The quadruple $(\mathcal{P}(X), \Delta, \emptyset, \text{id}_{\mathcal{P}(X)})$ is an abelian group.¹⁹

(b) Every element of $\mathcal{P}(X)$ has order 2 with respect to Δ , and thus $\mathcal{P}(X)$ is a *Boolean group* (i.e. an abelian 2-group).

005S

005T 4. *Interaction With Powersets and Vector Spaces I.* The pair $(\mathcal{P}(X), \alpha_{\mathcal{P}(X)})$ consisting of

- The group $\mathcal{P}(X)$ of ??;
- The map $\alpha_{\mathcal{P}(X)} : \mathbb{F}_2 \times \mathcal{P}(X) \rightarrow \mathcal{P}(X)$ defined by

$$\begin{aligned} 0 \cdot U &\stackrel{\text{def}}{=} \emptyset, \\ 1 \cdot U &\stackrel{\text{def}}{=} U; \end{aligned}$$

¹⁹Here are some examples:

1. When $X = \emptyset$, we have an isomorphism of groups between $\mathcal{P}(\emptyset)$ and the trivial group:

$$(\mathcal{P}(\emptyset), \Delta, \emptyset, \text{id}_{\mathcal{P}(\emptyset)}) \cong \text{pt.}$$

2. When $X = \text{pt}$, we have an isomorphism of groups between $\mathcal{P}(\text{pt})$ and $\mathbb{Z}/2$:

$$(\mathcal{P}(\text{pt}), \Delta, \emptyset, \text{id}_{\mathcal{P}(\text{pt})}) \cong \mathbb{Z}/2.$$

3. When $X = \{0, 1\}$, we have an isomorphism of groups between $\mathcal{P}(\{0, 1\})$ and $\mathbb{Z}/2 \times \mathbb{Z}/2$:

$$(\mathcal{P}(\{0, 1\}), \Delta, \emptyset, \text{id}_{\mathcal{P}(\{0, 1\})}) \cong \mathbb{Z}/2 \times \mathbb{Z}/2.$$

is an \mathbb{F}_2 -vector space.

- 005U 5. *Interaction With Powersets and Vector Spaces II.* If X is finite, then:
- (a) The set of singletons sets on the elements of X forms a basis for the \mathbb{F}_2 -vector space $(\mathcal{P}(X), \alpha_{\mathcal{P}(X)})$ of [Item 4](#).
 - (b) We have

$$\dim(\mathcal{P}(X)) = \#\mathcal{P}(X).$$
- 005V 6. *Interaction With Powersets and Rings.* The quintuple $(\mathcal{P}(X), \Delta, \cap, \emptyset, X)$ is a commutative ring.²⁰

Proof. [Item 1](#), *Lack of Functoriality*: Omitted.

[Item 2](#), *Via Unions and Intersections*: See [[Pro24r](#)].

[Item 3](#), *Associativity*: See [[Pro24as](#)].

[Item 4](#), *Commutativity*: See [[Pro24at](#)].

[Item 5](#), *Unitality*: This follows from [Item 4](#) and [[Pro24ax](#)].

[Item 6](#), *Invertibility*: See [[Pro24az](#)].

[Item 7](#), *Interaction With Unions*: See [[Pro24bg](#)].

[Item 8](#), *Interaction With Complements I*: See [[Pro24aw](#)].

[Item 9](#), *Interaction With Complements II*: This follows from [Item 4](#) and [[Pro24bb](#)].

[Item 10](#), *Interaction With Complements III*: See [[Pro24au](#)].

[Item 11](#), “*Transitivity*”: We have

$$\begin{aligned} (U \Delta V) \Delta (V \Delta W) &= U \Delta (V \Delta (V \Delta W)) && \text{(by Item 3)} \\ &= U \Delta ((V \Delta V) \Delta W) && \text{(by Item 3)} \\ &= U \Delta (\emptyset \Delta W) && \text{(by Item 6)} \\ &= U \Delta W && \text{(by Item 5)} \end{aligned}$$

[Item 12](#), *The Triangle Inequality for Symmetric Differences*: This follows from [Items 2](#) and [11](#).


[Item 13](#), *Distributivity Over Intersections*: See [[Pro24u](#)].

[Item 14](#), *Interaction With Characteristic Functions*: See [[Pro24j](#)].

[Item 15](#), *Bijectivity*: Clear.

[Item 16](#), *Interaction With Powersets and Groups*: [Item 16a](#) follows from²¹ [Items 3](#) to [6](#), while [Item 3b](#) follows from [Item 6](#).

[Item 4](#), *Interaction With Powersets and Vector Spaces I*: Clear.

²⁰  *Warning*: The analogous statement replacing intersections by unions (i.e. that the quintuple $(\mathcal{P}(X), \Delta, \cup, \emptyset, X)$ is a ring) is false, however. See [[Pro24ba](#)] for a proof.

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²¹Reference: [[Pro24av](#)].

Item 5, Interaction With Powersets and Vector Spaces II: Omitted.

Item 6, Interaction With Powersets and Rings: This follows from Items 8 and 11 of Proposition 2.3.9.1.2 and Items 13 and 16.²² \square

005W 2.4 Powersets

005X 2.4.1 Characteristic Functions

Let X be a set.

005Y **Definition 2.4.1.1.1.** Let $U \subset X$ and let $x \in X$.

005Z 1. The **characteristic function of U** ²³ is the function²⁴

$$\chi_U: X \rightarrow \{t, f\}$$

defined by

$$\chi_U(x) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x \in U, \\ \text{false} & \text{if } x \notin U \end{cases}$$

for each $x \in X$.

0060 2. The **characteristic function of x** is the function²⁵

$$\chi_x: X \rightarrow \{t, f\}$$

defined by

$$\chi_x \stackrel{\text{def}}{=} \chi_{\{x\}},$$

i.e. by

$$\chi_x(y) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x = y, \\ \text{false} & \text{if } x \neq y \end{cases}$$

for each $y \in X$.

0061 3. The **characteristic relation on X** ²⁶ is the relation²⁷

$$\chi_X(-1, -2): X \times X \rightarrow \{t, f\}$$

²²Reference: [Pro24ay].

²³Further Terminology: Also called the **indicator function of U** .

²⁴Further Notation: Also written $\chi_X(U, -)$ or $\chi_X(-, U)$.

²⁵Further Notation: Also written χ^x , $\chi_X(x, -)$, or $\chi_X(-, x)$.

²⁶Further Terminology: Also called the **identity relation on X** .

²⁷Further Notation: Also written χ_{-1}^{-2} , or \sim_{id} in the context of relations.

on X defined by²⁸

$$\chi_X(x, y) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x = y, \\ \text{false} & \text{if } x \neq y \end{cases}$$

for each $x, y \in X$.

0062 4. The **characteristic embedding**²⁹ of X into $\mathcal{P}(X)$ is the function

$$\chi_{(-)} : X \hookrightarrow \mathcal{P}(X)$$

defined by

$$\chi_{(-)}(x) \stackrel{\text{def}}{=} \chi_x$$

for each $x \in X$.

0063 Remark 2.4.1.1.2. The definitions in **Definition 2.4.1.1.1** are decategorifications of co/presheaves, representable co/presheaves, Hom profunctors, and the Yoneda embedding:³⁰

²⁸As a subset of $X \times X$, the relation χ_X corresponds to the diagonal $\Delta_X \subset X \times X$ of X .

²⁹The name “characteristic embedding” comes from the fact that there is an analogue of fully faithfulness for $\chi_{(-)}$: given a set X , we have

$$\text{Hom}_{\mathcal{P}(X)}(\chi_x, \chi_y) = \chi_X(x, y),$$

for each $x, y \in X$.

³⁰These statements can be made precise by using the embeddings

$$\begin{aligned} (-)_{\text{disc}} &: \text{Sets} \hookrightarrow \text{Cats}, \\ (-)_{\text{disc}} &: \{\text{t}, \text{f}\}_{\text{disc}} \hookrightarrow \text{Sets} \end{aligned}$$

of sets into categories and of classical truth values into sets.

For instance, in this approach the characteristic function

$$\chi_x : X \rightarrow \{\text{t}, \text{f}\}$$

of an element x of X , defined by

$$\chi_x(y) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x = y, \\ \text{false} & \text{if } x \neq y \end{cases}$$

for each $y \in X$, is recovered as the representable presheaf

$$\text{Hom}_{X_{\text{disc}}}(-, x) : X_{\text{disc}} \rightarrow \text{Sets}$$

of the corresponding object x of X_{disc} , defined on objects by

$$\text{Hom}_{X_{\text{disc}}}(y, x) \stackrel{\text{def}}{=} \begin{cases} \text{pt} & \text{if } x = y, \\ \emptyset & \text{if } x \neq y \end{cases}$$

for each $y \in \text{Obj}(X_{\text{disc}})$.

0064 1. A function

$$f: X \rightarrow \{t, f\}$$

is a decategorification of a presheaf

$$\mathcal{F}: C^{\text{op}} \rightarrow \text{Sets},$$

with the characteristic functions χ_U of the subsets of X being the primordial examples (and, in fact, all examples) of these.

0065 2. The characteristic function

$$\chi_x: X \rightarrow \{t, f\}$$

of an *element* x of X is a decategorification of the representable presheaf

$$h_x: C^{\text{op}} \rightarrow \text{Sets}$$

of an *object* x of a category C .

0066 3. The characteristic relation

$$\chi_X(-_1, -_2): X \times X \rightarrow \{t, f\}$$

of X is a decategorification of the Hom profunctor

$$\text{Hom}_C(-_1, -_2): C^{\text{op}} \times C \rightarrow \text{Sets}$$

of a category C .

0067 4. The characteristic embedding

$$\chi_{(-)}: X \hookrightarrow \mathcal{P}(X)$$

of X into $\mathcal{P}(X)$ is a decategorification of the Yoneda embedding

$$\mathcal{Y}: C^{\text{op}} \hookrightarrow \text{PSh}(C)$$

of a category C into $\text{PSh}(C)$.

0068 5. There is also a direct parallel between unions and colimits:

- An element of $\mathcal{P}(X)$ is a union of elements of X , viewed as one-point subsets $\{x\} \in \mathcal{P}(A)$.
- An object of $\text{PSh}(C)$ is a colimit of objects of C , viewed as representable presheaves $h_X \in \text{Obj}(\text{PSh}(C))$.

0069 **Proposition 2.4.1.1.3.** Let X be a set.

006A 1. *The Inclusion of Characteristic Relations Associated to a Function.* Let $f: A \rightarrow B$ be a function. We have an inclusion³¹

$$\chi_B \circ (f \times f) \subset \chi_A,$$

$$\begin{array}{ccc} A \times A & \xrightarrow{f \times f} & B \times B \\ \chi_A \searrow & \curvearrowright & \swarrow \chi_B \\ & & \{t, f\}. \end{array}$$

006B 2. *Interaction With Unions I.* We have

$$\chi_{U \cup V} = \max(\chi_U, \chi_V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

006C 3. *Interaction With Unions II.* We have

$$\chi_{U \cup V} = \chi_U + \chi_V - \chi_{U \cap V}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

006D 4. *Interaction With Intersections I.* We have

$$\chi_{U \cap V} = \chi_U \chi_V$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

006E 5. *Interaction With Intersections II.* We have

$$\chi_{U \cap V} = \min(\chi_U, \chi_V)$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

006F 6. *Interaction With Differences.* We have

$$\chi_{U \setminus V} = \chi_U - \chi_{U \cap V}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

006G 7. *Interaction With Complements.* We have

$$\chi_{U^c} = 1 - \chi_U$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U \in \mathcal{P}(X)$.

³¹This is the 0-categorical version of [Definition 8.4.4.1.1](#).

006H 8. *Interaction With Symmetric Differences.* We have

$$\chi_{U\Delta V} = \chi_U + \chi_V - 2\chi_{U\cap V}$$

and thus, in particular, we have

$$\chi_{U\Delta V} \equiv \chi_U + \chi_V \pmod{2}$$

for each $X \in \text{Obj}(\text{Sets})$ and each $U, V \in \mathcal{P}(X)$.

006J 9. *Interaction Between the Characteristic Embedding and Morphisms.* Let $f: X \rightarrow Y$ be a map of sets. The diagram

$$f_* \circ \chi_X = \chi_{X'} \circ f,$$

$$\begin{array}{ccc} X & \xrightarrow{f} & X' \\ \chi_X \downarrow & & \downarrow \chi_{X'} \\ \mathcal{P}(X) & \xrightarrow{f_*} & \mathcal{P}(X'). \end{array}$$

commutes.

Proof. Item 1, The Inclusion of Characteristic Relations Associated to a Function: The inclusion $\chi_B(f(a), f(b)) \subset \chi_A(a, b)$ is equivalent to the statement “if $a = b$, then $f(a) = f(b)$ ”, which is true.

Item 2, Interaction With Unions I: This is a repetition of **Item 8** of **Proposition 2.3.7.1.2** and is proved there.

Item 3, Interaction With Unions II: This is a repetition of **Item 9** of **Proposition 2.3.7.1.2** and is proved there.

Item 4, Interaction With Intersections I: This is a repetition of **Item 9** of **Proposition 2.3.9.1.2** and is proved there.

Item 5, Interaction With Intersections II: This is a repetition of **Item 10** of **Proposition 2.3.9.1.2** and is proved there.

Item 6, Interaction With Differences: This is a repetition of **Item 15** of **Proposition 2.3.10.1.2** and is proved there.

Item 7, Interaction With Complements: This is a repetition of **Item 4** of **Proposition 2.3.11.1.2** and is proved there.

Item 8, Interaction With Symmetric Differences: This is a repetition of **Item 14** of **Proposition 2.3.12.1.2** and is proved there.

Item 9, Interaction Between the Characteristic Embedding and Morphisms: In-

deed, we have

$$\begin{aligned}
 [f_* \circ \chi_X](x) &\stackrel{\text{def}}{=} f_*(\chi_X(x)) \\
 &\stackrel{\text{def}}{=} f_*({x}) \\
 &= \{f(x)\} \\
 &\stackrel{\text{def}}{=} \chi_{X'}(f(x)) \\
 &\stackrel{\text{def}}{=} [\chi_{X'} \circ f](x),
 \end{aligned}$$

for each $x \in X$, showing the desired equality. \square

006K 2.4.2 The Yoneda Lemma for Sets

Let X be a set and let $U \subset X$ be a subset of X .

006L **Proposition 2.4.2.1.1.** We have

$$\chi_{\mathcal{P}(X)}(\chi_x, \chi_U) = \chi_U(x)$$

for each $x \in X$, giving an equality of functions

$$\chi_{\mathcal{P}(X)}(\chi_{(-)}, \chi_U) = \chi_U.$$

Proof. Clear. \square

006M **Corollary 2.4.2.1.2.** The characteristic embedding is fully faithful, i.e., we have

$$\chi_{\mathcal{P}(X)}(\chi_x, \chi_y) = \chi_X(x, y)$$

for each $x, y \in X$.

Proof. This follows from **Proposition 2.4.2.1.1.** \square

006N 2.4.3 Powersets

Let X be a set.

006P **Definition 2.4.3.1.1.** The **powerset of X** is the set $\mathcal{P}(X)$ defined by

$$\mathcal{P}(X) \stackrel{\text{def}}{=} \{U \in P \mid U \subset X\},$$

where P is the set in the axiom of powerset, ?? of ??.

006Q Remark 2.4.3.1.2. The powerset of a set is a decategorification of the category of presheaves of a category: while³²

- The powerset of a set X is equivalently (Items 1 and 2 of Proposition 2.4.3.1.6) the set

$$\text{Sets}(X, \{t, f\})$$

of functions from X to the set $\{t, f\}$ of classical truth values.

- The category of presheaves on a category C is the category

$$\text{Fun}(C^{\text{op}}, \text{Sets})$$

of functors from C^{op} to the category Sets of sets.

006R Proposition 2.4.3.1.3. Let X be a set.

006S 1. *Co/Completeness.* The (posetal) category (associated to) $(\mathcal{P}(X), \subset)$ is complete and cocomplete:

- Products.* The products in $\mathcal{P}(X)$ are given by intersection of subsets.
- Coproducts.* The coproducts in $\mathcal{P}(X)$ are given by union of subsets.
- Co/Equalisers.* Being a posetal category, $\mathcal{P}(X)$ only has at most one morphisms between any two objects, so co/equalisers are trivial.

006T 2. *Cartesian Closedness.* The category $\mathcal{P}(X)$ is Cartesian closed with internal Hom

$$\mathbf{Hom}_{\mathcal{P}(X)}(-_1, -_2): \mathcal{P}(X)^{\text{op}} \times \mathcal{P}(X) \rightarrow \mathcal{P}(X)$$

³²This parallel is based on the following comparison:

- A category is enriched over the category

$$\text{Sets} \stackrel{\text{def}}{=} \text{Cats}_0$$

of sets (i.e. “0-categories”), with presheaves taking values on it.

- A set is enriched over the set

$$\{t, f\} \stackrel{\text{def}}{=} \text{Cats}_{-1}$$

of classical truth values (i.e. “(-1)-categories”), with characteristic functions taking values on it.

given by³³

$$\mathbf{Hom}_{\mathcal{P}(X)}(U, V) \stackrel{\text{def}}{=} (X \setminus U) \cup V$$

for each $U, V \in \text{Obj}(\mathcal{P}(X))$.

Proof. *Item 1, Co/Completeness:* Clear.

Item 2, Cartesian Closedness: This follows from *Item 2* of *Proposition 2.3.9.1.2*.

□

006U Proposition 2.4.3.1.4. Let X be a set.

006V 1. *Functoriality I.* The assignment $X \mapsto \mathcal{P}(X)$ defines a functor

$$\mathcal{P}_* : \mathbf{Sets} \rightarrow \mathbf{Sets},$$

where

- *Action on Objects.* For each $A \in \text{Obj}(\mathbf{Sets})$, we have

$$\mathcal{P}_*(A) \stackrel{\text{def}}{=} \mathcal{P}(A).$$

- *Action on Morphisms.* For each $A, B \in \text{Obj}(\mathbf{Sets})$, the action on morphisms

$$\mathcal{P}_{*|A,B} : \mathbf{Sets}(A, B) \rightarrow \mathbf{Sets}(\mathcal{P}(A), \mathcal{P}(B))$$

of \mathcal{P}_* at (A, B) is the map defined by sending a map of sets $f : A \rightarrow B$ to the map

$$\mathcal{P}_*(f) : \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by

$$\mathcal{P}_*(f) \stackrel{\text{def}}{=} f_*,$$

as in *Definition 2.4.4.1.1*.

006W 2. *Functoriality II.* The assignment $X \mapsto \mathcal{P}(X)$ defines a functor

$$\mathcal{P}^{-1} : \mathbf{Sets}^{\text{op}} \rightarrow \mathbf{Sets},$$

where

- *Action on Objects.* For each $A \in \text{Obj}(\mathbf{Sets})$, we have

$$\mathcal{P}^{-1}(A) \stackrel{\text{def}}{=} \mathcal{P}(A).$$

³³For intuition regarding the expression defining $\mathbf{Hom}_{\mathcal{P}(X)}(U, V)$, see *Remark 2.3.9.1.3*.

- *Action on Morphisms.* For each $A, B \in \text{Obj}(\text{Sets})$, the action on morphisms

$$\mathcal{P}_{A,B}^{-1}: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(B), \mathcal{P}(A))$$

of \mathcal{P}^{-1} at (A, B) is the map defined by sending a map of sets $f: A \rightarrow B$ to the map

$$\mathcal{P}^{-1}(f): \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

defined by

$$\mathcal{P}^{-1}(f) \stackrel{\text{def}}{=} f^{-1},$$

as in [Definition 2.4.5.1.1](#).

- 006X** 3. *Functoriality III.* The assignment $X \mapsto \mathcal{P}(X)$ defines a functor

$$\mathcal{P}_!: \text{Sets} \rightarrow \text{Sets},$$

where

- *Action on Objects.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$\mathcal{P}_!(A) \stackrel{\text{def}}{=} \mathcal{P}(A).$$

- *Action on Morphisms.* For each $A, B \in \text{Obj}(\text{Sets})$, the action on morphisms

$$\mathcal{P}_{!|A,B}: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B))$$

of $\mathcal{P}_!$ at (A, B) is the map defined by sending a map of sets $f: A \rightarrow B$ to the map

$$\mathcal{P}_!(f): \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by

$$\mathcal{P}_!(f) \stackrel{\text{def}}{=} f!,$$

as in [Definition 2.4.6.1.1](#).

- 006Y** 4. *Adjointness I.* We have an adjunction

$$(\mathcal{P}^{-1} \dashv \mathcal{P}^{-1, \text{op}}): \text{Sets}^{\text{op}} \begin{array}{c} \xrightarrow{\mathcal{P}^{-1}} \\ \perp \\ \xleftarrow{\mathcal{P}^{-1, \text{op}}} \end{array} \text{Sets},$$

witnessed by a bijection

$$\underbrace{\text{Sets}^{\text{op}}(\mathcal{P}(A), B)}_{\stackrel{\text{def}}{=} \text{Sets}(B, \mathcal{P}(A))} \cong \text{Sets}(A, \mathcal{P}(B)),$$

natural in $A \in \text{Obj}(\text{Sets})$ and $B \in \text{Obj}(\text{Sets}^{\text{op}})$.

006Z 5. *Adjointness II.* We have an adjunction

$$(\text{Gr} \dashv \mathcal{P}_*): \text{Sets} \begin{array}{c} \xrightarrow{\text{Gr}} \\ \perp \\ \xleftarrow{\mathcal{P}_*} \end{array} \text{Rel},$$

witnessed by a bijection of sets

$$\text{Rel}(\text{Gr}(A), B) \cong \text{Sets}(A, \mathcal{P}(B))$$

natural in $A \in \text{Obj}(\text{Sets})$ and $B \in \text{Obj}(\text{Rel})$, where Gr is the graph functor of [Item 1 of Proposition 6.3.1.1.2](#) and \mathcal{P}_* is the functor of [Proposition 6.4.5.1.1](#).

Proof. Item 1, Functoriality I: This follows from [Items 3 and 4 of Proposition 2.4.4.1.5](#).

Item 2, Functoriality II: This follows [Items 3 and 4 of Proposition 2.4.5.1.4](#).

Item 3, Functoriality III: This follows [Items 3 and 4 of Proposition 2.4.6.1.7](#).

Item 4, Adjointness I: We have

$$\begin{aligned} \text{Sets}^{\text{op}}(\mathcal{P}(A), B) &\stackrel{\text{def}}{=} \text{Sets}(B, \mathcal{P}(A)) \\ &\cong \text{Sets}(B, \text{Sets}(A, \{t, f\})) && \text{(by Item 1 of Proposition 2.4.3.1.6)} \\ &\cong \text{Sets}(A \times B, \{t, f\}) && \text{(by Item 2 of Proposition 2.1.3.1.2)} \\ &\cong \text{Sets}(A, \text{Sets}(B, \{t, f\})) && \text{(by Item 2 of Proposition 2.1.3.1.2)} \\ &\cong \text{Sets}(A, \mathcal{P}(B)) && \text{(by Item 1 of Proposition 2.4.3.1.6)} \end{aligned}$$

with all bijections natural in A and B (where we use [Item 2 of Proposition 2.4.3.1.6](#) here).

Item 5, Adjointness II: We have

$$\begin{aligned} \text{Rel}(\text{Gr}(A), B) &\cong \mathcal{P}(A \times B) \\ &\cong \text{Sets}(A \times B, \{t, f\}) && \text{(by Item 1 of Proposition 2.4.3.1.6)} \\ &\cong \text{Sets}(A, \text{Sets}(B, \{t, f\})) && \text{(by Item 2 of Proposition 2.1.3.1.2)} \\ &\cong \text{Sets}(A, \mathcal{P}(B)) && \text{(by Item 1 of Proposition 2.4.3.1.6)} \end{aligned}$$

with all bijections natural in A (where we use [Item 2 of Proposition 2.4.3.1.6](#) here). Explicitly, this isomorphism is given by sending a relation $R: \text{Gr}(A) \rightarrow$

B to the map $R^\dagger: A \rightarrow \mathcal{P}(B)$ sending a to the subset $R(a)$ of B , as in [Remark 5.1.1.1.4](#).

Naturality in B is then the statement that given a relation $R: B \dashv\vdash B'$, the diagram

$$\begin{array}{ccc} \text{Rel}(\text{Gr}(A), B) & \xrightarrow{R \circ -} & \text{Rel}(\text{Gr}(A), B') \\ \downarrow \wr & & \downarrow \wr \\ \text{Sets}(A, \mathcal{P}(B)) & \xrightarrow{R_*} & \text{Sets}(A, \mathcal{P}(B')) \end{array}$$

commutes, which follows from [Remark 6.4.1.1.2](#). \square

0070 Proposition 2.4.3.1.5. Let X be a set.

0071 1. *Symmetric Strong Monoidality With Respect to Coproducts I.* The powerset functor \mathcal{P}_* of [Item 1](#) of [Proposition 2.4.3.1.4](#) has a symmetric strong monoidal structure

$$\left(\mathcal{P}_*, \mathcal{P}_* \amalg, \mathcal{P}_{*\mathbb{1}} \right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}, \amalg, \emptyset)$$

being equipped with isomorphisms

$$\begin{aligned} \mathcal{P}_{*|X,Y} \amalg: \mathcal{P}(X) \times \mathcal{P}(Y) &\xrightarrow{\cong} \mathcal{P}(X \amalg Y), \\ \mathcal{P}_{*\mathbb{1}} \amalg: \text{pt} &\xrightarrow{\cong} \mathcal{P}(\emptyset), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

0072 2. *Symmetric Strong Monoidality With Respect to Coproducts II.* The powerset functor \mathcal{P}^{-1} of [Item 2](#) of [Proposition 2.4.3.1.4](#) has a symmetric strong monoidal structure

$$\left(\mathcal{P}^{-1}, \mathcal{P}^{-1} \amalg, \mathcal{P}_{\mathbb{1}}^{-1} \amalg \right): (\text{Sets}^{\text{op}}, \times^{\text{op}}, \text{pt}) \rightarrow (\text{Sets}, \amalg, \emptyset)$$

being equipped with isomorphisms

$$\begin{aligned} \mathcal{P}_{X,Y}^{-1} \amalg: \mathcal{P}(X) \times \mathcal{P}(Y) &\xrightarrow{\cong} \mathcal{P}(X \amalg Y), \\ \mathcal{P}_{\mathbb{1}}^{-1} \amalg: \text{pt} &\xrightarrow{\cong} \mathcal{P}(\emptyset), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

0073 3. *Symmetric Strong Monoidality With Respect to Coproducts III.* The

powerset functor $\mathcal{P}_!$ of **Item 3** of **Proposition 2.4.3.1.4** has a symmetric strong monoidal structure

$$\left(\mathcal{P}_!, \mathcal{P}_!^{\amalg}, \mathcal{P}_!^{\amalg}\right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}, \amalg, \emptyset)$$

being equipped with isomorphisms

$$\begin{aligned} \mathcal{P}_!^{\amalg}|_{X,Y}: \mathcal{P}(X) \times \mathcal{P}(Y) &\xrightarrow{\cong} \mathcal{P}(X \amalg Y), \\ \mathcal{P}_!^{\amalg}: \text{pt} &\xrightarrow{\cong} \mathcal{P}(\emptyset), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

- 0074** 4. *Symmetric Lax Monoidality With Respect to Products I.* The powerset functor \mathcal{P}_* of **Item 1** of **Proposition 2.4.3.1.4** has a symmetric lax monoidal structure

$$\left(\mathcal{P}_*, \mathcal{P}_*^{\otimes}, \mathcal{P}_*^{\otimes}\right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}, \times, \text{pt})$$

being equipped with morphisms

$$\begin{aligned} \mathcal{P}_*^{\otimes}|_{X,Y}: \mathcal{P}(X) \times \mathcal{P}(Y) &\rightarrow \mathcal{P}(X \times Y), \\ \mathcal{P}_*^{\otimes}: \text{pt} &\rightarrow \mathcal{P}(\text{pt}), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$, where

- The map $\mathcal{P}_*^{\otimes}|_{X,Y}$ is given by

$$\mathcal{P}_*^{\otimes}|_{X,Y}(U, V) \stackrel{\text{def}}{=} U \times V$$

for each $(U, V) \in \mathcal{P}(X) \times \mathcal{P}(Y)$,

- The map \mathcal{P}_*^{\otimes} is given by

$$\mathcal{P}_*^{\otimes}(\star) = \text{pt}.$$

- 0075** 5. *Symmetric Lax Monoidality With Respect to Products II.* The powerset functor \mathcal{P}^{-1} of **Item 2** of **Proposition 2.4.3.1.4** has a symmetric lax monoidal structure

$$\left(\mathcal{P}^{-1}, \mathcal{P}^{-1|\otimes}, \mathcal{P}_!^{-1|\otimes}\right): (\text{Sets}^{\text{op}}, \times^{\text{op}}, \text{pt}) \rightarrow (\text{Sets}, \times, \text{pt})$$

being equipped with morphisms

$$\begin{aligned} \mathcal{P}^{-1|\otimes}|_{X,Y}: \mathcal{P}(X) \times \mathcal{P}(Y) &\rightarrow \mathcal{P}(X \times Y), \\ \mathcal{P}_!^{-1|\otimes}: \text{pt} &\rightarrow \mathcal{P}(\emptyset), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$, defined as in **Item 4**.

- 0076 6. *Symmetric Lax Monoidality With Respect to Products III.* The power-set functor $\mathcal{P}_!$ of **Item 3** of **Proposition 2.4.3.1.4** has a symmetric lax monoidal structure

$$\left(\mathcal{P}_!, \mathcal{P}_!^\otimes, \mathcal{P}_{! \amalg}^\otimes \right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}, \times, \text{pt})$$

being equipped with morphisms

$$\begin{aligned} \mathcal{P}_{! \times}^\times: \mathcal{P}(X) \times \mathcal{P}(Y) &\rightarrow \mathcal{P}(X \times Y), \\ \mathcal{P}_{! \amalg}^\times: \text{pt} &\rightarrow \mathcal{P}(\emptyset), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$, defined as in **Item 4**.

Proof. Item 1, Symmetric Strong Monoidality With Respect to Coproducts I: The isomorphism

$$\mathcal{P}_{* \amalg}^\amalg: \mathcal{P}(X) \times \mathcal{P}(Y) \rightarrow \mathcal{P}(X \amalg Y)$$

is given by sending $(U, V) \in \mathcal{P}(X) \times \mathcal{P}(Y)$ to $U \amalg V$, with inverse given by sending a subset S of $X \amalg Y$ to the pair $(S_X, S_Y) \in \mathcal{P}(X) \times \mathcal{P}(Y)$ with

$$\begin{aligned} S_X &\stackrel{\text{def}}{=} \{x \in X \mid (0, x) \in S\} \\ S_Y &\stackrel{\text{def}}{=} \{y \in Y \mid (1, y) \in S\}. \end{aligned}$$

The isomorphism $\text{pt} \cong \mathcal{P}(\emptyset)$ is given by $\star \mapsto \emptyset \in \mathcal{P}(\emptyset)$.

Naturality for the isomorphism $\mathcal{P}_{* \amalg}^\amalg$ is the statement that, given maps of sets $f: X \rightarrow X'$ and $g: Y \rightarrow Y'$, the diagram

$$\begin{array}{ccc} \mathcal{P}(X) \times \mathcal{P}(Y) & \xrightarrow{f_* \times g_*} & \mathcal{P}(X') \times \mathcal{P}(Y') \\ \downarrow \wr & & \downarrow \wr \\ \mathcal{P}(X \amalg Y) & \xrightarrow{(f \amalg g)_*} & \mathcal{P}(X' \amalg Y') \end{array}$$

commutes, which is clear, as it acts on elements as

$$\begin{array}{ccc} (U, V) & \longmapsto & (f_*(U), g_*(V)) \\ \downarrow & & \downarrow \\ U \amalg V & \longmapsto & (f \amalg g)_*(U \amalg V) = f_*(U) \amalg g_*(V), \end{array}$$

where we are using **Item 7** of **Proposition 2.4.4.1.4**.

Finally, monoidality, unity, and symmetry of \mathcal{P}_* as a monoidal functor follow by checking the commutativity of the relevant diagrams on elements.

Item 2, Symmetric Strong Monoidality With Respect to Coproducts II: The proof is similar to *Item 1*, and is hence omitted.

Item 3, Symmetric Strong Monoidality With Respect to Coproducts III: The proof is similar to *Item 1*, and is hence omitted.

Item 4, Symmetric Lax Monoidality With Respect to Products I: Naturality for the morphism $\mathcal{P}_{*|X,Y}^\times$ is the statement that, given maps of sets $f: X \rightarrow X'$ and $g: Y \rightarrow Y'$, the diagram

$$\begin{array}{ccc} \mathcal{P}(X) \times \mathcal{P}(Y) & \xrightarrow{f_* \times g_*} & \mathcal{P}(X') \times \mathcal{P}(Y') \\ \downarrow \wr & & \downarrow \wr \\ \mathcal{P}(X \times Y) & \xrightarrow{(f \times g)_*} & \mathcal{P}(X' \times Y') \end{array}$$

commutes, which is clear, as it acts on elements as

$$\begin{array}{ccc} (U, V) & \longmapsto & (f_*(U), g_*(V)) \\ \downarrow & & \downarrow \\ U \times V & \longmapsto & (f \times g)_*(U \times V) = f_*(U) \times g_*(V), \end{array}$$

where we are using *Item 8* of *Proposition 2.4.4.1.4*.

Finally, monoidality, unity, and symmetry of \mathcal{P}_* as a monoidal functor follow by checking the commutativity of the relevant diagrams on elements.

Item 5, Symmetric Lax Monoidality With Respect to Products II: The proof is similar to *Item 4*, and is hence omitted.

Item 6, Symmetric Lax Monoidality With Respect to Products III: The proof is similar to *Item 4*, and is hence omitted. \square

0077 Proposition 2.4.3.1.6. Let X be a set.

0078 1. *Powersets as Sets of Functions I.* The assignment $U \mapsto \chi_U$ defines a bijection

$$\chi_{(-)}: \mathcal{P}(X) \xrightarrow{\cong} \text{Sets}(X, \{\mathbf{t}, \mathbf{f}\}),$$

for each $X \in \text{Obj}(\text{Sets})$.

0079 2. *Powersets as Sets of Functions II.* The bijection

$$\mathcal{P}(X) \cong \text{Sets}(X, \{\mathbf{t}, \mathbf{f}\})$$

of **Item 1** is natural in $X \in \text{Obj}(\text{Sets})$, refining to a natural isomorphism of functors

$$\mathcal{P}^{-1} \cong \text{Sets}(-, \{\text{t}, \text{f}\}).$$

007A 3. *Powersets as Sets of Relations.* We have bijections

$$\mathcal{P}(X) \cong \text{Rel}(\text{pt}, X),$$

$$\mathcal{P}(X) \cong \text{Rel}(X, \text{pt}),$$

natural in $X \in \text{Obj}(\text{Sets})$.

Proof. Item 1, Powersets as Sets of Functions I: Indeed, the inverse of $\chi_{(-)}$ is given by sending a function $f: X \rightarrow \{\text{t}, \text{f}\}$ to the subset U_f of $\mathcal{P}(X)$ defined by

$$U_f \stackrel{\text{def}}{=} \{x \in X \mid f(x) = \text{true}\},$$

i.e. by $U_f = f^{-1}(\text{true})$. That $\chi_{(-)}$ and $f \mapsto U_f$ are inverses is then straightforward to check.

Item 2, Powersets as Sets of Functions II: We need to check that, given a function $f: X \rightarrow Y$, the diagram

$$\begin{array}{ccc} \mathcal{P}(Y) & \xrightarrow{f^{-1}} & \mathcal{P}(X) \\ \chi_{(-)} \downarrow \wr & & \wr \downarrow \chi_{(-)} \\ \text{Sets}(Y, \{\text{t}, \text{f}\}) & \xrightarrow{f^*} & \text{Sets}(X, \{\text{t}, \text{f}\}) \end{array}$$

commutes, i.e. that for each $V \in \mathcal{P}(Y)$, we have

$$\chi_V \circ f = \chi_{f^{-1}(V)}.$$

And indeed, we have

$$\begin{aligned} [\chi_V \circ f](v) &\stackrel{\text{def}}{=} \chi_V(f(v)) \\ &= \begin{cases} \text{true} & \text{if } f(v) \in V, \\ \text{false} & \text{otherwise} \end{cases} \\ &= \begin{cases} \text{true} & \text{if } v \in f^{-1}(V), \\ \text{false} & \text{otherwise} \end{cases} \\ &\stackrel{\text{def}}{=} \chi_{f^{-1}(V)}(v) \end{aligned}$$

for each $v \in V$.

Item 3, Powersets as Sets of Relations: Indeed, we have

$$\begin{aligned}\text{Rel}(\text{pt}, X) &\stackrel{\text{def}}{=} \mathcal{P}(\text{pt} \times X) \\ &\cong \mathcal{P}(X)\end{aligned}$$

and

$$\begin{aligned}\text{Rel}(X, \text{pt}) &\stackrel{\text{def}}{=} \mathcal{P}(X \times \text{pt}) \\ &\cong \mathcal{P}(X),\end{aligned}$$

where we have used *Item 4 of Proposition 2.1.3.1.2.* □

007B Remark 2.4.3.1.7. The bijection

$$\mathcal{P}(X) \cong \text{Sets}(X, \{\text{t}, \text{f}\})$$

of *Item 1 of Proposition 2.4.3.1.6,* which

- Takes a subset $U \hookrightarrow X$ of X and *straightens* it to a function $\chi_U : X \rightarrow \{\text{true}, \text{false}\}$;
- Takes a function $f : X \rightarrow \{\text{true}, \text{false}\}$ and *unstraightens* it to a subset $f^{-1}(\text{true}) \hookrightarrow X$ of X ;

may be viewed as the (-1) -categorical version of the un/straightening isomorphism for indexed and fibred sets

$$\underbrace{\text{FibSets}(X)}_{\stackrel{\text{def}}{=} \text{Sets}/X} \cong \underbrace{\text{ISets}(X)}_{\stackrel{\text{def}}{=} \text{Fun}(X_{\text{disc}}, \text{Sets})}$$

of ??, where we view:

- Subsets $U \hookrightarrow X$ as analogous to X -fibred sets $\phi_X : A \rightarrow X$.
- Functions $f : X \rightarrow \{\text{t}, \text{f}\}$ as analogous to X -indexed sets $A : X_{\text{disc}} \rightarrow \text{Sets}$.

007C Proposition 2.4.3.1.8. Let X be a set.

007D 1. *Universal Property.* The pair $(\mathcal{P}(X), \chi_{(-)})$ consisting of

- The powerset $\mathcal{P}(X)$ of X ;
- The characteristic embedding $\chi_{(-)} : X \hookrightarrow \mathcal{P}(X)$ of X into $\mathcal{P}(X)$;

satisfies the following universal property:

(★) Given another pair (Y, f) consisting of

- A cocomplete poset (Y, \preceq) ;
- A function $f: X \rightarrow Y$;

there exists a unique cocontinuous morphism of posets

$$(\mathcal{P}(X), \subset) \xrightarrow{\exists!} (Y, \preceq)$$

making the diagram

$$\begin{array}{ccc} & & \mathcal{P}(X) \\ & \nearrow \chi_X & \vdots \exists! \\ X & \xrightarrow{f} & Y \end{array}$$

commute.

007E 2. *Adjointness.* We have an adjunction³⁴

$$(\mathcal{P} \dashv \mathfrak{L}): \text{Sets} \begin{array}{c} \xrightarrow{\mathcal{P}} \\ \perp \\ \xleftarrow{\mathfrak{L}} \end{array} \text{Pos}^{\text{cocomp.}},$$

witnessed by a bijection

$$\text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \preceq)) \cong \text{Sets}(X, Y),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $(Y, \preceq) \in \text{Obj}(\text{Pos}^{\text{cocomp.}})$, where the maps witnessing this bijection are given by

- The map

$$\chi_X^*: \text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \preceq)) \rightarrow \text{Sets}(X, Y)$$

defined by

$$\chi_X^*(f) \stackrel{\text{def}}{=} f \circ \chi_X,$$

i.e. by sending a cocontinuous morphism of posets $f: \mathcal{P}(X) \rightarrow Y$ to the composition

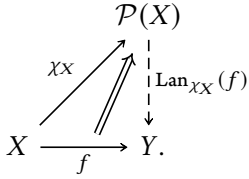
$$X \xrightarrow{\chi_X} \mathcal{P}(X) \xrightarrow{f} Y.$$

³⁴In this sense, $\mathcal{P}(A)$ is the free cocompletion of A . (Note that, despite its name, however, this is not an idempotent operation, as we have $\mathcal{P}(\mathcal{P}(A)) \neq \mathcal{P}(A)$.)

- The map

$$\text{Lan}_{\chi_X} : \text{Sets}(X, Y) \rightarrow \text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \preceq))$$

is given by sending a function $f : X \rightarrow Y$ to its left Kan extension along χ_X ,

$$\text{Lan}_{\chi_X}(f) : \mathcal{P}(X) \rightarrow Y,$$


Moreover, $\text{Lan}_{\chi_X}(f)$ can be explicitly computed by

$$\begin{aligned} [\text{Lan}_{\chi_X}(f)](U) &\cong \int^{x \in X} \chi_{\mathcal{P}(X)}(\chi_x, U) \odot f(x) \\ &\cong \int^{x \in X} \chi_U(x) \odot f(x) \quad (\text{by Proposition 2.4.2.1.1}) \\ &\cong \bigvee_{x \in X} (\chi_U(x) \odot f(x)) \end{aligned}$$

for each $U \in \mathcal{P}(X)$, where:

- \bigvee is the join in (Y, \preceq) .
- We have

$$\begin{aligned} \text{true} \odot f(x) &\stackrel{\text{def}}{=} f(x), \\ \text{false} \odot f(x) &\stackrel{\text{def}}{=} \emptyset_Y, \end{aligned}$$

where \emptyset_Y is the minimal element of (Y, \preceq) .

Proof. Item 1, Universal Property: This is a rephrasing of **Item 2**.

Item 2, Adjointness: We claim we have adjunction $\mathcal{P} \dashv \overline{\text{Lan}}$, witnessed by a bijection

$$\text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \preceq)) \cong \text{Sets}(X, Y),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $(Y, \preceq) \in \text{Obj}(\text{Pos}^{\text{cocomp.}})$.

- *Map I.* We define a map

$$\Phi_{X,Y} : \text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \preceq)) \rightarrow \text{Sets}(X, Y)$$

as in the statement, by

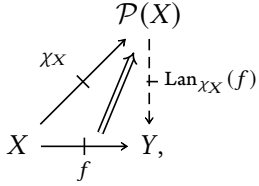
$$\Phi_{X,Y}(f) \stackrel{\text{def}}{=} f \circ \chi_X$$

for each $f \in \text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \preceq))$.

- *Map II.* We define a map

$$\Psi_{X,Y}: \text{Sets}(X, Y) \rightarrow \text{Pos}^{\text{cocomp}}((\mathcal{P}(X), \subset), (Y, \preceq))$$

as in the statement, by

$$\Psi_{X,Y}(f) \stackrel{\text{def}}{=} \text{Lan}_{\chi_X}(f),$$


for each $f \in \text{Sets}(X, Y)$.

- *Invertibility I.* We claim that

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \text{id}_{\text{Pos}^{\text{cocomp}}((\mathcal{P}(X), \subset), (Y, \preceq))}.$$

Indeed, given a cocontinuous morphism of posets

$$\xi: (\mathcal{P}(X), \subset) \rightarrow (Y, \preceq),$$

we have

$$\begin{aligned} [\Psi_{X,Y} \circ \Phi_{X,Y}](\xi) &\stackrel{\text{def}}{=} \Psi_{X,Y}(\Phi_{X,Y}(\xi)) \\ &\stackrel{\text{def}}{=} \Psi_{X,Y}(\xi \circ \chi_X) \\ &\stackrel{\text{def}}{=} \text{Lan}_{\chi_X}(\xi \circ \chi_X) \\ &\cong \bigvee_{x \in X} \chi_{(-)}(x) \odot \xi(\chi_X(x)) \\ &\stackrel{\text{clm}}{=} \xi, \end{aligned}$$

where indeed

$$\begin{aligned} \left[\bigvee_{x \in X} \chi_{(-)}(x) \odot \xi(\chi_X(x)) \right](U) &\stackrel{\text{def}}{=} \bigvee_{x \in X} \chi_U(x) \odot \xi(\chi_X(x)) \\ &= \left(\bigvee_{x \in U} \chi_U(x) \odot \xi(\chi_X(x)) \right) \vee \left(\bigvee_{x \in X \setminus U} \chi_U(x) \odot \xi(\chi_X(x)) \right) \\ &= \left(\bigvee_{x \in U} \xi(\chi_X(x)) \right) \vee \left(\bigvee_{x \in X \setminus U} \emptyset_Y \right) \\ &= \bigvee_{x \in U} \xi(\chi_X(x)) \\ &\stackrel{(\dagger)}{=} \xi \left(\bigvee_{x \in U} \chi_X(x) \right) \\ &= \xi(U) \end{aligned}$$

for each $U \in \mathcal{P}(X)$, where we have used that ξ is cocontinuous for the equality $\stackrel{(\dagger)}{=}$.

- *Invertibility II.* We claim that

$$\Phi_{X,Y} \circ \Psi_{X,Y} = \text{id}_{\text{Sets}(X,Y)}.$$

Indeed, given a function $f: X \rightarrow Y$, we have

$$\begin{aligned} [\Phi_{X,Y} \circ \Psi_{X,Y}](f) &\stackrel{\text{def}}{=} \Phi_{X,Y}(\Psi_{X,Y}(f)) \\ &\stackrel{\text{def}}{=} \Phi_{X,Y}(\text{Lan}_{\chi_X}(f)) \\ &\stackrel{\text{def}}{=} \text{Lan}_{\chi_X}(f) \circ \chi_X \\ &\stackrel{\text{clm}}{=} f, \end{aligned}$$

where indeed

$$\begin{aligned} [\text{Lan}_{\chi_X}(f) \circ \chi_X](x) &\stackrel{\text{def}}{=} \bigvee_{y \in X} \chi_{\{x\}}(y) \odot f(y) \\ &= (\chi_{\{x\}}(x) \odot f(x)) \vee \left(\bigvee_{y \in X \setminus \{x\}} \chi_{\{x\}}(y) \odot f(y) \right) \\ &= f(x) \vee \left(\bigvee_{y \in X \setminus \{x\}} \emptyset_Y \right) \\ &= f(x) \vee \emptyset_Y \\ &= f(x) \end{aligned}$$

for each $x \in X$.

- *Naturality for Φ , Part I.* We need to show that, given a function $f: X \rightarrow X'$, the diagram

$$\begin{array}{ccc} \text{Pos}^{\text{cocomp}}.((\mathcal{P}(X'), \subset), (Y, \preceq)) & \xrightarrow{\Phi_{X',Y}} & \text{Sets}(X', Y) \\ \mathcal{P}_*(f)^* \downarrow & & \downarrow f^* \\ \text{Pos}^{\text{cocomp}}.((\mathcal{P}(X), \subset), (Y, \preceq)) & \xrightarrow{\Phi_{X,Y}} & \text{Sets}(X, Y) \end{array}$$

commutes. Indeed, given a cocontinuous morphism of posets

$$\xi: (\mathcal{P}(X'), \subset) \rightarrow (Y, \preceq),$$

we have

$$\begin{aligned}
[\Phi_{X,Y} \circ \mathcal{P}_*(f)^*](\xi) &\stackrel{\text{def}}{=} \Phi_{X,Y}(\mathcal{P}_*(f)^*(\xi)) \\
&\stackrel{\text{def}}{=} \Phi_{X,Y}(\xi \circ f_*) \\
&\stackrel{\text{def}}{=} (\xi \circ f_*) \circ \chi_X \\
&= \xi \circ (f_* \circ \chi_X) \\
&\stackrel{(\dagger)}{=} \xi \circ (\chi_{X'} \circ f) \\
&= (\xi \circ \chi_{X'}) \circ f \\
&\stackrel{\text{def}}{=} \Phi_{X',Y}(\xi) \circ f \\
&\stackrel{\text{def}}{=} f^*(\Phi_{X',Y}(\xi)) \\
&\stackrel{\text{def}}{=} [f^* \circ \Phi_{X',Y}](\xi),
\end{aligned}$$

where we have used **Item 9 of Proposition 2.4.1.1.3** for the equality $\stackrel{(\dagger)}{=}$ above.

- *Naturality for Φ , Part II.* We need to show that, given a cocontinuous morphism of posets

$$g: (Y, \preceq_Y) \rightarrow (Y', \preceq_{Y'}),$$

the diagram

$$\begin{array}{ccc}
\text{Pos}^{\text{cocomp}}((\mathcal{P}(X), \subset), (Y, \preceq)) & \xrightarrow{\Phi_{X,Y}} & \text{Sets}(X, Y) \\
g_* \downarrow & & \downarrow g_* \\
\text{Pos}^{\text{cocomp}}((\mathcal{P}(X), \subset), (Y', \preceq)) & \xrightarrow{\Phi_{X,Y'}} & \text{Sets}(X, Y')
\end{array}$$

commutes. Indeed, given a cocontinuous morphism of posets

$$\xi: (\mathcal{P}(X), \subset) \rightarrow (Y, \preceq),$$

we have

$$\begin{aligned}
[\Phi_{X,Y'} \circ g_*](\xi) &\stackrel{\text{def}}{=} \Phi_{X,Y'}(g_*(\xi)) \\
&\stackrel{\text{def}}{=} \Phi_{X,Y'}(g \circ \xi) \\
&\stackrel{\text{def}}{=} (g \circ \xi) \circ \chi_X \\
&= g \circ (\xi \circ \chi_X) \\
&\stackrel{\text{def}}{=} g \circ (\Phi_{X,Y}(\xi)) \\
&\stackrel{\text{def}}{=} g_* (\Phi_{X,Y}(\xi)) \\
&\stackrel{\text{def}}{=} [g_* \circ \Phi_{X,Y}](\xi).
\end{aligned}$$

- *Naturality for Ψ* . Since Φ is natural in each argument and Φ is a componentwise inverse to Ψ in each argument, it follows from [Item 2 of Proposition 8.8.6.1.2](#) that Ψ is also natural in each argument.

This finishes the proof. \square

007F 2.4.4 Direct Images

Let A and B be sets and let $f: A \rightarrow B$ be a function.

007G Definition 2.4.4.1.1. The **direct image function associated to f** is the function

$$f_*: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by^{35,36}

$$\begin{aligned} f_*(U) &\stackrel{\text{def}}{=} f(U) \\ &\stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{there exists some } a \in U \\ \text{such that } b = f(a) \end{array} \right\} \\ &= \{f(a) \in B \mid a \in U\} \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

007H Notation 2.4.4.1.2. Sometimes one finds the notation

$$\exists_f: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

for f_* . This notation comes from the fact that the following statements are equivalent, where $b \in B$ and $U \in \mathcal{P}(A)$:

- We have $b \in \exists_f(U)$.
- There exists some $a \in U$ such that $f(a) = b$.

007J Remark 2.4.4.1.3. Identifying subsets of A with functions from A to $\{\text{true}, \text{false}\}$ via [Items 1 and 2 of Proposition 2.4.3.1.6](#), we see that the direct image function associated to f is equivalently the function

$$f_*: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

³⁵*Further Terminology:* The set $f(U)$ is called the **direct image of U by f** .

³⁶We also have

$$f_*(U) = B \setminus f_*(A \setminus U);$$

see [Item 9 of Proposition 2.4.4.1.4](#).

defined by

$$\begin{aligned}
 f_*(\chi_U) &\stackrel{\text{def}}{=} \text{Lan}_f(\chi_U) \\
 &= \text{colim} \left(\left(f \times \underline{(-1)} \right) \xrightarrow{\text{pr}} A \xrightarrow{\chi_U} \{t, f\} \right) \\
 &= \text{colim}_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)) \\
 &= \bigvee_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)),
 \end{aligned}$$

where we have used ?? for the second equality. In other words, we have

$$\begin{aligned}
 [f_*(\chi_U)](b) &= \bigvee_{\substack{a \in A \\ f(a) = b}} (\chi_U(a)) \\
 &= \begin{cases} \text{true} & \text{if there exists some } a \in A \text{ such} \\ & \text{that } f(a) = b \text{ and } a \in U, \\ \text{false} & \text{otherwise} \end{cases} \\
 &= \begin{cases} \text{true} & \text{if there exists some } a \in U \\ & \text{such that } f(a) = b, \\ \text{false} & \text{otherwise} \end{cases}
 \end{aligned}$$

for each $b \in B$.

007K Proposition 2.4.4.1.4. Let $f: A \rightarrow B$ be a function.

007L 1. *Functoriality.* The assignment $U \mapsto f_*(U)$ defines a functor

$$f_*: (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

where

- *Action on Objects.* For each $U \in \mathcal{P}(A)$, we have

$$[f_*](U) \stackrel{\text{def}}{=} f_*(U).$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(A)$:

$$(\star) \text{ If } U \subset V, \text{ then } f_*(U) \subset f_*(V).$$

007M 2. *Triple Adjointness.* We have a triple adjunction

$$(f_* \dashv f^{-1} \dashv f_!): \quad \mathcal{P}(A) \begin{array}{c} \xleftarrow{f_*} \\ \xleftarrow{f^{-1}} \\ \xrightarrow{f_!} \end{array} \mathcal{P}(B),$$

witnessed by bijections of sets

$$\begin{aligned}\mathrm{Hom}_{\mathcal{P}(B)}(f_*(U), V) &\cong \mathrm{Hom}_{\mathcal{P}(A)}(U, f^{-1}(V)), \\ \mathrm{Hom}_{\mathcal{P}(A)}(f^{-1}(U), V) &\cong \mathrm{Hom}_{\mathcal{P}(A)}(U, f_!(V)),\end{aligned}$$

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$ and (respectively) $V \in \mathcal{P}(A)$ and $U \in \mathcal{P}(B)$, i.e. where:

- (a) The following conditions are equivalent:
- i. We have $f_*(U) \subset V$.
 - ii. We have $U \subset f^{-1}(V)$.
- (b) The following conditions are equivalent:
- i. We have $f^{-1}(U) \subset V$.
 - ii. We have $U \subset f_!(V)$.

007N 3. *Preservation of Colimits.* We have an equality of sets

$$f_*\left(\bigcup_{i \in I} U_i\right) = \bigcup_{i \in I} f_*(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have equalities

$$\begin{aligned}f_*(U) \cup f_*(V) &= f_*(U \cup V), \\ f_*(\emptyset) &= \emptyset,\end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

007P 4. *Oplax Preservation of Limits.* We have an inclusion of sets

$$f_*\left(\bigcap_{i \in I} U_i\right) \subset \bigcap_{i \in I} f_*(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have inclusions

$$\begin{aligned}f_*(U \cap V) &\subset f_*(U) \cap f_*(V), \\ f_*(A) &\subset B,\end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

007Q 5. *Symmetric Strict Monoidality With Respect to Unions.* The direct image function of **Item 1** has a symmetric strict monoidal structure

$$(f_*, f_*^\otimes, f_{*|\mathbb{1}}^\otimes): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} f_{*|U,V}^{\otimes} &: f_*(U) \cup f_*(V) \xrightarrow{=} f_*(U \cup V), \\ f_{*|\mathbb{1}}^{\otimes} &: \emptyset \xrightarrow{=} \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 007R** 6. *Symmetric Oplax Monoidality With Respect to Intersections.* The direct image function of **Item 1** has a symmetric oplax monoidal structure

$$(f_*, f_*^{\otimes}, f_{*|\mathbb{1}}^{\otimes}) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} f_{*|U,V}^{\otimes} &: f_*(U \cap V) \hookrightarrow f_*(U) \cap f_*(V), \\ f_{*|\mathbb{1}}^{\otimes} &: f_*(A) \hookrightarrow B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 007S** 7. *Interaction With Coproducts.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \amalg g)_*(U \amalg V) = f_*(U) \amalg g_*(V)$$

for each $U \in \mathcal{P}(A)$ and each $V \in \mathcal{P}(B)$.

- 007T** 8. *Interaction With Products.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \times g)_*(U \times V) = f_*(U) \times g_*(V)$$

for each $U \in \mathcal{P}(A)$ and each $V \in \mathcal{P}(B)$.

- 007U** 9. *Relation to Direct Images With Compact Support.* We have

$$f_*(U) = B \setminus f_!(A \setminus U)$$

for each $U \in \mathcal{P}(A)$.

Proof. Item 1, Functoriality: Clear.

Item 2, Triple Adjointness: This follows from **Remark 2.4.4.1.3**, **Remark 2.4.5.1.2**, **Remark 2.4.6.1.3**, and ?? of ??.

Item 3, Preservation of Colimits: This follows from **Item 2** and ?? of ??.³⁷

³⁷See also [Pro24t].

Item 4, Oplax Preservation of Limits: The inclusion $f_*(A) \subset B$ is clear. See [Pro24s] for the other inclusions.

Item 5, Symmetric Strict Monoidality With Respect to Unions: This follows from *Item 3*.

Item 6, Symmetric Oplax Monoidality With Respect to Intersections: This follows from *Item 4*.

Item 7, Interaction With Coproducts: Clear.

Item 8, Interaction With Products: Clear.

Item 9, Relation to Direct Images With Compact Support: Applying *Item 9* of *Proposition 2.4.6.1.6* to $A \setminus U$, we have

$$\begin{aligned} f_!(A \setminus U) &= B \setminus f_*(A \setminus (A \setminus U)) \\ &= B \setminus f_*(U). \end{aligned}$$

Taking complements, we then obtain

$$\begin{aligned} f_*(U) &= B \setminus (B \setminus f_!(A \setminus U)), \\ &= B \setminus f_!(A \setminus U), \end{aligned}$$

which finishes the proof. \square

007V Proposition 2.4.4.1.5. Let $f: A \rightarrow B$ be a function.

007W 1. *Functionality I.* The assignment $f \mapsto f_*$ defines a function

$$(-)_{*|A,B}: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

007X 2. *Functionality II.* The assignment $f \mapsto f_*$ defines a function

$$(-)_{*|A,B}: \text{Sets}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

007Y 3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$(\text{id}_A)_* = \text{id}_{\mathcal{P}(A)}.$$

007Z 4. *Interaction With Composition.* For each pair of composable functions $f: A \rightarrow B$ and $g: B \rightarrow C$, we have

$$(g \circ f)_* = g_* \circ f_*$$

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{f_*} & \mathcal{P}(B) \\ & \searrow (g \circ f)_* & \downarrow g_* \\ & & \mathcal{P}(C). \end{array}$$

Proof. Item 1, Functionality I: Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: This follows from [Remark 2.4.4.1.3](#) and ?? of ??.

Item 4, Interaction With Composition: This follows from [Remark 2.4.4.1.3](#) and ?? of ??.

0080 2.4.5 Inverse Images

Let A and B be sets and let $f: A \rightarrow B$ be a function.

0081 Definition 2.4.5.1.1. The **inverse image function associated to f** is the function³⁸

$$f^{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

defined by³⁹

$$f^{-1}(V) \stackrel{\text{def}}{=} \{a \in A \mid \text{we have } f(a) \in V\}$$

for each $V \in \mathcal{P}(B)$.

0082 Remark 2.4.5.1.2. Identifying subsets of B with functions from B to $\{\text{true}, \text{false}\}$ via [Items 1](#) and [2](#) of [Proposition 2.4.3.1.6](#), we see that the inverse image function associated to f is equivalently the function

$$f^*: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

defined by

$$f^*(\chi_V) \stackrel{\text{def}}{=} \chi_V \circ f$$

for each $\chi_V \in \mathcal{P}(B)$, where $\chi_V \circ f$ is the composition

$$A \xrightarrow{f} B \xrightarrow{\chi_V} \{\text{true}, \text{false}\}$$

in Sets.

0083 Proposition 2.4.5.1.3. Let $f: A \rightarrow B$ be a function.

0084 1. *Functoriality.* The assignment $V \mapsto f^{-1}(V)$ defines a functor

$$f^{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

where

³⁸*Further Notation:* Also written $f^*: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$.

³⁹*Further Terminology:* The set $f^{-1}(V)$ is called the **inverse image of V by f** .

- *Action on Objects.* For each $V \in \mathcal{P}(B)$, we have

$$[f^{-1}](V) \stackrel{\text{def}}{=} f^{-1}(V).$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(B)$:

$$(\star) \text{ If } U \subset V, \text{ then } f^{-1}(U) \subset f^{-1}(V).$$

0085 2. *Triple Adjointness.* We have a triple adjunction

$$(f_* \dashv f^{-1} \dashv f_!): \quad \mathcal{P}(A) \begin{array}{c} \xrightarrow{f_*} \\ \perp \\ \xleftarrow{f^{-1}} \\ \perp \\ \xrightarrow{f_!} \end{array} \mathcal{P}(B),$$

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\mathcal{P}(B)}(f_*(U), V) &\cong \text{Hom}_{\mathcal{P}(A)}(U, f^{-1}(V)), \\ \text{Hom}_{\mathcal{P}(A)}(f^{-1}(U), V) &\cong \text{Hom}_{\mathcal{P}(A)}(U, f_!(V)), \end{aligned}$$

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$ and (respectively) $V \in \mathcal{P}(A)$ and $U \in \mathcal{P}(B)$, i.e. where:

- The following conditions are equivalent:
 - We have $f_*(U) \subset V$;
 - We have $U \subset f^{-1}(V)$;
- The following conditions are equivalent:
 - We have $f^{-1}(U) \subset V$.
 - We have $U \subset f_!(V)$.

0086 3. *Preservation of Colimits.* We have an equality of sets

$$f^{-1}\left(\bigcup_{i \in I} U_i\right) = \bigcup_{i \in I} f^{-1}(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(B)^{\times I}$. In particular, we have equalities

$$\begin{aligned} f^{-1}(U) \cup f^{-1}(V) &= f^{-1}(U \cup V), \\ f^{-1}(\emptyset) &= \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

- 0087 4. *Preservation of Limits.* We have an equality of sets

$$f^{-1}\left(\bigcap_{i \in I} U_i\right) = \bigcap_{i \in I} f^{-1}(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(B)^{\times I}$. In particular, we have equalities

$$\begin{aligned} f^{-1}(U) \cap f^{-1}(V) &= f^{-1}(U \cap V), \\ f^{-1}(B) &= A, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

- 0088 5. *Symmetric Strict Monoidality With Respect to Unions.* The inverse image function of **Item 1** has a symmetric strict monoidal structure

$$\left(f^{-1}, f^{-1, \otimes}, f_{\perp}^{-1, \otimes}\right): (\mathcal{P}(B), \cup, \emptyset) \rightarrow (\mathcal{P}(A), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} f_{U, V}^{-1, \otimes}: f^{-1}(U) \cup f^{-1}(V) &\xrightarrow{=} f^{-1}(U \cup V), \\ f_{\perp}^{-1, \otimes}: \emptyset &\xrightarrow{=} f^{-1}(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

- 0089 6. *Symmetric Strict Monoidality With Respect to Intersections.* The inverse image function of **Item 1** has a symmetric strict monoidal structure

$$\left(f^{-1}, f^{-1, \otimes}, f_{\perp}^{-1, \otimes}\right): (\mathcal{P}(B), \cap, B) \rightarrow (\mathcal{P}(A), \cap, A),$$

being equipped with equalities

$$\begin{aligned} f_{U, V}^{-1, \otimes}: f^{-1}(U) \cap f^{-1}(V) &\xrightarrow{=} f^{-1}(U \cap V), \\ f_{\perp}^{-1, \otimes}: A &\xrightarrow{=} f^{-1}(B), \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

- 008A 7. *Interaction With Coproducts.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \amalg g)^{-1}(U' \amalg V') = f^{-1}(U') \amalg g^{-1}(V')$$

for each $U' \in \mathcal{P}(A')$ and each $V' \in \mathcal{P}(B')$.

- 008B 8. *Interaction With Products.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \times g)^{-1}(U' \times V') = f^{-1}(U') \times g^{-1}(V')$$

for each $U' \in \mathcal{P}(A')$ and each $V' \in \mathcal{P}(B')$.

Proof. Item 1, Functoriality: Clear.

Item 2, Triple Adjointness: This follows from [Remark 2.4.4.1.3](#), [Remark 2.4.5.1.2](#), [Remark 2.4.6.1.3](#), and ?? of ??.

Item 3, Preservation of Colimits: This follows from [Item 2](#) and ?? of ??.⁴⁰

Item 4, Preservation of Limits: This follows from [Item 2](#) and ?? of ??.⁴¹

Item 5, Symmetric Strict Monoidality With Respect to Unions: This follows from [Item 3](#).

Item 6, Symmetric Strict Monoidality With Respect to Intersections: This follows from [Item 4](#).

Item 7, Interaction With Coproducts: Clear.

Item 8, Interaction With Products: Clear. □

- 008C **Proposition 2.4.5.1.4.** Let $f: A \rightarrow B$ be a function.

- 008D 1. *Functionality I.* The assignment $f \mapsto f^{-1}$ defines a function

$$(-)_{A,B}^{-1}: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(B), \mathcal{P}(A)).$$

- 008E 2. *Functionality II.* The assignment $f \mapsto f^{-1}$ defines a function

$$(-)_{A,B}^{-1}: \text{Sets}(A, B) \rightarrow \text{Pos}((\mathcal{P}(B), \subset), (\mathcal{P}(A), \subset)).$$

- 008F 3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$\text{id}_A^{-1} = \text{id}_{\mathcal{P}(A)}.$$

- 008G 4. *Interaction With Composition.* For each pair of composable functions $f: A \rightarrow B$ and $g: B \rightarrow C$, we have

$$(g \circ f)^{-1} = f^{-1} \circ g^{-1},$$

$$\begin{array}{ccc} \mathcal{P}(C) & \xrightarrow{g^{-1}} & \mathcal{P}(B) \\ & \searrow (g \circ f)^{-1} & \downarrow f^{-1} \\ & & \mathcal{P}(A). \end{array}$$

⁴⁰See also [[Pro24ac](#)].

⁴¹See also [[Pro24ab](#)].

Proof. Item 1, Functionality I: Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: This follows from [Remark 2.4.5.1.2](#) and [Item 5](#) of [Proposition 8.1.6.1.2](#).

Item 4, Interaction With Composition: This follows from [Remark 2.4.5.1.2](#) and [Item 2](#) of [Proposition 8.1.6.1.2](#). \square

008H 2.4.6 Direct Images With Compact Support

Let A and B be sets and let $f: A \rightarrow B$ be a function.

008J Definition 2.4.6.1.1. The **direct image with compact support function associated to f** is the function

$$f_! : \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by^{42,43}

$$\begin{aligned} f_!(U) &\stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ if we have} \\ f(a) = b, \text{ then } a \in U \end{array} \right\} \\ &= \{ b \in B \mid \text{we have } f^{-1}(b) \subset U \} \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

008K Notation 2.4.6.1.2. Sometimes one finds the notation

$$\forall_f : \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

for f_* . This notation comes from the fact that the following statements are equivalent, where $b \in B$ and $U \in \mathcal{P}(A)$:

- We have $b \in \forall_f(U)$.
- For each $a \in A$, if $b = f(a)$, then $a \in U$.

008L Remark 2.4.6.1.3. Identifying subsets of A with functions from A to $\{\text{true}, \text{false}\}$ via [Items 1](#) and [2](#) of [Proposition 2.4.3.1.6](#), we see that the direct image with compact support function associated to f is equivalently the function

$$f_! : \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

⁴²*Further Terminology:* The set $f_!(U)$ is called the **direct image with compact support of U by f** .

⁴³We also have

$$f_!(U) = B \setminus f_*(A \setminus U);$$

defined by

$$\begin{aligned}
 f_!(\chi_U) &\stackrel{\text{def}}{=} \text{Ran}_f(\chi_U) \\
 &= \lim \left(\left(\underline{(-1)} \vec{\times} f \right) \xrightarrow{\text{pr}} A \xrightarrow{\chi_U} \{\text{true}, \text{false}\} \right) \\
 &= \lim_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)) \\
 &= \bigwedge_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)).
 \end{aligned}$$

where we have used ?? for the second equality. In other words, we have

$$\begin{aligned}
 [f_!(\chi_U)](b) &= \bigwedge_{\substack{a \in A \\ f(a) = b}} (\chi_U(a)) \\
 &= \begin{cases} \text{true} & \text{if, for each } a \in A \text{ such that} \\ & f(a) = b, \text{ we have } a \in U, \\ \text{false} & \text{otherwise} \end{cases} \\
 &= \begin{cases} \text{true} & \text{if } f^{-1}(b) \subset U \\ \text{false} & \text{otherwise} \end{cases}
 \end{aligned}$$

for each $b \in B$.

008M Definition 2.4.6.1.4. Let U be a subset of A .^{44,45}

see Item 9 of Proposition 2.4.6.1.6.

⁴⁴Note that we have

$$f_!(U) = f_{!,\text{im}}(U) \cup f_{!,\text{cp}}(U),$$

as

$$\begin{aligned}
 f_!(U) &= f_!(U) \cap B \\
 &= f_!(U) \cap (\text{Im}(f) \cup (B \setminus \text{Im}(f))) \\
 &= (f_!(U) \cap \text{Im}(f)) \cup (f_!(U) \cap (B \setminus \text{Im}(f))) \\
 &\stackrel{\text{def}}{=} f_{!,\text{im}}(U) \cup f_{!,\text{cp}}(U).
 \end{aligned}$$

⁴⁵In terms of the meet computation of $f_!(U)$ of Remark 2.4.6.1.3, namely

$$f_!(\chi_U) = \bigwedge_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)),$$

we see that $f_{!,\text{im}}$ corresponds to meets indexed over nonempty sets, while $f_{!,\text{cp}}$ corresponds to meets indexed over the empty set.

- 008N 1. The **image part of the direct image with compact support** $f_{i,\text{im}}(U)$ of U is the set $f_{i,\text{im}}(U)$ defined by

$$\begin{aligned} f_{i,\text{im}}(U) &\stackrel{\text{def}}{=} f_i(U) \cap \text{Im}(f) \\ &= \left\{ b \in B \mid \begin{array}{l} \text{we have } f^{-1}(b) \subset \\ U \text{ and } f^{-1}(b) \neq \emptyset \end{array} \right\}. \end{aligned}$$

- 008P 2. The **complement part of the direct image with compact support** $f_{i,\text{cp}}(U)$ of U is the set $f_{i,\text{cp}}(U)$ defined by

$$\begin{aligned} f_{i,\text{cp}}(U) &\stackrel{\text{def}}{=} f_i(U) \cap (B \setminus \text{Im}(f)) \\ &= B \setminus \text{Im}(f) \\ &= \left\{ b \in B \mid \begin{array}{l} \text{we have } f^{-1}(b) \subset \\ U \text{ and } f^{-1}(b) = \emptyset \end{array} \right\} \\ &= \{ b \in B \mid f^{-1}(b) = \emptyset \}. \end{aligned}$$

- 008Q **Example 2.4.6.1.5.** Here are some examples of direct images with compact support.

1. *The Multiplication by Two Map on the Natural Numbers.* Consider the function $f: \mathbb{N} \rightarrow \mathbb{N}$ given by

$$f(n) \stackrel{\text{def}}{=} 2n$$

for each $n \in \mathbb{N}$. Since f is injective, we have

$$\begin{aligned} f_{i,\text{im}}(U) &= f_*(U) \\ f_{i,\text{cp}}(U) &= \{\text{odd natural numbers}\} \end{aligned}$$

for any $U \subset \mathbb{N}$.

2. *Parabolas.* Consider the function $f: \mathbb{R} \rightarrow \mathbb{R}$ given by

$$f(x) \stackrel{\text{def}}{=} x^2$$

for each $x \in \mathbb{R}$. We have

$$f_{i,\text{cp}}(U) = \mathbb{R}_{<0}$$

for any $U \subset \mathbb{R}$. Moreover, since $f^{-1}(x) = \{-\sqrt{x}, \sqrt{x}\}$, we have e.g.:

$$\begin{aligned} f_{i,\text{im}}([0, 1]) &= \{0\}, \\ f_{i,\text{im}}([-1, 1]) &= [0, 1], \\ f_{i,\text{im}}([1, 2]) &= \emptyset, \\ f_{i,\text{im}}([-2, -1] \cup [1, 2]) &= [1, 4]. \end{aligned}$$

3. *Circles.* Consider the function $f: \mathbb{R}^2 \rightarrow \mathbb{R}$ given by

$$f(x, y) \stackrel{\text{def}}{=} x^2 + y^2$$

for each $(x, y) \in \mathbb{R}^2$. We have

$$f_{!,\text{cp}}(U) = \mathbb{R}_{<0}$$

for any $U \subset \mathbb{R}^2$, and since

$$f^{-1}(r) = \begin{cases} \text{a circle of radius } r \text{ about the origin} & \text{if } r > 0, \\ \{(0, 0)\} & \text{if } r = 0, \\ \emptyset & \text{if } r < 0, \end{cases}$$

we have e.g.:

$$\begin{aligned} f_{!,\text{im}}([-1, 1] \times [-1, 1]) &= [0, 1], \\ f_{!,\text{im}}([-1, 1] \times [-1, 1] \setminus [-1, 1] \times \{0\}) &= \emptyset. \end{aligned}$$

008R Proposition 2.4.6.1.6. Let $f: A \rightarrow B$ be a function.

008S 1. *Functoriality.* The assignment $U \mapsto f_!(U)$ defines a functor

$$f_!: (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

where

- *Action on Objects.* For each $U \in \mathcal{P}(A)$, we have

$$[f_!](U) \stackrel{\text{def}}{=} f_!(U).$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(A)$:

(★) If $U \subset V$, then $f_!(U) \subset f_!(V)$.

008T 2. *Triple Adjointness.* We have a triple adjunction

$$(f_* \dashv f^{-1} \dashv f_!): \quad \mathcal{P}(A) \begin{array}{c} \xrightarrow{f_*} \\ \perp \\ \xleftarrow{f^{-1}} \\ \perp \\ \xrightarrow{f_!} \end{array} \mathcal{P}(B),$$

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\mathcal{P}(B)}(f_*(U), V) &\cong \text{Hom}_{\mathcal{P}(A)}(U, f^{-1}(V)), \\ \text{Hom}_{\mathcal{P}(A)}(f^{-1}(U), V) &\cong \text{Hom}_{\mathcal{P}(A)}(U, f_!(V)), \end{aligned}$$

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$ and (respectively) $V \in \mathcal{P}(A)$ and $U \in \mathcal{P}(B)$, i.e. where:

(a) The following conditions are equivalent:

- i. We have $f_*(U) \subset V$.
- ii. We have $U \subset f^{-1}(V)$.

(b) The following conditions are equivalent:

- i. We have $f^{-1}(U) \subset V$.
- ii. We have $U \subset f_!(V)$.

008U 3. *Lax Preservation of Colimits.* We have an inclusion of sets

$$\bigcup_{i \in I} f_!(U_i) \subset f_!\left(\bigcup_{i \in I} U_i\right),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have inclusions

$$\begin{aligned} f_!(U) \cup f_!(V) &\hookrightarrow f_!(U \cup V), \\ \emptyset &\hookrightarrow f_!(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

008V 4. *Preservation of Limits.* We have an equality of sets

$$f_!\left(\bigcap_{i \in I} U_i\right) = \bigcap_{i \in I} f_!(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have equalities

$$\begin{aligned} f^{-1}(U \cap V) &= f_!(U) \cap f^{-1}(V), \\ f_!(A) &= B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

008W 5. *Symmetric Lax Monoidality With Respect to Unions.* The direct image with compact support function of **Item 1** has a symmetric lax monoidal structure

$$\left(f_!, f_!^\otimes, f_{! \perp}^\otimes\right): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with inclusions

$$\begin{aligned} f_{! \perp, V}^\otimes: f_!(U) \cup f_!(V) &\hookrightarrow f_!(U \cup V), \\ f_{! \perp}^\otimes: \emptyset &\hookrightarrow f_!(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 008X 6. *Symmetric Strict Monoidality With Respect to Intersections.* The direct image function of **Item 1** has a symmetric strict monoidal structure

$$\left(f_!, f_!^\otimes, f_{!|\mathbb{1}}^\otimes\right): (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

$$\begin{aligned} f_{!|U,V}^\otimes: f_!(U \cap V) &\xrightarrow{=} f_!(U) \cap f_!(V), \\ f_{!|\mathbb{1}}^\otimes: f_!(A) &\xrightarrow{=} B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 008Y 7. *Interaction With Coproducts.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \amalg g)_!(U \amalg V) = f_!(U) \amalg g_!(V)$$

for each $U \in \mathcal{P}(A)$ and each $V \in \mathcal{P}(B)$.

- 008Z 8. *Interaction With Products.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \times g)_!(U \times V) = f_!(U) \times g_!(V)$$

for each $U \in \mathcal{P}(A)$ and each $V \in \mathcal{P}(B)$.

- 0090 9. *Relation to Direct Images.* We have

$$f_!(U) = B \setminus f_*(A \setminus U)$$

for each $U \in \mathcal{P}(A)$.

- 0091 10. *Interaction With Injections.* If f is injective, then we have

$$\begin{aligned} f_{!,\text{im}}(U) &= f_*(U), \\ f_{!,\text{cp}}(U) &= B \setminus \text{Im}(f), \\ f_!(U) &= f_{!,\text{im}}(U) \cup f_{!,\text{cp}}(U) \\ &= f_*(U) \cup (B \setminus \text{Im}(f)) \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

- 0092 11. *Interaction With Surjections.* If f is surjective, then we have

$$\begin{aligned} f_{!,\text{im}}(U) &\subset f_*(U), \\ f_{!,\text{cp}}(U) &= \emptyset, \\ f_!(U) &\subset f_*(U) \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

Proof. Item 1, Functoriality: Clear.

Item 2, Triple Adjointness: This follows from [Remark 2.4.4.1.3](#), [Remark 2.4.5.1.2](#), [Remark 2.4.6.1.3](#), and ?? of ??.

Item 3, Lax Preservation of Colimits: Omitted.

Item 4, Preservation of Limits: This follows from [Item 2](#) and ?? of ??.

Item 5, Symmetric Lax Monoidality With Respect to Unions: This follows from [Item 3](#).

Item 6, Symmetric Strict Monoidality With Respect to Intersections: This follows from [Item 4](#).

Item 7, Interaction With Coproducts: Clear.

Item 8, Interaction With Products: Clear.

Item 9, Relation to Direct Images: We claim that $f_!(U) = B \setminus f_*(A \setminus U)$.

- *The First Implication.* We claim that

$$f_!(U) \subset B \setminus f_*(A \setminus U).$$

Let $b \in f_!(U)$. We need to show that $b \notin f_*(A \setminus U)$, i.e. that there is no $a \in A \setminus U$ such that $f(a) = b$.

This is indeed the case, as otherwise we would have $a \in f^{-1}(b)$ and $a \notin U$, contradicting $f^{-1}(b) \subset U$ (which holds since $b \in f_!(U)$).

Thus $b \in B \setminus f_*(A \setminus U)$.

- *The Second Implication.* We claim that

$$B \setminus f_*(A \setminus U) \subset f_!(U).$$

Let $b \in B \setminus f_*(A \setminus U)$. We need to show that $b \in f_!(U)$, i.e. that $f^{-1}(b) \subset U$.

Since $b \notin f_*(A \setminus U)$, there exists no $a \in A \setminus U$ such that $b = f(a)$, and hence $f^{-1}(b) \subset U$.

Thus $b \in f_!(U)$.

This finishes the proof of [Item 9](#).

Item 10, Interaction With Injections: Clear.

Item 11, Interaction With Surjections: Clear. □

0093 Proposition 2.4.6.1.7. Let $f: A \rightarrow B$ be a function.

0094 1. *Functionality I.* The assignment $f \mapsto f_!$ defines a function

$$(-)_{!|A,B}: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

0095 2. *Functionality II.* The assignment $f \mapsto f_!$ defines a function

$$(-)_{!A,B}: \text{Sets}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

0096 3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$(\text{id}_A)_! = \text{id}_{\mathcal{P}(A)}.$$

0097 4. *Interaction With Composition.* For each pair of composable functions $f: A \rightarrow B$ and $g: B \rightarrow C$, we have

$$(g \circ f)_! = g_! \circ f_!$$

Proof. Item 1, Functionality I: Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: This follows from Remark 2.4.6.1.3 and ?? of ??.

Item 4, Interaction With Composition: This follows from Remark 2.4.6.1.3 and ?? of ??.

□

Appendices

2.A Other Chapters

Sets

- 1. Sets
- 2. Constructions With Sets
- 3. Pointed Sets
- 4. Tensor Products of Pointed Sets

6. Constructions With Relations

- 7. Equivalence Relations and Apartness Relations

Category Theory

- 8. Categories

Bicategories

- 9. Types of Morphisms in Bicategories

Relations

- 5. Relations

Chapter 3

Pointed Sets

0098 This chapter contains some foundational material on pointed sets.

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0099 3.1 Pointed Sets

009A 3.1.1 Foundations

009B **Definition 3.1.1.1.1.** A **pointed set**¹ is equivalently:

- An \mathbb{E}_0 -monoid in $(\mathbf{N}_\bullet(\mathbf{Sets}), \text{pt})$.
- A pointed object in $(\mathbf{Sets}, \text{pt})$.

009C **Remark 3.1.1.1.2.** In detail, a **pointed set** is a pair (X, x_0) consisting of:

- *The Underlying Set.* A set X , called the **underlying set of** (X, x_0) .
- *The Basepoint.* A morphism

$$[x_0]: \text{pt} \rightarrow X$$

in \mathbf{Sets} , determining an element $x_0 \in X$, called the **basepoint of** X .

009D **Example 3.1.1.1.3.** The **0-sphere**² is the pointed set $(S^0, 0)$ ³ consisting of:

- *The Underlying Set.* The set S^0 defined by

$$S^0 \stackrel{\text{def}}{=} \{0, 1\}.$$

- *The Basepoint.* The element 0 of S^0 .

009E **Example 3.1.1.1.4.** The **trivial pointed set** is the pointed set (pt, \star) consisting of:

- *The Underlying Set.* The punctual set $\text{pt} \stackrel{\text{def}}{=} \{\star\}$.
- *The Basepoint.* The element \star of pt .

009F **Example 3.1.1.1.5.** The **underlying pointed set** of a semimodule (M, α_M) is the pointed set $(M, 0_M)$.

009G **Example 3.1.1.1.6.** The **underlying pointed set** of a module (M, α_M) is the pointed set $(M, 0_M)$.

¹*Further Terminology:* In the context of monoids with zero as models for \mathbb{F}_1 -algebras, pointed sets are viewed as \mathbb{F}_1 -**modules**.

²*Further Terminology:* In the context of monoids with zero as models for \mathbb{F}_1 -algebras, the 0-sphere is viewed as the **underlying pointed set of the field with one element**.

³*Further Notation:* In the context of monoids with zero as models for \mathbb{F}_1 -algebras, S^0 is also denoted $(\mathbb{F}_1, 0)$.

009H 3.1.2 Morphisms of Pointed Sets**009J Definition 3.1.2.1.1.** A **morphism of pointed sets**^{4,5} is equivalently:

- A morphism of \mathbb{E}_0 -monoids in $(\mathbf{N}_\bullet(\mathbf{Sets}), \text{pt})$.
- A morphism of pointed objects in $(\mathbf{Sets}, \text{pt})$.

009K Remark 3.1.2.1.2. In detail, a **morphism of pointed sets** $f: (X, x_0) \rightarrow (Y, y_0)$ is a morphism of sets $f: X \rightarrow Y$ such that the diagram

$$\begin{array}{ccc} & \text{pt} & \\ [x_0] \swarrow & & \searrow [y_0] \\ X & \xrightarrow{f} & Y \end{array}$$

commutes, i.e. such that

$$f(x_0) = y_0.$$

009L 3.1.3 The Category of Pointed Sets**009M Definition 3.1.3.1.1.** The **category of pointed sets** is the category \mathbf{Sets}_* defined equivalently as

- The homotopy category of the ∞ -category $\text{Mon}_{\mathbb{E}_0}(\mathbf{N}_\bullet(\mathbf{Sets}), \text{pt})$ of ??;
- The category \mathbf{Sets}_* of ??.

009N Remark 3.1.3.1.2. In detail, the **category of pointed sets** is the category \mathbf{Sets}_* where

- *Objects.* The objects of \mathbf{Sets}_* are pointed sets;
- *Morphisms.* The morphisms of \mathbf{Sets}_* are morphisms of pointed sets;
- *Identities.* For each $(X, x_0) \in \text{Obj}(\mathbf{Sets}_*)$, the unit map

$$\mathbb{1}_{(X, x_0)}^{\mathbf{Sets}_*} : \text{pt} \rightarrow \mathbf{Sets}_*((X, x_0), (X, x_0))$$

of \mathbf{Sets}_* at (X, x_0) is defined by⁶

$$\text{id}_{(X, x_0)}^{\mathbf{Sets}_*} \stackrel{\text{def}}{=} \text{id}_X;$$

⁴*Further Terminology:* Also called a **pointed function**.⁵*Further Terminology:* In the context of monoids with zero as models for \mathbb{F}_1 -algebras, morphisms of pointed sets are also called **morphism of \mathbb{F}_1 -modules**.⁶Note that id_X is indeed a morphism of pointed sets, as we have $\text{id}_X(x_0) = x_0$.

- *Composition.* For each $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$, the composition map

$$\circ_{(X,x_0),(Y,y_0),(Z,z_0)}^{\text{Sets}_*} : \text{Sets}_*((Y, y_0), (Z, z_0)) \times \text{Sets}_*((X, x_0), (Y, y_0)) \rightarrow \text{Sets}_*((X, x_0), (Z, z_0))$$

of Sets_* at $((X, x_0), (Y, y_0), (Z, z_0))$ is defined by⁷

$$g \circ_{(X,x_0),(Y,y_0),(Z,z_0)}^{\text{Sets}_*} f \stackrel{\text{def}}{=} g \circ f.$$

009P 3.1.4 Elementary Properties of Pointed Sets

009Q Proposition 3.1.4.1.1. Let (X, x_0) be a pointed set.

009R 1. *Completeness.* The category Sets_* of pointed sets and morphisms between them is complete, having in particular:

- 009S** (a) Products, described as in [Definition 3.2.3.1.1](#);
- 009T** (b) Pullbacks, described as in [Definition 3.2.4.1.1](#);
- 009U** (c) Equalisers, described as in [Definition 3.2.5.1.1](#).

009V 2. *Cocompleteness.* The category Sets_* of pointed sets and morphisms between them is cocomplete, having in particular:

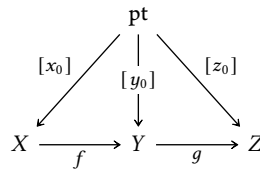
- 009W** (a) Coproducts, described as in [Definition 3.3.3.1.1](#);
- 009X** (b) Pushouts, described as in [Definition 3.3.4.1.1](#);
- 009Y** (c) Coequalisers, described as in [Definition 3.3.5.1.1](#).

009Z 3. *Failure To Be Cartesian Closed.* The category Sets_* is not Cartesian closed.⁸

⁷Note that the composition of two morphisms of pointed sets is indeed a morphism of pointed sets, as we have

$$\begin{aligned} g(f(x_0)) &= g(y_0) \\ &= z_0, \end{aligned}$$

or



in terms of diagrams.

⁸The category Sets_* does admit monoidal closed structures however; see [Tensor Products of Pointed Sets](#).

00A0 4. *Morphisms From the Monoidal Unit.* We have a bijection of sets⁹

$$\mathbf{Sets}_*(S^0, X) \cong X,$$

natural in $(X, x_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$, internalising also to an isomorphism of pointed sets

$$\mathbf{Sets}_*(S^0, X) \cong (X, x_0),$$

again natural in $(X, x_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$.

00A1 5. *Relation to Partial Functions.* We have an equivalence of categories¹⁰

$$\mathbf{Sets}_* \stackrel{\text{eq.}}{\cong} \mathbf{Sets}^{\text{part.}}$$

between the category of pointed sets and pointed functions between them and the category of sets and partial functions between them, where:

(a) *From Pointed Sets to Sets With Partial Functions.* The equivalence

$$\xi: \mathbf{Sets}_* \xrightarrow{\cong} \mathbf{Sets}^{\text{part.}}$$

sends:

- i. A pointed set (X, x_0) to X .
- ii. A pointed function

$$f: (X, x_0) \rightarrow (Y, y_0)$$

to the partial function

$$\xi_f: X \rightarrow Y$$

defined on $f^{-1}(Y \setminus y_0)$ and given by


$$\xi_f(x) \stackrel{\text{def}}{=} f(x)$$

for each $x \in f^{-1}(Y \setminus y_0)$.

⁹In other words, the forgetful functor

$$\overline{\omega}: \mathbf{Sets}_* \rightarrow \mathbf{Sets}$$

defined on objects by sending a pointed set to its underlying set is corepresentable by S^0 .

¹⁰ *Warning:* This is not an isomorphism of categories, only an equivalence.

(b) *From Sets With Partial Functions to Pointed Sets.* The equivalence

$$\xi^{-1} : \mathbf{Sets}^{\text{part.}} \xrightarrow{\cong} \mathbf{Sets}_*$$

sends:

- i. A set X is to the pointed set (X, \star) with \star an element that is not in X .
- ii. A partial function

$$f : X \rightarrow Y$$

defined on $U \subset X$ to the pointed function

$$\xi_f^{-1} : (X, x_0) \rightarrow (Y, y_0)$$

defined by

$$\xi_f(x) \stackrel{\text{def}}{=} \begin{cases} f(x) & \text{if } x \in U, \\ y_0 & \text{otherwise.} \end{cases}$$

for each $x \in X$.

Proof. Item 1, Completeness: This follows from (the proofs) of [Definitions 3.2.3.1.1](#), [3.2.4.1.1](#) and [3.2.5.1.1](#) and [??](#).

Item 2, Cocompleteness: This follows from (the proofs) of [Definitions 3.3.3.1.1](#), [3.3.4.1.1](#) and [3.3.5.1.1](#) and [??](#).

Item 3, Failure To Be Cartesian Closed: See [[MSE 2855868](#)].

Item 4, Morphisms From the Monoidal Unit: Since a morphism from S^0 to a pointed set (X, x_0) sends $0 \in S^0$ to x_0 and then can send $1 \in S^0$ to any element of X , we obtain a bijection between pointed maps $S^0 \rightarrow X$ and the elements of X .

The isomorphism then

$$\mathbf{Sets}_*(S^0, X) \cong (X, x_0)$$

follows by noting that $\Delta_{x_0} : S^0 \rightarrow X$, the basepoint of $\mathbf{Sets}_*(S^0, X)$, corresponds to the pointed map $S^0 \rightarrow X$ picking the element x_0 of X , and thus we see that the bijection between pointed maps $S^0 \rightarrow X$ and elements of X is compatible with basepoints, lifting to an isomorphism of pointed sets.

Item 5, Relation to Partial Functions: See [[MSE 884460](#)]. \square

END TEXTDBEND

00A2 3.2 Limits of Pointed Sets

00A3 3.2.1 The Terminal Pointed Set

00A4 **Definition 3.2.1.1.1.** The **terminal pointed set** is the pair $\left((\text{pt}, \star), \{!_X\}_{(X, x_0) \in \text{Obj}(\text{Sets}_*)} \right)$ consisting of:

- *The Limit.* The pointed set (pt, \star) .
- *The Cone.* The collection of morphisms of pointed sets

$$\{!_X : (X, x_0) \rightarrow (\text{pt}, \star)\}_{(X, x_0) \in \text{Obj}(\text{Sets})}$$

defined by

$$!_X(x) \stackrel{\text{def}}{=} \star$$

for each $x \in X$ and each $(X, x_0) \in \text{Obj}(\text{Sets})$.

Proof. We claim that (pt, \star) is the terminal object of Sets_* . Indeed, suppose we have a diagram of the form

$$(X, x_0) \quad (\text{pt}, \star)$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi : (X, x_0) \rightarrow (\text{pt}, \star)$$

making the diagram

$$(X, x_0) \xrightarrow[\exists!]{\phi} (\text{pt}, \star)$$

commute, namely $!_X$. □

00A5 3.2.2 Products of Families of Pointed Sets

Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

00A6 **Definition 3.2.2.1.1.** The **product** of $\{(X_i, x_0^i)\}_{i \in I}$ is the pair $\left(\left(\prod_{i \in I} X_i, (x_0^i)_{i \in I} \right), \{\text{pr}_i\}_{i \in I} \right)$ consisting of:

- *The Limit.* The pointed set $\left(\prod_{i \in I} X_i, (x_0^i)_{i \in I} \right)$.
- *The Cone.* The collection

$$\left\{ \text{pr}_i : \left(\prod_{i \in I} X_i, (x_0^i)_{i \in I} \right) \rightarrow (X_i, x_0^i) \right\}_{i \in I}$$

of maps given by

$$\text{pr}_i \left((x_j)_{j \in I} \right) \stackrel{\text{def}}{=} x_i$$

for each $(x_j)_{j \in I} \in \prod_{i \in I} X_i$ and each $i \in I$.

Proof. We claim that $(\prod_{i \in I} X_i, (x_0^i)_{i \in I})$ is the categorical product of $\{(X_i, x_0^i)\}_{i \in I}$ in \mathbf{Sets}_* . Indeed, suppose we have, for each $i \in I$, a diagram of the form

$$\begin{array}{ccc} (P, *) & & \\ & \searrow p_i & \\ (\prod_{i \in I} X_i, (x_0^i)_{i \in I}) & \xrightarrow{\text{pr}_i} & (X_i, x_0^i) \end{array}$$

in \mathbf{Sets}_* . Then there exists a unique morphism of pointed sets

$$\phi: (P, *) \rightarrow \left(\prod_{i \in I} X_i, (x_0^i)_{i \in I} \right)$$

making the diagram

$$\begin{array}{ccc} (P, *) & & \\ \downarrow \phi \exists! & \searrow p_i & \\ (\prod_{i \in I} X_i, (x_0^i)_{i \in I}) & \xrightarrow{\text{pr}_i} & (X_i, x_0^i) \end{array}$$

commute, being uniquely determined by the condition $\text{pr}_i \circ \phi = p_i$ for each $i \in I$ via

$$\phi(x) = (p_i(x))_{i \in I}$$

for each $x \in P$. Note that this is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \phi(*) &= (p_i(*))_{i \in I} \\ &= (x_0^i)_{i \in I}, \end{aligned}$$

where we have used that p_i is a morphism of pointed sets for each $i \in I$. \square

00A7 Proposition 3.2.2.1.2. Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

00A8 1. *Functoriality.* The assignment $\{(X_i, x_0^i)\}_{i \in I} \mapsto (\prod_{i \in I} X_i, (x_0^i)_{i \in I})$ defines a functor

$$\prod_{i \in I}: \text{Fun}(I_{\text{disc}}, \mathbf{Sets}_*) \rightarrow \mathbf{Sets}_*.$$

Proof. Item 1, Functoriality: This follows from ?? of ??. \square

00A9 3.2.3 Products

Let (X, x_0) and (Y, y_0) be pointed sets.

00AA Definition 3.2.3.1.1. The **product of (X, x_0) and (Y, y_0)** is the pair consisting of:

- *The Limit.* The pointed set $(X \times Y, (x_0, y_0))$.
- *The Cone.* The morphisms of pointed sets

$$\begin{aligned} \text{pr}_1 &: (X \times Y, (x_0, y_0)) \rightarrow (X, x_0), \\ \text{pr}_2 &: (X \times Y, (x_0, y_0)) \rightarrow (Y, y_0) \end{aligned}$$

defined by

$$\begin{aligned} \text{pr}_1(x, y) &\stackrel{\text{def}}{=} x, \\ \text{pr}_2(x, y) &\stackrel{\text{def}}{=} y \end{aligned}$$

for each $(x, y) \in X \times Y$.

Proof. We claim that $(X \times Y, (x_0, y_0))$ is the categorical product of (X, x_0) and (Y, y_0) in Sets_* . Indeed, suppose we have a diagram of the form

$$\begin{array}{ccc} & (P, *) & \\ p_1 \swarrow & & \searrow p_2 \\ (X, x_0) & \xleftarrow{\text{pr}_1} (X \times Y, (x_0, y_0)) \xrightarrow{\text{pr}_2} & (Y, y_0) \end{array}$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (P, *) \rightarrow (X \times Y, (x_0, y_0))$$

making the diagram

$$\begin{array}{ccc} & (P, *) & \\ p_1 \swarrow & \downarrow \phi \exists! & \searrow p_2 \\ (X, x_0) & \xleftarrow{\text{pr}_1} (X \times Y, (x_0, y_0)) \xrightarrow{\text{pr}_2} & (Y, y_0) \end{array}$$

commute, being uniquely determined by the conditions

$$\begin{aligned} \text{pr}_1 \circ \phi &= p_1, \\ \text{pr}_2 \circ \phi &= p_2 \end{aligned}$$

via

$$\phi(x) = (p_1(x), p_2(x))$$

for each $x \in P$. Note that this is indeed a morphism of pointed sets, as we have

$$\begin{aligned}\phi(*) &= (p_1(*), p_2(*)) \\ &= (x_0, y_0),\end{aligned}$$

where we have used that p_1 and p_2 are morphisms of pointed sets. \square

00AB Proposition 3.2.3.1.2. Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

00AC 1. *Functoriality.* The assignments

$$(X, x_0), (Y, y_0), ((X, x_0), (Y, y_0)) \mapsto (X \times Y, (x_0, y_0))$$

define functors

$$\begin{aligned}X \times - &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ - \times Y &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ -_1 \times -_2 &: \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*,\end{aligned}$$

defined in the same way as the functors of **Item 1** of **Proposition 2.1.3.1.2**.

00AD 2. *Associativity.* We have an isomorphism of pointed sets

$$((X \times Y) \times Z, ((x_0, y_0), z_0)) \cong (X \times (Y \times Z), (x_0, (y_0, z_0)))$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$.

00AE 3. *Unitality.* We have isomorphisms of pointed sets

$$\begin{aligned}(\mathbf{pt}, \star) \times (X, x_0) &\cong (X, x_0), \\ (X, x_0) \times (\mathbf{pt}, \star) &\cong (X, x_0),\end{aligned}$$

natural in $(X, x_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$.

00AF 4. *Commutativity.* We have an isomorphism of pointed sets

$$(X \times Y, (x_0, y_0)) \cong (Y \times X, (y_0, x_0)),$$

natural in $(X, x_0), (Y, y_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$.

00AG 5. *Symmetric Monoidality.* The triple $(\mathbf{Sets}_*, \times, (\mathbf{pt}, \star))$ is a symmetric monoidal category.

Proof. Item 1, Functoriality: This is a special case of functoriality of limits, ?? of ??.

Item 2, Associativity: This follows from *Item 3* of *Proposition 2.1.3.1.2*.

Item 3, Unitality: This follows from *Item 4* of *Proposition 2.1.3.1.2*.

Item 4, Commutativity: This follows from *Item 5* of *Proposition 2.1.3.1.2*.

Item 5, Symmetric Monoidality: This follows from *Item 12* of *Proposition 2.1.3.1.2*.

□

00AH 3.2.4 Pullbacks

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets and let $f: (X, x_0) \rightarrow (Z, z_0)$ and $g: (Y, y_0) \rightarrow (Z, z_0)$ be morphisms of pointed sets.

00AJ Definition 3.2.4.1.1. The **pullback of (X, x_0) and (Y, y_0) over (Z, z_0) along (f, g)** is the pair consisting of:

- *The Limit.* The pointed set $(X \times_Z Y, (x_0, y_0))$.
- *The Cone.* The morphisms of pointed sets

$$\text{pr}_1: (X \times_Z Y, (x_0, y_0)) \rightarrow (X, x_0),$$

$$\text{pr}_2: (X \times_Z Y, (x_0, y_0)) \rightarrow (Y, y_0)$$

defined by

$$\begin{aligned} \text{pr}_1(x, y) &\stackrel{\text{def}}{=} x, \\ \text{pr}_2(x, y) &\stackrel{\text{def}}{=} y \end{aligned}$$

for each $(x, y) \in X \times_Z Y$.

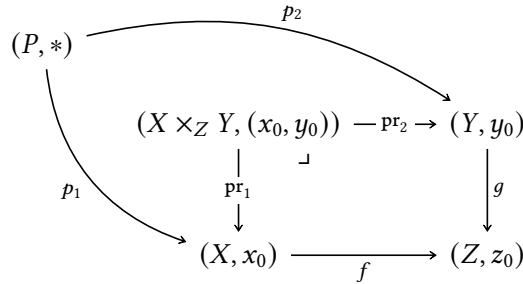
Proof. We claim that $X \times_Z Y$ is the categorical pullback of (X, x_0) and (Y, y_0) over (Z, z_0) with respect to (f, g) in Sets_* . First we need to check that the relevant pullback diagram commutes, i.e. that we have

$$\begin{array}{ccc} (X \times_Z Y, (x_0, y_0)) & \xrightarrow{\text{pr}_2} & (Y, y_0) \\ f \circ \text{pr}_1 = g \circ \text{pr}_2, & \begin{array}{c} \text{pr}_1 \downarrow \\ (X, x_0) \end{array} & \begin{array}{c} \downarrow g \\ (Z, z_0) \end{array} \\ & \xrightarrow{f} & \end{array}$$

Indeed, given $(x, y) \in X \times_Z Y$, we have

$$\begin{aligned} [f \circ \text{pr}_1](x, y) &= f(\text{pr}_1(x, y)) \\ &= f(x) \\ &= g(y) \\ &= g(\text{pr}_2(x, y)) \\ &= [g \circ \text{pr}_2](x, y), \end{aligned}$$

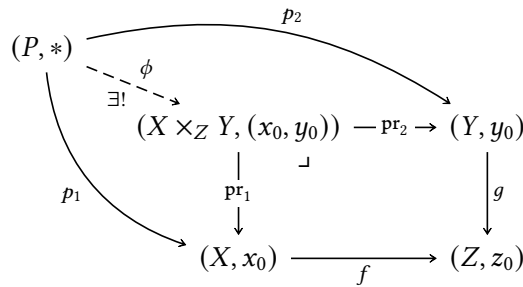
where $f(x) = g(y)$ since $(x, y) \in X \times_Z Y$. Next, we prove that $X \times_Z Y$ satisfies the universal property of the pullback. Suppose we have a diagram of the form



in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (P, *) \rightarrow (X \times_Z Y, (x_0, y_0))$$

making the diagram



commute, being uniquely determined by the conditions

$$\begin{aligned}
 \text{pr}_1 \circ \phi &= p_1, \\
 \text{pr}_2 \circ \phi &= p_2
 \end{aligned}$$

via

$$\phi(x) = (p_1(x), p_2(x))$$

for each $x \in P$, where we note that $(p_1(x), p_2(x)) \in X \times Y$ indeed lies in $X \times_Z Y$ by the condition

$$f \circ p_1 = g \circ p_2,$$

which gives

$$f(p_1(x)) = g(p_2(x))$$

for each $x \in P$, so that $(p_1(x), p_2(x)) \in X \times_Z Y$. Lastly, we note that ϕ is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \phi(*) &= (p_1(*), p_2(*)) \\ &= (x_0, y_0), \end{aligned}$$

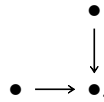
where we have used that p_1 and p_2 are morphisms of pointed sets. \square

00AK Proposition 3.2.4.1.2. Let $(X, x_0), (Y, y_0), (Z, z_0)$, and (A, a_0) be pointed sets.

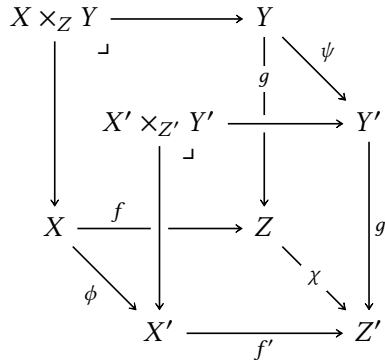
00AL 1. *Functoriality.* The assignment $(X, Y, Z, f, g) \mapsto X \times_{f,Z,g} Y$ defines a functor

$$-_1 \times_{-3} -_1 : \text{Fun}(\mathcal{P}, \text{Sets}_*) \rightarrow \text{Sets}_*,$$

where \mathcal{P} is the category that looks like this:



In particular, the action on morphisms of ${}_1 \times_{-3} -_1$ is given by sending a morphism



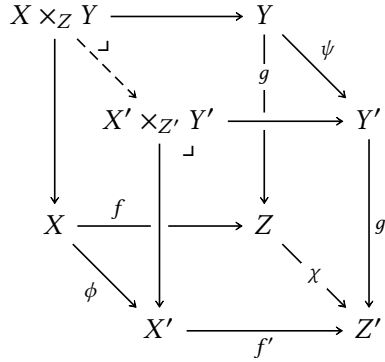
in $\text{Fun}(\mathcal{P}, \text{Sets}_*)$ to the morphism of pointed sets

$$\xi : (X \times_Z Y, (x_0, y_0)) \xrightarrow{\exists!} (X' \times_{Z'} Y', (x'_0, y'_0))$$

given by

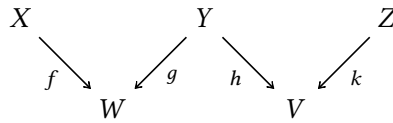
$$\xi(x, y) \stackrel{\text{def}}{=} (\phi(x), \psi(y))$$

for each $(x, y) \in X \times_Z Y$, which is the unique morphism of pointed sets making the diagram



commute.

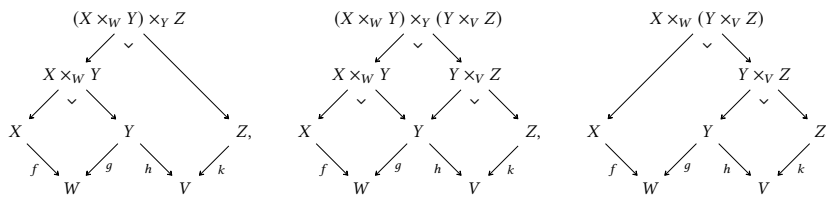
00AM 2. *Associativity.* Given a diagram



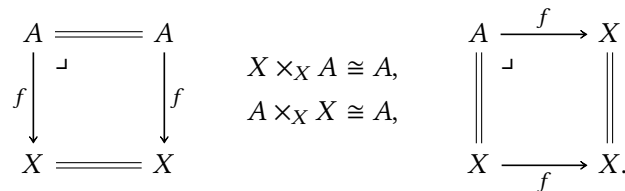
in \mathbf{Sets}_* , we have isomorphisms of pointed sets

$$(X \times_W Y) \times_V Z \cong (X \times_W Y) \times_Y (Y \times_V Z) \cong X \times_W (Y \times_V Z),$$

where these pullbacks are built as in the diagrams



00AN 3. *Unitality.* We have isomorphisms of pointed sets



00AP 4. *Commutativity.* We have an isomorphism of pointed sets

$$\begin{array}{ccc}
 A \times_X B & \longrightarrow & B \\
 \downarrow \lrcorner & & \downarrow g \\
 A & \xrightarrow{f} & X,
 \end{array}
 \quad
 A \times_X B \cong B \times_X A
 \quad
 \begin{array}{ccc}
 B \times_X A & \longrightarrow & A \\
 \downarrow \lrcorner & & \downarrow f \\
 B & \xrightarrow{g} & X.
 \end{array}$$

00AQ 5. *Interaction With Products.* We have an isomorphism of pointed sets

$$X \times_{\text{pt}} Y \cong X \times Y,
 \quad
 \begin{array}{ccc}
 X \times Y & \longrightarrow & Y \\
 \downarrow \lrcorner & & \downarrow !_Y \\
 X & \xrightarrow{!_X} & \text{pt}.
 \end{array}$$

00AR 6. *Symmetric Monoidality.* The triple $(\text{Sets}_*, \times_X, X)$ is a symmetric monoidal category.

Proof. Item 1, Functoriality: This is a special case of functoriality of co/limits, ?? of ??, with the explicit expression for ξ following from the commutativity of the cube pullback diagram.

Item 2, Associativity: This follows from *Item 2* of [Proposition 3.2.4.1.2](#).

Item 3, Unitality: This follows from *Item 3* of [Proposition 2.1.4.1.3](#).

Item 4, Commutativity: This follows from *Item 4* of [Proposition 2.1.4.1.3](#).

Item 5, Interaction With Products: This follows from *Item 6* of [Proposition 2.1.4.1.3](#).

Item 6, Symmetric Monoidality: This follows from *Item 7* of [Proposition 2.1.4.1.3](#).

□

00AS 3.2.5 Equalisers

Let $f, g: (X, x_0) \rightrightarrows (Y, y_0)$ be morphisms of pointed sets.

00AT **Definition 3.2.5.1.1.** The **equaliser of (f, g)** is the pair consisting of:

- *The Limit.* The pointed set $(\text{Eq}(f, g), x_0)$.
- *The Cone.* The morphism of pointed sets

$$\text{eq}(f, g): (\text{Eq}(f, g), x_0) \hookrightarrow (X, x_0)$$

given by the canonical inclusion $\text{eq}(f, g) \hookrightarrow \text{Eq}(f, g) \hookrightarrow X$.

Proof. We claim that $(\text{Eq}(f, g), x_0)$ is the categorical equaliser of f and g in Sets_* . First we need to check that the relevant equaliser diagram commutes, i.e. that we have

$$f \circ \text{eq}(f, g) = g \circ \text{eq}(f, g),$$

which indeed holds by the definition of the set $\text{Eq}(f, g)$. Next, we prove that $\text{Eq}(f, g)$ satisfies the universal property of the equaliser. Suppose we have a diagram of the form

$$\begin{array}{ccc} (\text{Eq}(f, g), x_0) & \xrightarrow{\text{eq}(f, g)} & (X, x_0) \xrightarrow[f]{g} (Y, y_0) \\ & \nearrow e & \\ (E, *) & & \end{array}$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (E, *) \rightarrow (\text{Eq}(f, g), x_0)$$

making the diagram

$$\begin{array}{ccc} (\text{Eq}(f, g), x_0) & \xrightarrow{\text{eq}(f, g)} & (X, x_0) \xrightarrow[f]{g} (Y, y_0) \\ \uparrow \phi \exists! & \nearrow e & \\ (E, *) & & \end{array}$$

commute, being uniquely determined by the condition

$$\text{eq}(f, g) \circ \phi = e$$

via

$$\phi(x) = e(x)$$

for each $x \in E$, where we note that $e(x) \in A$ indeed lies in $\text{Eq}(f, g)$ by the condition

$$f \circ e = g \circ e,$$

which gives

$$f(e(x)) = g(e(x))$$

for each $x \in E$, so that $e(x) \in \text{Eq}(f, g)$. Lastly, we note that ϕ is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \phi(*) &= e(*) \\ &= x_0, \end{aligned}$$

where we have used that e is a morphism of pointed sets. \square

00AU Proposition 3.2.5.1.2. Let (X, x_0) and (Y, y_0) be pointed sets and let $f, g, h: (X, x_0) \rightarrow (Y, y_0)$ be morphisms of pointed sets.

00AV 1. *Associativity.* We have isomorphisms of pointed sets

$$\underbrace{\text{Eq}(f \circ \text{eq}(g, h), g \circ \text{eq}(g, h))}_{=\text{Eq}(f \circ \text{eq}(g, h), h \circ \text{eq}(g, h))} \cong \text{Eq}(f, g, h) \cong \underbrace{\text{Eq}(f \circ \text{eq}(f, g), h \circ \text{eq}(f, g))}_{=\text{Eq}(g \circ \text{eq}(f, g), h \circ \text{eq}(f, g))},$$

where $\text{Eq}(f, g, h)$ is the limit of the diagram

$$(X, x_0) \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{-g} \\ \xrightarrow{h} \end{array} (Y, y_0)$$

in Sets_* , being explicitly given by

$$\text{Eq}(f, g, h) \cong \{a \in A \mid f(a) = g(a) = h(a)\}.$$

00AW 2. *Unitality.* We have an isomorphism of pointed sets

$$\text{Eq}(f, f) \cong X.$$

00AX 3. *Commutativity.* We have an isomorphism of pointed sets

$$\text{Eq}(f, g) \cong \text{Eq}(g, f).$$

Proof. **Item 1, Associativity:** This follows from **Item 1** of **Proposition 2.1.5.1.2.**

Item 2, Unitality: This follows from **Item 4** of **Proposition 2.1.5.1.2.**

Item 3, Commutativity: This follows from **Item 5** of **Proposition 2.1.5.1.2.** \square

00AY 3.3 Colimits of Pointed Sets

00AZ 3.3.1 The Initial Pointed Set

00B0 Definition 3.3.1.1.1. The **initial pointed set** is the pair $\left((\text{pt}, \star), \{\iota_X\}_{(X, x_0) \in \text{Obj}(\text{Sets}_*)} \right)$ consisting of:

- *The Limit.* The pointed set (pt, \star) .
- *The Cone.* The collection of morphisms of pointed sets

$$\{\iota_X : (\text{pt}, \star) \rightarrow (X, x_0)\}_{(X, x_0) \in \text{Obj}(\text{Sets})}$$

defined by

$$\iota_X(\star) \stackrel{\text{def}}{=} x_0.$$

Proof. We claim that (pt, \star) is the initial object of Sets_* . Indeed, suppose we have a diagram of the form

$$(\text{pt}, \star) \quad (X, x_0)$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (\text{pt}, \star) \rightarrow (X, x_0)$$

making the diagram

$$(\text{pt}, \star) \xrightarrow{\exists! \phi} (X, x_0)$$

commute, namely ι_X . □

00B1 3.3.2 Coproducts of Families of Pointed Sets

Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

00B2 **Definition 3.3.2.1.1.** The **coproduct of the family** $\{(X_i, x_0^i)\}_{i \in I}$, also called their **wedge sum**, is the pair consisting of:

- *The Colimit.* The pointed set $(\bigvee_{i \in I} X_i, p_0)$ consisting of:
 - *The Underlying Set.* The set $\bigvee_{i \in I} X_i$ defined by

$$\bigvee_{i \in I} X_i \stackrel{\text{def}}{=} \left(\coprod_{i \in I} X_i \right) / \sim,$$

where \sim is the equivalence relation on $\coprod_{i \in I} X_i$ given by declaring

$$(i, x_0^i) \sim (j, x_0^j)$$

for each $i, j \in I$.

- *The Basepoint.* The element p_0 of $\bigvee_{i \in I} X_i$ defined by

$$\begin{aligned} p_0 &\stackrel{\text{def}}{=} [(i, x_0^i)] \\ &= [(j, x_0^j)] \end{aligned}$$

for any $i, j \in I$.

- *The Cocone.* The collection

$$\left\{ \text{inj}_i: (X_i, x_0^i) \rightarrow \left(\bigvee_{i \in I} X_i, p_0 \right) \right\}_{i \in I}$$

of morphism of pointed sets given by

$$\text{inj}_i(x) \stackrel{\text{def}}{=} (i, x)$$

for each $x \in X_i$ and each $i \in I$.

Proof. We claim that $(\bigvee_{i \in I} X_i, p_0)$ is the categorical coproduct of $\{(X_i, x_0^i)\}_{i \in I}$ in Sets_* . Indeed, suppose we have, for each $i \in I$, a diagram of the form

$$\begin{array}{ccc} & & (C, *) \\ & \nearrow \iota_i & \\ (X_i, x_0^i) & \xrightarrow{\text{inj}_i} & \left(\bigvee_{i \in I} X_i, p_0 \right) \end{array}$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: \left(\bigvee_{i \in I} X_i, p_0 \right) \rightarrow (C, *)$$

making the diagram

$$\begin{array}{ccc} & & (C, *) \\ & \nearrow \iota_i & \uparrow \phi \exists! \\ (X_i, x_0^i) & \xrightarrow{\text{inj}_i} & \left(\bigvee_{i \in I} X_i, p_0 \right) \end{array}$$

commute, being uniquely determined by the condition $\phi \circ \text{inj}_i = \iota_i$ for each $i \in I$ via

$$\phi([(i, x)]) = \iota_i(x)$$

for each $[(i, x)] \in \bigvee_{i \in I} X_i$, where we note that ϕ is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \phi(p_0) &= \iota_i([(i, x_0^i)]) \\ &= *, \end{aligned}$$

as ι_i is a morphism of pointed sets. □

00B3 Proposition 3.3.2.1.2. Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

00B4 1. *Functoriality.* The assignment $\{(X_i, x_0^i)\}_{i \in I} \mapsto (\bigvee_{i \in I} X_i, p_0)$ defines a functor

$$\bigvee_{i \in I}: \text{Fun}(I_{\text{disc}}, \text{Sets}_*) \rightarrow \text{Sets}_*.$$

Proof. Item 1, Functoriality: This follows from ?? of ??. □

00B5 3.3.3 Coproducts

Let (X, x_0) and (Y, y_0) be pointed sets.

00B6 Definition 3.3.3.1.1. The **coproduct** of (X, x_0) and (Y, y_0) , also called their **wedge sum**, is the pair consisting of:

- *The Colimit.* The pointed set $(X \vee Y, p_0)$ consisting of:

- *The Underlying Set.* The set $X \vee Y$ defined by

$$\begin{aligned}
 (X \vee Y, p_0) &\stackrel{\text{def}}{=} (X, x_0) \amalg (Y, y_0) && \begin{array}{ccc} X \vee Y & \longleftarrow & Y \\ \uparrow \ulcorner & & \uparrow [y_0] \\ X & \xleftarrow{[x_0]} & \text{pt} \end{array} \\
 &\cong (X \amalg_{\text{pt}} Y, p_0) \\
 &\cong (X \amalg Y / \sim, p_0),
 \end{aligned}$$

where \sim is the equivalence relation on $X \amalg Y$ obtained by declaring $(0, x_0) \sim (1, y_0)$.

- *The Basepoint.* The element p_0 of $X \vee Y$ defined by

$$\begin{aligned}
 p_0 &\stackrel{\text{def}}{=} [(0, x_0)] \\
 &= [(1, y_0)].
 \end{aligned}$$

- *The Cocone.* The morphisms of pointed sets

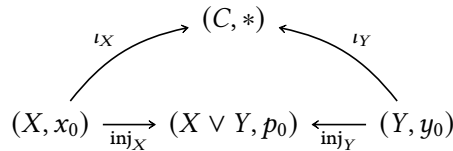
$$\begin{aligned}
 \text{inj}_1 &: (X, x_0) \rightarrow (X \vee Y, p_0), \\
 \text{inj}_2 &: (Y, y_0) \rightarrow (X \vee Y, p_0),
 \end{aligned}$$

given by

$$\begin{aligned}
 \text{inj}_1(x) &\stackrel{\text{def}}{=} [(0, x)], \\
 \text{inj}_2(y) &\stackrel{\text{def}}{=} [(1, y)],
 \end{aligned}$$

for each $x \in X$ and each $y \in Y$.

Proof. We claim that $(X \vee Y, p_0)$ is the categorical coproduct of (X, x_0) and (Y, y_0) in Sets_* . Indeed, suppose we have a diagram of the form



in \mathbf{Sets} . Then there exists a unique morphism of pointed sets

$$\phi: (X \vee Y, p_0) \rightarrow (C, *)$$

making the diagram

$$\begin{array}{ccccc} & & (C, *) & & \\ & \nearrow \iota_X & \uparrow \phi \uparrow \exists! & \nwarrow \iota_Y & \\ (X, x_0) & \xrightarrow{\text{inj}_X} & (X \vee Y, p_0) & \xleftarrow{\text{inj}_Y} & (Y, y_0) \end{array}$$

commute, being uniquely determined by the conditions

$$\begin{aligned} \phi \circ \text{inj}_X &= \iota_X, \\ \phi \circ \text{inj}_Y &= \iota_Y \end{aligned}$$

via

$$\phi(z) = \begin{cases} \iota_X(x) & \text{if } z = [(0, x)] \text{ with } x \in X, \\ \iota_Y(y) & \text{if } z = [(1, y)] \text{ with } y \in Y \end{cases}$$

for each $z \in X \vee Y$, where we note that ϕ is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \phi(p_0) &= \iota_X([(0, x_0)]) \\ &= \iota_Y([(1, y_0)]) \\ &= *, \end{aligned}$$

as ι_X and ι_Y are morphisms of pointed sets. \square

00B7 Proposition 3.3.3.1.2. Let (X, x_0) and (Y, y_0) be pointed sets.

00B8 1. *Functoriality.* The assignments

$$(X, x_0), (Y, y_0), ((X, x_0), (Y, y_0)) \mapsto (X \vee Y, p_0)$$

define functors

$$\begin{aligned} X \vee -: \mathbf{Sets}_* &\rightarrow \mathbf{Sets}_*, \\ - \vee Y: \mathbf{Sets}_* &\rightarrow \mathbf{Sets}_*, \\ -_1 \vee -_2: \mathbf{Sets}_* \times \mathbf{Sets}_* &\rightarrow \mathbf{Sets}_*. \end{aligned}$$

00B9 2. *Associativity.* We have an isomorphism of pointed sets

$$(X \vee Y) \vee Z \cong X \vee (Y \vee Z),$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \mathbf{Sets}_*$.

00BA 3. *Unitality.* We have isomorphisms of pointed sets

$$\begin{aligned} (\text{pt}, *) \vee (X, x_0) &\cong (X, x_0), \\ (X, x_0) \vee (\text{pt}, *) &\cong (X, x_0), \end{aligned}$$

natural in $(X, x_0) \in \text{Sets}_*$.

00BB 4. *Commutativity.* We have an isomorphism of pointed sets

$$X \vee Y \cong Y \vee X,$$

natural in $(X, x_0), (Y, y_0) \in \text{Sets}_*$.

00BC 5. *Symmetric Monoidality.* The triple $(\text{Sets}_*, \vee, \text{pt})$ is a symmetric monoidal category.

00BD 6. *The Fold Map.* We have a natural transformation

$$\nabla : \vee \circ \Delta_{\text{Sets}_*}^{\text{Cats}} \implies \text{id}_{\text{Sets}_*},$$

called the **fold map**, whose component

$$\nabla_X : X \vee X \rightarrow X$$

at X is given by

$$\nabla_X(p) \stackrel{\text{def}}{=} \begin{cases} x & \text{if } p = [(0, x)], \\ x & \text{if } p = [(1, x)] \end{cases}$$

for each $p \in X \vee X$.

Proof. Item 1, Functoriality: This follows from ?? of ??.

Item 2, Associativity: Clear.

Item 3, Unitality: Clear.

Item 4, Commutativity: Clear.

Item 5, Symmetric Monoidality: Omitted.

Item 6, The Fold Map: Naturality for the transformation ∇ is the statement that, given a morphism of pointed sets $f : (X, x_0) \rightarrow (Y, y_0)$, we have

$$\nabla_Y \circ (f \vee f) = f \circ \nabla_X,$$

Indeed, we have

$$\begin{aligned} [\nabla_Y \circ (f \vee f)]([(i, x)]) &= \nabla_Y([(i, f(x))]) \\ &= f(x) \\ &= f(\nabla_X([(i, x)])) \\ &= [f \circ \nabla_X]([(i, x)]) \end{aligned}$$

for each $[(i, x)] \in X \vee X$, and thus ∇ is indeed a natural transformation. \square

00BE 3.3.4 Pushouts

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets and let $f: (Z, z_0) \rightarrow (X, x_0)$ and $g: (Z, z_0) \rightarrow (Y, y_0)$ be morphisms of pointed sets.

00BF Definition 3.3.4.1.1. The **pushout of (X, x_0) and (Y, y_0) over (Z, z_0) along (f, g)** is the pair consisting of:

- *The Colimit.* The pointed set $(X \coprod_{f,Z,g} Y, p_0)$, where:
 - The set $X \coprod_{f,Z,g} Y$ is the pushout (of unpointed sets) of X and Y over Z with respect to f and g ;
 - We have $p_0 = [x_0] = [y_0]$.
- *The Cocone.* The morphisms of pointed sets

$$\begin{aligned} \text{inj}_1: (X, x_0) &\rightarrow (X \coprod_Z Y, p_0), \\ \text{inj}_2: (Y, y_0) &\rightarrow (X \coprod_Z Y, p_0) \end{aligned}$$

given by

$$\begin{aligned} \text{inj}_1(x) &\stackrel{\text{def}}{=} [(0, x)] \\ \text{inj}_2(y) &\stackrel{\text{def}}{=} [(1, y)] \end{aligned}$$

for each $x \in X$ and each $y \in Y$.

Proof. Firstly, we note that indeed $[x_0] = [y_0]$, as we have

$$\begin{aligned} x_0 &= f(z_0), \\ y_0 &= g(z_0) \end{aligned}$$

since f and g are morphisms of pointed sets, with the relation \sim on $X \coprod_Z Y$ then identifying $x_0 = f(z_0) \sim g(z_0) = y_0$.

We now claim that $(X \coprod_Z Y, p_0)$ is the categorical pushout of (X, x_0) and

(Y, y_0) over (Z, z_0) with respect to (f, g) in Sets_* . First we need to check that the relevant pushout diagram commutes, i.e. that we have

$$\text{inj}_1 \circ f = \text{inj}_2 \circ g, \quad \begin{array}{ccc} (X \amalg_Z Y, p_0) & \xleftarrow{\text{inj}_2} & (Y, y_0) \\ \text{inj}_1 \uparrow & & \uparrow g \\ (X, x_0) & \xleftarrow{f} & (Z, z_0). \end{array}$$

Indeed, given $z \in Z$, we have

$$\begin{aligned} [\text{inj}_1 \circ f](z) &= \text{inj}_1(f(z)) \\ &= [(0, f(z))] \\ &= [(1, g(z))] \\ &= \text{inj}_2(g(z)) \\ &= [\text{inj}_2 \circ g](z), \end{aligned}$$

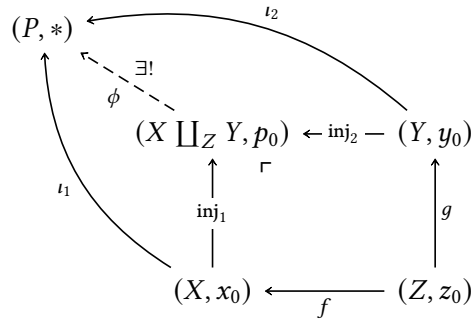
where $[(0, f(z))] = [(1, g(z))]$ by the definition of the relation \sim on $X \amalg Y$ (the coproduct of unpointed sets of X and Y). Next, we prove that $X \amalg_Z Y$ satisfies the universal property of the pushout. Suppose we have a diagram of the form

$$\begin{array}{ccc} (P, *) & \xleftarrow{t_2} & (Y, y_0) \\ & & \uparrow g \\ (X \amalg_Z Y, p_0) & \xleftarrow{\text{inj}_2} & (Y, y_0) \\ \uparrow \text{inj}_1 & \lrcorner & \uparrow g \\ (X, x_0) & \xleftarrow{f} & (Z, z_0) \end{array}$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (X \amalg_Z Y, p_0) \rightarrow (P, *)$$

making the diagram



commute, being uniquely determined by the conditions

$$\begin{aligned} \phi \circ \text{inj}_1 &= \iota_1, \\ \phi \circ \text{inj}_2 &= \iota_2 \end{aligned}$$

via

$$\phi(p) = \begin{cases} \iota_1(x) & \text{if } x = [(0, x)], \\ \iota_2(y) & \text{if } x = [(1, y)] \end{cases}$$

for each $p \in X \amalg_Z Y$, where the well-definedness of ϕ is proven in the same way as in the proof of **Definition 2.2.4.1.1**. Finally, we show that ϕ is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \phi(p_0) &= \phi([(0, x_0)]) \\ &= \iota_1(x_0) \\ &= *, \end{aligned}$$

or alternatively

$$\begin{aligned} \phi(p_0) &= \phi([(1, y_0)]) \\ &= \iota_2(y_0) \\ &= *, \end{aligned}$$

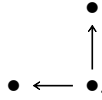
where we use that ι_1 (resp. ι_2) is a morphism of pointed sets. □

00BG Proposition 3.3.4.1.2. Let (X, x_0) , (Y, y_0) , (Z, z_0) , and (A, a_0) be pointed sets.

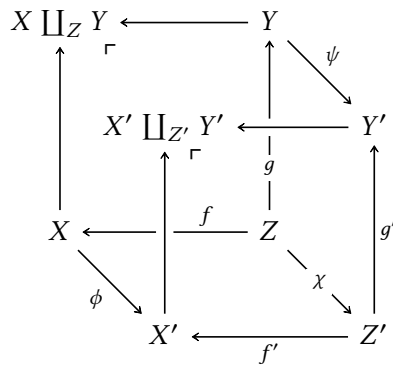
00BH 1. *Functoriality.* The assignment $(X, Y, Z, f, g) \mapsto X \amalg_{f,Z,g} Y$ defines a functor

$$-1 \amalg_{-3} -1: \text{Fun}(\mathcal{P}, \text{Sets}) \rightarrow \text{Sets}_*$$

where \mathcal{P} is the category that looks like this:



In particular, the action on morphisms of ${}_{-1} \coprod_{-3} {}_{-1}$ is given by sending a morphism



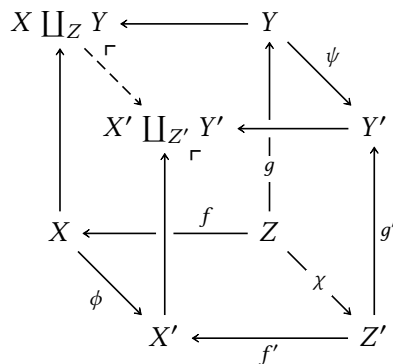
in $\text{Fun}(\mathcal{P}, \text{Sets}_*)$ to the morphism of pointed sets

$$\xi: (X \amalg_Z Y, p_0) \xrightarrow{\exists!} (X' \amalg_{Z'} Y', p'_0)$$

given by

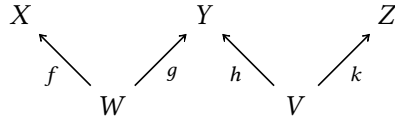
$$\xi(p) \stackrel{\text{def}}{=} \begin{cases} \phi(x) & \text{if } p = [(0, x)], \\ \psi(y) & \text{if } p = [(1, y)] \end{cases}$$

for each $p \in X \amalg_Z Y$, which is the unique morphism of pointed sets making the diagram



commute.

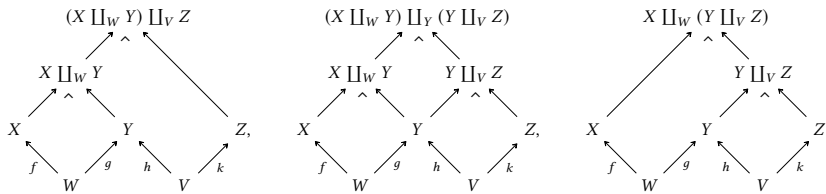
00BJ 2. *Associativity.* Given a diagram



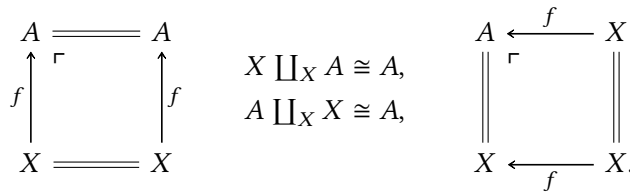
in Sets, we have isomorphisms of pointed sets

$$(X \amalg_W Y) \amalg_V Z \cong (X \amalg_W Y) \amalg_Y (Y \amalg_V Z) \cong X \amalg_W (Y \amalg_V Z),$$

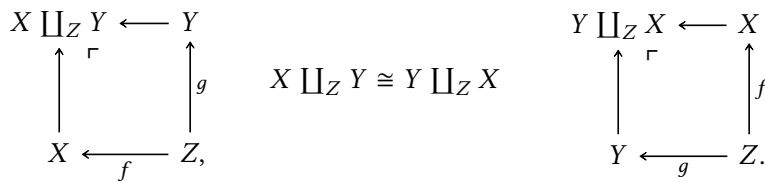
where these pullbacks are built as in the diagrams



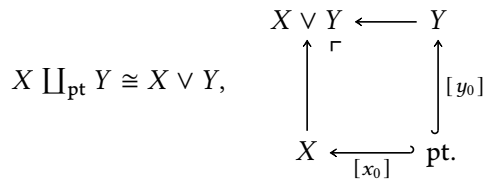
00BK 3. *Unitality.* We have isomorphisms of sets



00BL 4. *Commutativity.* We have an isomorphism of sets



00BM 5. *Interaction With Coproducts.* We have



00BN 6. *Symmetric Monoidality.* The triple $(\mathbf{Sets}_*, \coprod_X, (X, x_0))$ is a symmetric monoidal category.

Proof. Item 1, Functoriality: This is a special case of functoriality of co/limits, ?? of ??, with the explicit expression for ξ following from the commutativity of the cube pushout diagram.

Item 2, Associativity: This follows from **Item 2** of **Proposition 2.2.4.1.4**.

Item 3, Unitality: This follows from **Item 3** of **Proposition 2.2.4.1.4**.

Item 4, Commutativity: This follows from **Item 4** of **Proposition 2.2.4.1.4**.

Item 5, Interaction With Coproducts: Clear.

Item 6, Symmetric Monoidality: Omitted. \square

00BP 3.3.5 Coequalisers

Let $f, g: (X, x_0) \rightrightarrows (Y, y_0)$ be morphisms of pointed sets.

00BQ **Definition 3.3.5.1.1.** The **coequaliser** of (f, g) is the pointed set $(\mathbf{CoEq}(f, g), [y_0])$.

Proof. We claim that $(\mathbf{CoEq}(f, g), [y_0])$ is the categorical coequaliser of f and g in \mathbf{Sets}_* . First we need to check that the relevant coequaliser diagram commutes, i.e. that we have

$$\mathbf{coeq}(f, g) \circ f = \mathbf{coeq}(f, g) \circ g.$$

Indeed, we have

$$\begin{aligned} [\mathbf{coeq}(f, g) \circ f](x) &\stackrel{\text{def}}{=} [\mathbf{coeq}(f, g)](f(x)) \\ &\stackrel{\text{def}}{=} [f(x)] \\ &= [g(x)] \\ &\stackrel{\text{def}}{=} [\mathbf{coeq}(f, g)](g(x)) \\ &\stackrel{\text{def}}{=} [\mathbf{coeq}(f, g) \circ g](x) \end{aligned}$$

for each $x \in X$. Next, we prove that $\mathbf{CoEq}(f, g)$ satisfies the universal property of the coequaliser. Suppose we have a diagram of the form

$$\begin{array}{ccc} (X, x_0) & \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} & (Y, y_0) & \xrightarrow{\mathbf{coeq}(f, g)} & (\mathbf{CoEq}(f, g), [y_0]) \\ & & & \searrow c & \\ & & & & (C, *) \end{array}$$

in \mathbf{Sets} . Then, since $c(f(a)) = c(g(a))$ for each $a \in A$, it follows from **Items 4** and **5** of **Proposition 7.5.2.1.3** that there exists a unique map $\phi: \mathbf{CoEq}(f, g) \xrightarrow{\exists!}$

C making the diagram

$$\begin{array}{ccc}
 (X, x_0) & \xrightarrow[g]{f} & (Y, y_0) & \xrightarrow{\text{coeq}(f, g)} & (\text{CoEq}(f, g), [y_0]) \\
 & & \searrow c & & \downarrow \phi \exists! \\
 & & & & (C, *)
 \end{array}$$

commute, where we note that ϕ is indeed a morphism of pointed sets since

$$\begin{aligned}
 \phi([y_0]) &= [\phi \circ \text{coeq}(f, g)]([y_0]) \\
 &= c([y_0]) \\
 &= *,
 \end{aligned}$$

where we have used that c is a morphism of pointed sets. \square

00BR Proposition 3.3.5.1.2. Let (X, x_0) and (Y, y_0) be pointed sets and let $f, g, h: (X, x_0) \rightarrow (Y, y_0)$ be morphisms of pointed sets.

00BS 1. *Associativity.* We have isomorphisms of pointed sets

$$\underbrace{\text{CoEq}(\text{coeq}(f, g) \circ f, \text{coeq}(f, g) \circ h)}_{=\text{CoEq}(\text{coeq}(f, g) \circ g, \text{coeq}(f, g) \circ h)} \cong \text{CoEq}(f, g, h) \cong \underbrace{\text{CoEq}(\text{coeq}(g, h) \circ f, \text{coeq}(g, h) \circ g)}_{=\text{CoEq}(\text{coeq}(g, h) \circ f, \text{coeq}(g, h) \circ h)},$$

where $\text{CoEq}(f, g, h)$ is the colimit of the diagram

$$(X, x_0) \begin{array}{c} \xrightarrow{f} \\ \xrightarrow[g]{\cong} \\ \xrightarrow{h} \end{array} (Y, y_0)$$

in Sets_* .

00BT 2. *Unitality.* We have an isomorphism of pointed sets

$$\text{CoEq}(f, f) \cong B.$$

00BU 3. *Commutativity.* We have an isomorphism of pointed sets

$$\text{CoEq}(f, g) \cong \text{CoEq}(g, f).$$

Proof. **Item 1, Associativity:** This follows from **Item 1** of **Proposition 2.2.5.1.4.**

Item 2, Unitality: This follows from **Item 4** of **Proposition 2.2.5.1.4.**

Item 3, Commutativity: This follows from **Item 5** of **Proposition 2.2.5.1.4.** \square

00BV 3.4 Constructions With Pointed Sets

00BW 3.4.1 Free Pointed Sets

Let X be a set.

00BX Definition 3.4.1.1.1. The **free pointed set on X** is the pointed set X^+ consisting of:

- *The Underlying Set.* The set X^+ defined by¹¹

$$\begin{aligned} X^+ &\stackrel{\text{def}}{=} X \amalg \text{pt} \\ &\stackrel{\text{def}}{=} X \amalg \{\star\}. \end{aligned}$$

- *The Basepoint.* The element \star of X^+ .

00BY Proposition 3.4.1.1.2. Let X be a set.

00BZ 1. *Functoriality.* The assignment $X \mapsto X^+$ defines a functor

$$(-)^+ : \text{Sets} \rightarrow \text{Sets}_*,$$

where

- *Action on Objects.* For each $X \in \text{Obj}(\text{Sets})$, we have

$$[(-)^+](X) \stackrel{\text{def}}{=} X^+,$$

where X^+ is the pointed set of **Definition 3.4.1.1.1**;

- *Action on Morphisms.* For each morphism $f : X \rightarrow Y$ of Sets, the image

$$f^+ : X^+ \rightarrow Y^+$$

of f by $(-)^+$ is the map of pointed sets defined by

$$f^+(x) \stackrel{\text{def}}{=} \begin{cases} f(x) & \text{if } x \in X, \\ \star_Y & \text{if } x = \star_X. \end{cases}$$

00C0 2. *Adjointness.* We have an adjunction

$$((-)^+ \dashv \overset{\circlearrowleft}{\text{忘}}) : \text{Sets} \begin{array}{c} \xrightarrow{(-)^+} \\ \perp \\ \xleftarrow{\overset{\circlearrowleft}{\text{忘}}} \end{array} \text{Sets}_*,$$

¹¹*Further Notation:* We sometimes write \star_X for the basepoint of X^+ for clarity when there

witnessed by a bijection of sets

$$\text{Sets}_*((X^+, \star_X), (Y, y_0)) \cong \text{Sets}(X, Y),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $(Y, y_0) \in \text{Obj}(\text{Sets}_*)$.

- 00C1** 3. *Symmetric Strong Monoidality With Respect to Wedge Sums.* The free pointed set functor of **Item 1** has a symmetric strong monoidal structure

$$\left((-)^+, (-)^+, \amalg, (-)^+, \amalg \right): (\text{Sets}, \amalg, \emptyset) \rightarrow (\text{Sets}_*, \vee, \text{pt}),$$

being equipped with isomorphisms of pointed sets

$$\begin{aligned} (-)_{X,Y}^+, \amalg: X^+ \vee Y^+ &\xrightarrow{\cong} (X \amalg Y)^+, \\ (-)_{\mathbb{1}}^+, \amalg: \text{pt} &\xrightarrow{\cong} \emptyset^+, \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

- 00C2** 4. *Symmetric Strong Monoidality With Respect to Smash Products.* The free pointed set functor of **Item 1** has a symmetric strong monoidal structure

$$\left((-)^+, (-)^+, \times, (-)^+, \times \right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}_*, \wedge, S^0),$$

being equipped with isomorphisms of pointed sets

$$\begin{aligned} (-)_{X,Y}^+, \times: X^+ \wedge Y^+ &\xrightarrow{\cong} (X \times Y)^+, \\ (-)_{\mathbb{1}}^+, \times: S^0 &\xrightarrow{\cong} \text{pt}^+, \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness: We claim there's an adjunction $(-)^+ \dashv \overline{\text{Set}}$, witnessed by a bijection of sets

$$\text{Sets}_*((X^+, \star_X), (Y, y_0)) \cong \text{Sets}(X, Y),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $(Y, y_0) \in \text{Obj}(\text{Sets}_*)$.

are multiple free pointed sets involved in the current discussion.

- *Map I.* We define a map

$$\Phi_{X,Y}: \text{Sets}_*((X^+, \star_X), (Y, y_0)) \rightarrow \text{Sets}(X, Y)$$

by sending a pointed function

$$\xi: (X^+, \star_X) \rightarrow (Y, y_0)$$

to the function

$$\xi^\dagger: X \rightarrow Y$$

given by

$$\xi^\dagger(x) \stackrel{\text{def}}{=} \xi(x)$$

for each $x \in X$.

- *Map II.* We define a map

$$\Psi_{X,Y}: \text{Sets}(X, Y) \rightarrow \text{Sets}_*((X^+, \star_X), (Y, y_0))$$

given by sending a function $\xi: X \rightarrow Y$ to the pointed function

$$\xi^\dagger: (X^+, \star_X) \rightarrow (Y, y_0)$$

defined by

$$\xi^\dagger(x) \stackrel{\text{def}}{=} \begin{cases} \xi(x) & \text{if } x \in X, \\ y_0 & \text{if } x = \star_X \end{cases}$$

for each $x \in X^+$.

- *Invertibility I.* We claim that

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \text{id}_{\text{Sets}_*((X^+, \star_X), (Y, y_0))},$$

which is clear.

- *Invertibility II.* We claim that

$$\Phi_{X,Y} \circ \Psi_{X,Y} = \text{id}_{\text{Sets}(X, Y)},$$

which is clear.

- *Naturality for Φ , Part I.* We need to show that, given a pointed function $g: (Y, y_0) \rightarrow (Y', y'_0)$, the diagram

$$\begin{array}{ccc} \text{Sets}_*((X^+, \star_X), (Y, y_0)) & \xrightarrow{\Phi_{X,Y}} & \text{Sets}(X, Y) \\ g_* \downarrow & & \downarrow g_* \\ \text{Sets}_*((X^+, \star_X), (Y', y'_0)) & \xrightarrow{\Phi_{X,Y'}} & \text{Sets}(X, Y') \end{array}$$

commutes. Indeed, given a pointed function

$$\xi^\dagger: (X^+, \star_X) \rightarrow (Y, y_0)$$

we have

$$\begin{aligned} [\Phi_{X,Y'} \circ g_*](\xi) &= \Phi_{X,Y'}(g_*(\xi)) \\ &= \Phi_{X,Y'}(g \circ \xi) \\ &= g \circ \xi \\ &= g \circ \Phi_{X,Y'}(\xi) \\ &= g_*(\Phi_{X,Y'}(\xi)) \\ &= [g_* \circ \Phi_{X,Y'}](\xi). \end{aligned}$$

- *Naturality for Φ , Part II.* We need to show that, given a pointed function $f: (X, x_0) \rightarrow (X', x'_0)$, the diagram

$$\begin{array}{ccc} \text{Sets}_* \left((X'^+, \star_{X'}), (Y, y_0) \right) & \xrightarrow{\Phi_{X',Y}} & \text{Sets}(X', Y) \\ f_* \downarrow & & \downarrow f_* \\ \text{Sets}_* \left((X^+, \star_X), (Y, y_0) \right) & \xrightarrow{\Phi_{X,Y}} & \text{Sets}(X, Y) \end{array}$$

commutes. Indeed, given a function

$$\xi: X' \rightarrow Y,$$

we have

$$\begin{aligned} [\Phi_{X,Y} \circ f_*](\xi) &= \Phi_{X,Y}(f_*(\xi)) \\ &= \Phi_{X,Y}(\xi \circ f) \\ &= \xi \circ f \\ &= \Phi_{X',Y}(\xi) \circ f \\ &= f_*(\Phi_{X',Y}(\xi)) \\ &= f_* \circ \Phi_{X',Y}(\xi) \\ &= [f_* \circ \Phi_{X',Y}](\xi). \end{aligned}$$

- *Naturality for Ψ .* Since Φ is natural in each argument and Φ is a componentwise inverse to Ψ in each argument, it follows from [Item 2 of Proposition 8.8.6.1.2](#) that Ψ is also natural in each argument.

Item 3, Symmetric Strong Monoidality With Respect to Wedge Sums: The isomorphism

$$\phi: X^+ \vee Y^+ \xrightarrow{\cong} (X \amalg Y)^+$$

is given by

$$\phi(z) = \begin{cases} x & \text{if } z = [(0, x)] \text{ with } x \in X, \\ y & \text{if } z = [(1, y)] \text{ with } y \in Y, \\ \star_X \amalg Y & \text{if } z = [(0, \star_X)], \\ \star_X \amalg Y & \text{if } z = [(1, \star_Y)] \end{cases}$$

for each $z \in X^+ \vee Y^+$, with inverse

$$\phi^{-1}: (X \amalg Y)^+ \xrightarrow{\cong} X^+ \vee Y^+$$

given by

$$\phi^{-1}(z) \stackrel{\text{def}}{=} \begin{cases} [(0, x)] & \text{if } z = [(0, x)], \\ [(0, y)] & \text{if } z = [(1, y)], \\ p_0 & \text{if } z = \star_X \amalg Y \end{cases}$$

for each $z \in (X \amalg Y)^+$.

Meanwhile, the isomorphism $\text{pt} \cong \emptyset^+$ is given by sending \star_X to \star_\emptyset .

That these isomorphisms satisfy the coherence conditions making the functor $(-)^+$ symmetric strong monoidal can be directly checked element by element.

Item 4, Symmetric Strong Monoidality With Respect to Smash Products: The isomorphism

$$\phi: X^+ \wedge Y^+ \xrightarrow{\cong} (X \times Y)^+$$

is given by

$$\phi(x \wedge y) = \begin{cases} (x, y) & \text{if } x \neq \star_X \text{ and } y \neq \star_Y \\ \star_{X \times Y} & \text{otherwise} \end{cases}$$

for each $x \wedge y \in X^+ \wedge Y^+$, with inverse

$$\phi^{-1}: (X \times Y)^+ \xrightarrow{\cong} X^+ \wedge Y^+$$

given by

$$\phi^{-1}(z) \stackrel{\text{def}}{=} \begin{cases} x \wedge y & \text{if } z = (x, y) \text{ with } (x, y) \in X \times Y, \\ \star_X \wedge \star_Y & \text{if } z = \star_{X \times Y}, \end{cases}$$

for each $z \in (X \times Y)^+$.

Meanwhile, the isomorphism $S^0 \cong \text{pt}^+$ is given by sending \star to $1 \in S^0 = \{0, 1\}$ and \star_{pt} to $0 \in S^0$.

That these isomorphisms satisfy the coherence conditions making the functor $(-)^+$ symmetric strong monoidal can be directly checked element by element.

□

Appendices

3.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets

Relations

5. Relations

6. Constructions With Relations

7. Equivalence Relations and Apartness Relations

Category Theory

8. Categories

Bicategories

9. Types of Morphisms in Bicategories

Chapter 4

Tensor Products of Pointed Sets

00C3 In this chapter we introduce, construct, and study tensor products of pointed sets. The most well-known among these is the *smash product of pointed sets*

$$\wedge : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*,$$

introduced in [Section 4.5.1](#), defined via a universal property as inducing a bijection between the following data:

- Pointed maps $f : X \wedge Y \rightarrow Z$.
- Maps of sets $f : X \times Y \rightarrow Z$ satisfying

$$\begin{aligned} f(x_0, y) &= z_0, \\ f(x, y_0) &= z_0 \end{aligned}$$

for each $x \in X$ and each $y \in Y$.

As it turns out, however, dropping either of the *bilinearity* conditions

$$\begin{aligned} f(x_0, y) &= z_0, \\ f(x, y_0) &= z_0 \end{aligned}$$

while retaining the other leads to two other tensor products of pointed sets,

$$\begin{aligned} \triangleleft : \text{Sets}_* \times \text{Sets}_* &\rightarrow \text{Sets}_*, \\ \triangleright : \text{Sets}_* \times \text{Sets}_* &\rightarrow \text{Sets}_*, \end{aligned}$$

called the *left* and *right tensor products of pointed sets*. In contrast to \wedge , which turns out to endow Sets_* with a monoidal category structure ([Proposition 4.5.9.1.1](#)), these do not admit invertible associators and unitors, but do endow Sets_*

with the structure of a skew monoidal category, however ([Propositions 4.3.8.1.1](#) and [4.4.8.1.1](#)).

Finally, in addition to the tensor products \triangleleft , \triangleright , and \wedge , we also have a “tensor product” of the form

$$\odot : \mathbf{Sets} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*,$$

called the *tensor* of sets with pointed sets. All in all, these tensor products assemble into a family of functors of the form

$$\begin{aligned} \otimes_{k,\ell} : \mathbf{Mon}_{\mathbb{E}_k}(\mathbf{Sets}) \times \mathbf{Mon}_{\mathbb{E}_\ell}(\mathbf{Sets}) &\rightarrow \mathbf{Mon}_{\mathbb{E}_{k+\ell}}(\mathbf{Sets}), \\ \triangleleft_{i,k} : \mathbf{Mon}_{\mathbb{E}_k}(\mathbf{Sets}) \times \mathbf{Mon}_{\mathbb{E}_k}(\mathbf{Sets}) &\rightarrow \mathbf{Mon}_{\mathbb{E}_k}(\mathbf{Sets}), \\ \triangleright_{i,k} : \mathbf{Mon}_{\mathbb{E}_k}(\mathbf{Sets}) \times \mathbf{Mon}_{\mathbb{E}_k}(\mathbf{Sets}) &\rightarrow \mathbf{Mon}_{\mathbb{E}_k}(\mathbf{Sets}), \end{aligned}$$

where $k, \ell, i \in \mathbb{N}$ with $i \leq k - 1$. Together with the Cartesian product \times of Sets, the tensor products studied in this chapter form the cases:

- $(k, \ell) = (-1, -1)$ for the Cartesian product of Sets;
- $(k, \ell) = (0, -1)$ and $(-1, 0)$ for the tensor of sets with pointed sets of [Definition 4.2.1.1.1](#);
- $(i, k) = (-1, 0)$ for the left and right tensor products of pointed sets of [Sections 4.3](#) and [4.4](#);
- $(k, \ell) = (-1, -1)$ for the smash product of pointed sets of [Section 4.5](#).

In this chapter, we will carefully define and study bilinearity for pointed sets, as well as all the tensor products described above. Then, in [??](#), we will extend these to tensor products involving also monoids and commutative monoids, which will end up covering all cases up to $k, \ell \leq 2$, and hence *all* cases since \mathbb{E}_k -monoids on Sets are the same as \mathbb{E}_2 -monoids on Sets when $k \geq 2$.

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00C4 4.1 Bilinear Morphisms of Pointed Sets

00C5 4.1.1 Left Bilinear Morphisms of Pointed Sets

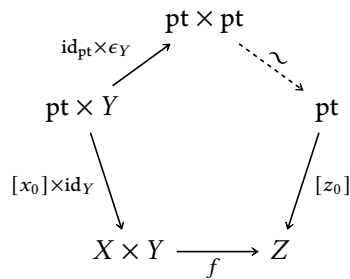
Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

00C6 Definition 4.1.1.1.1. A **left bilinear morphism of pointed sets from $(X \times Y, (x_0, y_0))$ to (Z, z_0)** is a map of sets

$$f: X \times Y \rightarrow Z$$

satisfying the following condition:^{1,2}

(★) *Left Unital Bilinearity.* The diagram



commutes, i.e. for each $y \in Y$, we have

$$f(x_0, y) = z_0.$$

00C7 Definition 4.1.1.1.2. The **set of left bilinear morphisms of pointed sets from $(X \times Y, (x_0, y_0))$ to (Z, z_0)** is the set $\text{Hom}_{\text{Sets}_*}^{\otimes, L}(X \times Y, Z)$ defined by

$$\text{Hom}_{\text{Sets}_*}^{\otimes, L}(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Hom}_{\text{Sets}}(X \times Y, Z) \mid f \text{ is left bilinear}\}.$$

¹Slogan: The map f is left bilinear if it preserves basepoints in its first argument.

²Succinctly, f is bilinear if we have

$$f(x_0, y) = z_0$$

00C8 4.1.2 Right Bilinear Morphisms of Pointed Sets

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

00C9 Definition 4.1.2.1.1. A **right bilinear morphism of pointed sets from $(X \times Y, (x_0, y_0))$ to (Z, z_0)** is a map of sets

$$f: X \times Y \rightarrow Z$$

satisfying the following condition:^{3,4}

(★) *Right Unital Bilinearity.* The diagram

$$\begin{array}{ccccc}
 & & \text{pt} \times \text{pt} & & \\
 & \nearrow^{\epsilon_X \times \text{id}_{\text{pt}}} & & \dashrightarrow^{\sim} & \\
 X \times \text{pt} & & & & \text{pt} \\
 \downarrow^{\text{id}_X \times [y_0]} & & & & \downarrow^{[z_0]} \\
 X \times Y & \xrightarrow{f} & Z & &
 \end{array}$$

commutes, i.e. for each $x \in X$, we have

$$f(x, y_0) = z_0.$$

00CA Definition 4.1.2.1.2. The **set of right bilinear morphisms of pointed sets from $(X \times Y, (x_0, y_0))$ to (Z, z_0)** is the set $\text{Hom}_{\text{Sets}_*}^{\otimes, \text{R}}(X \times Y, Z)$ defined by

$$\text{Hom}_{\text{Sets}_*}^{\otimes, \text{R}}(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Hom}_{\text{Sets}}(X \times Y, Z) \mid f \text{ is right bilinear}\}.$$

00CB 4.1.3 Bilinear Morphisms of Pointed Sets

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

00CC Definition 4.1.3.1.1. A **bilinear morphism of pointed sets from $(X \times Y, (x_0, y_0))$ to (Z, z_0)** is a map of sets

$$f: X \times Y \rightarrow Z$$

that is both left bilinear and right bilinear.

for each $y \in Y$.

³*Slogan:* The map f is right bilinear if it preserves basepoints in its second argument.

⁴Succinctly, f is bilinear if we have

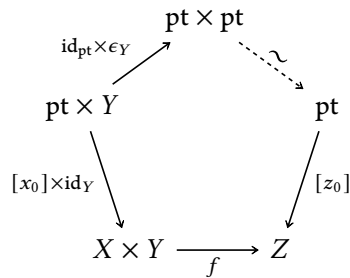
$$f(x, y_0) = z_0$$

00CD Remark 4.1.3.1.2. In detail, a **bilinear morphism of pointed sets from** $(X \times Y, (x_0, y_0))$ **to** (Z, z_0) is a map of sets

$$f: (X \times Y, (x_0, y_0)) \rightarrow (Z, z_0)$$

satisfying the following conditions:^{5,6}

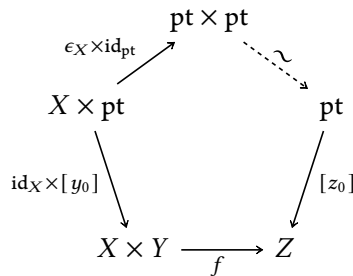
1. *Left Unital Bilinearity.* The diagram



commutes, i.e. for each $y \in Y$, we have

$$f(x_0, y) = z_0.$$

2. *Right Unital Bilinearity.* The diagram



commutes, i.e. for each $x \in X$, we have

$$f(x, y_0) = z_0.$$

00CE Definition 4.1.3.1.3. The **set of bilinear morphisms of pointed sets from** $(X \times Y, (x_0, y_0))$ **to** (Z, z_0) is the set $\text{Hom}_{\text{Sets}_*}^{\otimes}(X \times Y, Z)$ defined by

$$\text{Hom}_{\text{Sets}_*}^{\otimes}(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Hom}_{\text{Sets}}(X \times Y, Z) \mid f \text{ is bilinear}\}.$$

for each $x \in X$.

⁵*Slogan:* The map f is bilinear if it preserves basepoints in each argument.

⁶Succinctly, f is bilinear if we have

$$f(x_0, y) = z_0,$$

$$f(x, y_0) = z_0$$

00CF 4.2 Tensors and Cotensors of Pointed Sets by Sets**00CG 4.2.1 Tensors of Pointed Sets by Sets**

Let (X, x_0) be a pointed set and let A be a set.

00CH Definition 4.2.1.1.1. The **tensor of (X, x_0) by A** ⁷ is the pointed set⁸ $A \odot (X, x_0)$ satisfying the following universal property:

(UP) We have a bijection

$$\text{Sets}_*(A \odot X, K) \cong \text{Sets}(A, \text{Sets}_*(X, K)),$$

natural in $(K, k_0) \in \text{Obj}(\text{Sets}_*)$.

00CJ Remark 4.2.1.1.2. The universal property in **Definition 4.2.1.1.1** is equivalent to the following one:

(UP) We have a bijection

$$\text{Sets}_*(A \odot X, K) \cong \text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times X, K),$$

natural in $(K, k_0) \in \text{Obj}(\text{Sets}_*)$, where $\text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times X, K)$ is the set defined by

$$\text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times X, K) \stackrel{\text{def}}{=} \left\{ f \in \text{Sets}(A \times X, K) \left| \begin{array}{l} \text{for each } a \in A, \text{ we} \\ \text{have } f(a, x_0) = k_0 \end{array} \right. \right\}.$$

Proof. We claim we have a bijection

$$\text{Sets}(A, \text{Sets}_*(X, K)) \cong \text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times X, K)$$

natural in $(K, k_0) \in \text{Obj}(\text{Sets}_*)$. Indeed, this bijection is a restriction of the bijection

$$\text{Sets}(A, \text{Sets}(X, K)) \cong \text{Sets}(A \times X, K)$$

of **Item 2** of **Proposition 2.1.3.1.2**:

- A map

$$\begin{aligned} \xi: A &\longrightarrow \text{Sets}_*(X, K), \\ a &\longmapsto (\xi_a: X \rightarrow K), \end{aligned}$$

for each $x \in X$ and each $y \in Y$.

⁷*Further Terminology:* Also called the **copower of (X, x_0) by A** .

⁸*Further Notation:* Often written $A \odot X$ for simplicity.

in $\text{Sets}(A, \text{Sets}_*(X, K))$ gets sent to the map

$$\xi^\dagger : A \times X \rightarrow K$$

defined by

$$\xi^\dagger(a, x) \stackrel{\text{def}}{=} \xi_a(x)$$

for each $(a, x) \in A \times X$, which indeed lies in $\text{Sets}_{\mathbb{E}_0}^\otimes(A \times X, K)$, as we have

$$\begin{aligned} \xi^\dagger(a, x_0) &\stackrel{\text{def}}{=} \xi_a(x_0) \\ &\stackrel{\text{def}}{=} k_0 \end{aligned}$$

for each $a \in A$, where we have used that $\xi_a \in \text{Sets}_*(X, K)$ is a morphism of pointed sets.

- Conversely, a map

$$\xi : A \times X \rightarrow K$$

in $\text{Sets}_{\mathbb{E}_0}^\otimes(A \times X, K)$ gets sent to the map

$$\begin{aligned} \xi^\dagger : A &\rightarrow \text{Sets}_*(X, K), \\ a &\mapsto \left(\xi_a^\dagger : X \rightarrow K \right), \end{aligned}$$

where

$$\xi_a^\dagger : X \rightarrow K$$

is the map defined by

$$\xi_a^\dagger(x) \stackrel{\text{def}}{=} \xi(a, x)$$

for each $x \in X$, and indeed lies in $\text{Sets}_*(X, K)$, as we have

$$\begin{aligned} \xi_a^\dagger(x_0) &\stackrel{\text{def}}{=} \xi(a, x_0) \\ &\stackrel{\text{def}}{=} k_0. \end{aligned}$$

This finishes the proof. □

00CK Construction 4.2.1.1.3. Concretely, the **tensor of (X, x_0) by A** is the pointed set $A \odot (X, x_0)$ consisting of:

- *The Underlying Set.* The set $A \odot X$ given by

$$A \odot X \cong \bigvee_{a \in A} (X, x_0),$$

where $\bigvee_{a \in A} (X, x_0)$ is the wedge product of the A -indexed family $((X, x_0))_{a \in A}$ of **Definition 3.3.2.1.1**.

- *The Basepoint.* The point $[(a, x_0)] = [(a', x_0)]$ of $\bigvee_{a \in A} (X, x_0)$.

Proof. (Proven below in a bit.) □

00CL Notation 4.2.1.1.4. We write $a \odot x$ for the element $[(a, x)]$ of

$$\begin{aligned} A \odot X &\cong \bigvee_{a \in A} (X, x_0) \\ &\stackrel{\text{def}}{=} \left(\prod_{i \in I} X_i \right) / \sim. \end{aligned}$$

00CM Remark 4.2.1.1.5. Taking the tensor of any element of A with the basepoint x_0 of X leads to the same element in $A \odot X$, i.e. we have

$$a \odot x_0 = a' \odot x_0,$$

for each $a, a' \in A$. This is due to the equivalence relation \sim on

$$\bigvee_{a \in A} (X, x_0) \stackrel{\text{def}}{=} \prod_{a \in A} X / \sim$$

identifying (a, x_0) with (a', x_0) , so that the equivalence class $a \odot x_0$ is independent from the choice of $a \in A$.

Proof. We claim we have a bijection

$$\text{Sets}_*(A \odot X, K) \cong \text{Sets}(A, \text{Sets}_*(X, K))$$

natural in $(K, k_0) \in \text{Obj}(\text{Sets}_*)$.

- *Map I.* We define a map

$$\Phi_K : \text{Sets}_*(A \odot X, K) \rightarrow \text{Sets}(A, \text{Sets}_*(X, K))$$

by sending a morphism of pointed sets

$$\xi : (A \odot X, a \odot x_0) \rightarrow (K, k_0)$$

to the map of sets

$$\begin{aligned}\xi^\dagger : A &\longrightarrow \text{Sets}_*(X, K), \\ a &\longmapsto (\xi_a : X \rightarrow K),\end{aligned}$$

where

$$\xi_a : (X, x_0) \rightarrow (K, k_0)$$

is the morphism of pointed sets defined by

$$\xi_a(x) \stackrel{\text{def}}{=} \xi(a \odot x)$$

for each $x \in X$. Note that we have

$$\begin{aligned}\xi_a(x_0) &\stackrel{\text{def}}{=} \xi(a \odot x_0) \\ &= k_0,\end{aligned}$$

so that ξ_a is indeed a morphism of pointed sets, where we have used that ξ is a morphism of pointed sets.

- *Map II.* We define a map

$$\Psi_K : \text{Sets}(A, \text{Sets}_*(X, K)) \rightarrow \text{Sets}_*(A \odot X, K)$$

given by sending a map

$$\begin{aligned}\zeta : A &\longrightarrow \text{Sets}_*(X, K), \\ a &\longmapsto (\zeta_a : X \rightarrow K),\end{aligned}$$

to the morphism of pointed sets

$$\xi^\dagger : (A \odot X, a \odot x_0) \rightarrow (K, k_0)$$

defined by

$$\xi^\dagger(a \odot x) \stackrel{\text{def}}{=} \zeta_a(x)$$

for each $a \odot x \in A \odot X$. Note that ξ^\dagger is indeed a morphism of pointed sets, as we have

$$\begin{aligned}\xi^\dagger(a \odot x_0) &\stackrel{\text{def}}{=} \zeta_a(x_0) \\ &= k_0,\end{aligned}$$

where we have used that $\zeta(a) \in \text{Sets}_*(X, K)$ is a morphism of pointed sets.

- *Invertibility I.* We claim that

$$\Psi_K \circ \Phi_K = \text{id}_{\text{Sets}_*(A \odot X, K)}.$$

Indeed, given a morphism of pointed sets

$$\xi: (A \odot X, a \odot x_0) \rightarrow (K, k_0),$$

we have

$$\begin{aligned} [\Psi_K \circ \Phi_K](\xi) &= \Psi_K(\Phi_K(\xi)) \\ &= \Psi_K(\llbracket a \mapsto \llbracket x \mapsto \xi(a \odot x) \rrbracket \rrbracket) \\ &= \Psi_K(\llbracket a' \mapsto \llbracket x' \mapsto \xi(a' \odot x') \rrbracket \rrbracket) \\ &= \llbracket a \odot x \mapsto \text{ev}_x(\text{ev}_a(\llbracket a' \mapsto \llbracket x' \mapsto \xi(a' \odot x') \rrbracket \rrbracket)) \rrbracket \\ &= \llbracket a \odot x \mapsto \text{ev}_x(\llbracket x' \mapsto \xi(a \odot x') \rrbracket) \rrbracket \\ &= \llbracket a \odot x \mapsto \xi(a \odot x) \rrbracket \\ &= \xi. \end{aligned}$$

- *Invertibility II.* We claim that

$$\Phi_K \circ \Psi_K = \text{id}_{\text{Sets}(A, \text{Sets}_*(X, K))}.$$

Indeed, given a morphism $\xi: A \rightarrow \text{Sets}_*(X, K)$, we have

$$\begin{aligned} [\Phi_K \circ \Psi_K](\xi) &= \Phi_K(\Psi_K(\xi)) \\ &= \Phi_K(\llbracket a \odot x \mapsto \xi_a(x) \rrbracket) \\ &= \llbracket a \mapsto \llbracket x \mapsto \xi_a(x) \rrbracket \rrbracket \\ &= \llbracket a \mapsto \xi(a) \rrbracket \\ &= \xi. \end{aligned}$$

- *Naturality of Φ .* We need to show that, given a morphism of pointed sets

$$\phi: (K, k_0) \rightarrow (K', k'_0),$$

the diagram

$$\begin{array}{ccc} \text{Sets}_*(A \odot X, K) & \xrightarrow{\Phi_K} & \text{Sets}(A, \text{Sets}_*(X, K)) \\ \phi_* \downarrow & & \downarrow (\phi_*)_* \\ \text{Sets}_*(A \odot X, K') & \xrightarrow{\Phi_{K'}} & \text{Sets}(A, \text{Sets}_*(X, K')) \end{array}$$

commutes. Indeed, given a morphism of pointed sets

$$\xi: (A \odot X, a \odot x_0) \rightarrow (K, k_0),$$

we have

$$\begin{aligned} [\Phi_{K'} \circ \phi_*](\xi) &= \Phi_{K'}(\phi_*(\xi)) \\ &= \Phi_{K'}(\phi \circ \xi) \\ &= (\phi \circ \xi)^\dagger \\ &= \llbracket a \mapsto \phi \circ \xi(a \odot -) \rrbracket \\ &= \llbracket a \mapsto \phi_*(\xi(a \odot -)) \rrbracket \\ &= (\phi_*)_* (\llbracket a \mapsto \xi(a \odot -) \rrbracket) \\ &= (\phi_*)_*(\Phi_K(\xi)) \\ &= [(\phi_*)_* \circ \Phi_K](\xi). \end{aligned}$$

- *Naturality of Ψ .* Since Φ is natural and Φ is a componentwise inverse to Ψ , it follows from **Item 2** of **Proposition 8.8.6.1.2** that Ψ is also natural.

This finishes the proof. \square

00CN Proposition 4.2.1.1.6. Let (X, x_0) be a pointed set and let A be a set.

- 00CP** 1. *Functoriality.* The assignments $A, (X, x_0), (A, (X, x_0))$ define functors

$$\begin{aligned} A \odot - &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ - \odot X &: \mathbf{Sets} \rightarrow \mathbf{Sets}_*, \\ -_1 \odot -_2 &: \mathbf{Sets} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*. \end{aligned}$$

In particular, given:

- A map of sets $f: A \rightarrow B$;
- A pointed map $\phi: (X, x_0) \rightarrow (Y, y_0)$;

the induced map

$$f \odot \phi: A \odot X \rightarrow B \odot Y$$

is given by

$$[f \odot \phi](a \odot x) \stackrel{\text{def}}{=} f(a) \odot \phi(x)$$

for each $a \odot x \in A \odot X$.

00CQ 2. *Adjointness I.* We have an adjunction

$$(- \odot X \dashv \text{Sets}_*(X, -)): \text{Sets} \begin{array}{c} \xrightarrow{- \odot X} \\ \perp \\ \xleftarrow{\text{Sets}_*(X, -)} \end{array} \text{Sets}_*$$

witnessed by a bijection

$$\text{Sets}_*(A \odot X, K) \cong \text{Sets}(A, \text{Sets}_*(X, K)),$$

natural in $A \in \text{Obj}(\text{Sets})$ and $X, Y \in \text{Obj}(\text{Sets}_*)$.

00CR 3. *Adjointness II.* We have an adjunctions

$$(A \odot - \dashv A \pitchfork -): \text{Sets}_* \begin{array}{c} \xrightarrow{A \odot -} \\ \perp \\ \xleftarrow{A \pitchfork -} \end{array} \text{Sets}_*$$

witnessed by a bijection

$$\text{Hom}_{\text{Sets}_*}(A \odot X, Y) \cong \text{Hom}_{\text{Sets}_*}(X, A \pitchfork Y),$$

natural in $A \in \text{Obj}(\text{Sets})$ and $X, Y \in \text{Obj}(\text{Sets}_*)$.

00CS 4. *As a Weighted Colimit.* We have

$$A \odot X \cong \text{colim}^{[A]}(X),$$

where in the right hand side we write:

- A for the functor $A: \text{pt} \rightarrow \text{Sets}$ picking $A \in \text{Obj}(\text{Sets})$;
- X for the functor $X: \text{pt} \rightarrow \text{Sets}_*$ picking $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

00CT 5. *Iterated Tensors.* We have an isomorphism of pointed sets

$$A \odot (B \odot X) \cong (A \times B) \odot X,$$

natural in $A, B \in \text{Obj}(\text{Sets})$ and $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

00CU 6. *Interaction With Homs.* We have a natural isomorphism

$$\text{Sets}_*(A \odot X, -) \cong A \pitchfork \text{Sets}_*(X, -).$$

00CV 7. *The Tensor Evaluation Map.* For each $X, Y \in \text{Obj}(\text{Sets}_*)$, we have a map

$$\text{ev}_{X,Y}^\odot: \text{Sets}_*(X, Y) \odot X \rightarrow Y,$$

natural in $X, Y \in \text{Obj}(\text{Sets}_*)$, and given by

$$\text{ev}_{X,Y}^\odot(f \odot x) \stackrel{\text{def}}{=} f(x)$$

for each $f \odot x \in \text{Sets}_*(X, Y) \odot X$.

- 00CW** 8. *The Tensor Coevaluation Map.* For each $A \in \text{Obj}(\text{Sets})$ and each $X \in \text{Obj}(\text{Sets}_*)$, we have a map

$$\text{coev}_{A,X}^{\circlearrowleft}: A \rightarrow \text{Sets}_*(X, A \odot X),$$

natural in $A \in \text{Obj}(\text{Sets})$ and $X \in \text{Obj}(\text{Sets}_*)$, and given by

$$\text{coev}_{A,X}^{\circlearrowleft}(a) \stackrel{\text{def}}{=} \llbracket x \mapsto a \odot x \rrbracket$$

for each $a \in A$.

Proof. Item 1, Functoriality: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 2, Adjointness I: This is simply a rephrasing of [Definition 4.2.1.1.1](#).

Item 3, : Adjointness II: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 4, As a Weighted Colimit: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 5, Iterated Tensors: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 6, Interaction With Homs: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 7, The Tensor Evaluation Map: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 8, The Tensor Coevaluation Map: This is the special case of ?? of ?? for when $C = \text{Sets}_*$. \square

00CX 4.2.2 Cotensors of Pointed Sets by Sets

Let (X, x_0) be a pointed set and let A be a set.

- 00CY** **Definition 4.2.2.1.1.** The **cotensor of (X, x_0) by A** ⁹ is the pointed set¹⁰ $A \pitchfork (X, x_0)$ satisfying the following universal property:

(UP) We have a bijection

$$\text{Sets}_*(K, A \pitchfork X) \cong \text{Sets}(A, \text{Sets}_*(K, X)),$$

natural in $(K, k_0) \in \text{Obj}(\text{Sets}_*)$.

- 00CZ** **Remark 4.2.2.1.2.** The universal property of [Definition 4.2.2.1.1](#) is equivalent to the following one:

⁹*Further Terminology:* Also called the **power of (X, x_0) by A** .

¹⁰*Further Notation:* Often written $A \pitchfork X$ for simplicity.

(UP) We have a bijection

$$\mathbf{Sets}_*(K, A \pitchfork X) \cong \mathbf{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X),$$

natural in $(K, k_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$, where $\mathbf{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X)$ is the set defined by

$$\mathbf{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X) \stackrel{\text{def}}{=} \left\{ f \in \mathbf{Sets}(A \times K, X) \left| \begin{array}{l} \text{for each } a \in A, \text{ we} \\ \text{have } f(a, k_0) = x_0 \end{array} \right. \right\}.$$

Proof. This follows from the bijection

$$\mathbf{Sets}(A, \mathbf{Sets}_*(K, X)) \cong \mathbf{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X),$$

natural in $(K, k_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$ constructed in the proof of [Remark 4.2.1.1.2.](#)

□

00D0 Construction 4.2.2.1.3. Concretely, the **cotensor of (X, x_0) by A** is the pointed set $A \pitchfork (X, x_0)$ consisting of:

- *The Underlying Set.* The set $A \pitchfork X$ given by

$$A \pitchfork X \cong \bigwedge_{a \in A} (X, x_0),$$

where $\bigwedge_{a \in A} (X, x_0)$ is the smash product of the A -indexed family $((X, x_0))_{a \in A}$ of [Definition 4.6.1.1.1.](#)

- *The Basepoint.* The point $[(x_0)_{a \in A}] = [(x_0, x_0, x_0, \dots)]$ of $\bigwedge_{a \in A} (X, x_0)$.

Proof. We claim we have a bijection

$$\mathbf{Sets}_*(K, A \pitchfork X) \cong \mathbf{Sets}(A, \mathbf{Sets}_*(K, X)),$$

natural in $(K, k_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$.

- *Map I.* We define a map

$$\Phi_K: \mathbf{Sets}_*(K, A \pitchfork X) \rightarrow \mathbf{Sets}(A, \mathbf{Sets}_*(K, X)),$$

by sending a morphism of pointed sets

$$\xi: (K, k_0) \rightarrow (A \pitchfork X, [(x_0)_{a \in A}])$$

to the map of sets

$$\begin{aligned} \xi^\dagger: A &\rightarrow \mathbf{Sets}_*(K, X), \\ a &\mapsto (\xi_a: K \rightarrow X), \end{aligned}$$

where

$$\xi_a: (K, k_0) \rightarrow (X, x_0)$$

is the morphism of pointed sets defined by

$$\xi_a(k) = \begin{cases} x_a^k & \text{if } \xi(k) \neq [(x_0)_{a \in A}], \\ x_0 & \text{if } \xi(k) = [(x_0)_{a \in A}] \end{cases}$$

for each $k \in K$, where x_a^k is the a th component of $\xi(k) = [(x_a^k)_{a \in A}]$. Note that:

1. The definition of $\xi_a(k)$ is independent of the choice of equivalence class. Indeed, suppose we have

$$\begin{aligned} \xi(k) &= \left[(x_a^k)_{a \in A} \right] \\ &= \left[(y_a^k)_{a \in A} \right] \end{aligned}$$

with $x_a^k \neq y_a^k$ for some $a \in A$. Then there exist $a_x, a_y \in A$ such that $x_{a_x}^k = y_{a_y}^k = x_0$. The equivalence relation \sim on $\prod_{a \in A} X$ then forces

$$\begin{aligned} \left[(x_a^k)_{a \in A} \right] &= [(x_0)_{a \in A}], \\ \left[(y_a^k)_{a \in A} \right] &= [(x_0)_{a \in A}], \end{aligned}$$

however, and $\xi_a(k)$ is defined to be x_0 in this case.

2. The map ξ_a is indeed a morphism of pointed sets, as we have

$$\xi_a(k_0) = x_0$$

since $\xi(k_0) = [(x_0)_{a \in A}]$ as ξ is a morphism of pointed sets and $\xi_a(k_0)$, defined to be the a th component of $[(x_0)_{a \in A}]$, is equal to x_0 .

- *Map II.* We define a map

$$\Psi_K: \text{Sets}(A, \text{Sets}_*(K, X)) \rightarrow \text{Sets}_*(K, A \pitchfork X),$$

given by sending a map

$$\begin{aligned} \xi: A &\rightarrow \text{Sets}_*(K, X), \\ a &\mapsto (\xi_a: K \rightarrow X), \end{aligned}$$

to the morphism of pointed sets

$$\xi^\dagger : (K, k_0) \rightarrow (A \pitchfork X, [(x_0)_{a \in A}])$$

defined by

$$\xi^\dagger(k) \stackrel{\text{def}}{=} [(\xi_a(k))_{a \in A}]$$

for each $k \in K$. Note that ξ^\dagger is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \xi^\dagger(k_0) &\stackrel{\text{def}}{=} [(\xi_a(k_0))_{a \in A}] \\ &= x_0, \end{aligned}$$

where we have used that $\xi_a \in \text{Sets}_*(K, X)$ is a morphism of pointed sets for each $a \in A$.

- *Naturality of Ψ .* We need to show that, given a morphism of pointed sets

$$\phi : (K, k_0) \rightarrow (K', k'_0),$$

the diagram

$$\begin{array}{ccc} \text{Sets}(A, \text{Sets}_*(K', X)) & \xrightarrow{\Psi_{K'}} & \text{Sets}_*(K', A \pitchfork X) \\ (\phi^*)_* \downarrow & & \downarrow \phi^* \\ \text{Sets}(A, \text{Sets}_*(K, X)) & \xrightarrow{\Psi_K} & \text{Sets}_*(K, A \pitchfork X) \end{array}$$

commutes. Indeed, given a map of sets

$$\begin{aligned} \xi : A &\rightarrow \text{Sets}_*(K', X), \\ a &\mapsto (\xi_a : K' \rightarrow X), \end{aligned}$$

we have

$$\begin{aligned} [\Psi_K \circ (\phi^*)_*](\xi) &= \Psi_K((\phi^*)_*(\xi)) \\ &= \Psi_K((\phi^*)_*([a \mapsto \xi_a])) \\ &= \Psi_K([a \mapsto \phi^*(\xi_a)]) \\ &= \Psi_K([a \mapsto [k \mapsto \xi_a(\phi(k))]]) \\ &= [k \mapsto [(\xi_a(\phi(k)))_{a \in A}]] \\ &= \phi^*([k' \mapsto [(\xi_a(k'))_{a \in A}]]) \\ &= \phi^*(\Psi_{K'}(\xi)) \\ &= [\phi^* \circ \Psi_{K'}](\xi). \end{aligned}$$

- *Naturality of Φ* . Since Ψ is natural and Ψ is a componentwise inverse to Φ , it follows from **Item 2** of **Proposition 8.8.6.1.2** that Φ is also natural.
- *Invertibility I*. We claim that

$$\Psi_K \circ \Phi_K = \text{id}_{\text{Sets}_*(K, A \pitchfork X)}.$$

Indeed, given a morphism of pointed sets

$$\xi: (K, k_0) \rightarrow (A \pitchfork X, [(x_0)_{a \in A}])$$

we have

$$\begin{aligned} [\Psi_K \circ \Phi_K](\xi) &= \Psi_K(\Phi_K(\xi)) \\ &= \Psi_K(\llbracket a \mapsto \xi_a \rrbracket) \\ &= \Psi_K(\llbracket a' \mapsto \xi_{a'} \rrbracket) \\ &= \llbracket k \mapsto [(\text{ev}_a(\llbracket a' \mapsto \xi_{a'}(k) \rrbracket))_{a \in A}] \rrbracket \\ &= \llbracket k \mapsto [(\xi_a(k))_{a \in A}] \rrbracket. \end{aligned}$$

Now, we have two cases:

1. If $\xi(k) = [(x_0)_{a \in A}]$, we have

$$\begin{aligned} [\Psi_K \circ \Phi_K](\xi) &= \dots \\ &= \llbracket k \mapsto [(\xi_a(k))_{a \in A}] \rrbracket \\ &= \llbracket k \mapsto [(x_0)_{a \in A}] \rrbracket \\ &= \llbracket k \mapsto \xi(k) \rrbracket \\ &= \xi. \end{aligned}$$

2. If $\xi(k) \neq [(x_0)_{a \in A}]$ and $\xi(k) = [(x_a^k)_{a \in A}]$ instead, we have

$$\begin{aligned} [\Psi_K \circ \Phi_K](\xi) &= \dots \\ &= \llbracket k \mapsto [(\xi_a(k))_{a \in A}] \rrbracket \\ &= \llbracket k \mapsto [(x_a^k)_{a \in A}] \rrbracket \\ &= \llbracket k \mapsto \xi(k) \rrbracket \\ &= \xi. \end{aligned}$$

In both cases, we have $[\Psi_K \circ \Phi_K](\xi) = \xi$, and thus we are done.

- *Invertibility II.* We claim that

$$\Phi_K \circ \Psi_K = \text{id}_{\text{Sets}(A, \text{Sets}_*(K, X))}.$$

Indeed, given a morphism $\xi: A \rightarrow \text{Sets}_*(K, X)$, we have

$$\begin{aligned} [\Phi_K \circ \Psi_K](\xi) &= \Phi_K(\Psi_K(\xi)) \\ &= \Phi_K(\llbracket k \mapsto [(\xi_a(k))_{a \in A}] \rrbracket) \\ &= \llbracket a \mapsto \llbracket k \mapsto \xi_a(k) \rrbracket \rrbracket \\ &= \xi \end{aligned}$$

This finishes the proof. \square

00D1 Proposition 4.2.2.1.4. Let (X, x_0) be a pointed set and let A be a set.

00D2 1. *Functoriality.* The assignments $A, (X, x_0), (A, (X, x_0))$ define functors

$$\begin{aligned} A \pitchfork - &: \text{Sets}_* \rightarrow \text{Sets}_*, \\ - \pitchfork X &: \text{Sets}^{\text{op}} \rightarrow \text{Sets}_*, \\ -_1 \pitchfork -_2 &: \text{Sets}^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*. \end{aligned}$$

In particular, given:

- A map of sets $f: A \rightarrow B$;
- A pointed map $\phi: (X, x_0) \rightarrow (Y, y_0)$;

the induced map

$$f \odot \phi: A \pitchfork X \rightarrow B \pitchfork Y$$

is given by

$$[f \odot \phi](\llbracket (x_a)_{a \in A} \rrbracket) \stackrel{\text{def}}{=} \llbracket (\phi(x_{f(a)}))_{a \in A} \rrbracket$$

for each $\llbracket (x_a)_{a \in A} \rrbracket \in A \pitchfork X$.

00D3 2. *Adjointness I.* We have an adjunction

$$(- \pitchfork X \dashv \text{Sets}_*(-, X)): \text{Sets}^{\text{op}} \begin{array}{c} \xrightarrow{- \pitchfork X} \\ \perp \\ \xleftarrow{\text{Sets}_*(-, X)} \end{array} \text{Sets}_*,$$

witnessed by a bijection

$$\text{Sets}_*^{\text{op}}(A \pitchfork X, K) \cong \text{Sets}(A, \text{Sets}_*(K, X)),$$

i.e. by a bijection

$$\text{Sets}_*(K, A \pitchfork X) \cong \text{Sets}(A, \text{Sets}_*(K, X)),$$

natural in $A \in \text{Obj}(\text{Sets})$ and $X, Y \in \text{Obj}(\text{Sets}_*)$.

00D4 3. *Adjointness II.* We have an adjunctions

$$(A \odot - \dashv A \pitchfork -): \text{Sets}_* \begin{array}{c} \xrightarrow{A \odot -} \\ \perp \\ \xleftarrow{A \pitchfork -} \end{array} \text{Sets}_*$$

witnessed by a bijection

$$\text{Hom}_{\text{Sets}_*}(A \odot X, Y) \cong \text{Hom}_{\text{Sets}_*}(X, A \pitchfork Y),$$

natural in $A \in \text{Obj}(\text{Sets})$ and $X, Y \in \text{Obj}(\text{Sets}_*)$.

00D5 4. *As a Weighted Limit.* We have

$$A \pitchfork X \cong \lim^{[A]}(X),$$

where in the right hand side we write:

- A for the functor $A: \text{pt} \rightarrow \text{Sets}$ picking $A \in \text{Obj}(\text{Sets})$;
- X for the functor $X: \text{pt} \rightarrow \text{Sets}_*$ picking $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

00D6 5. *Iterated Cotensors.* We have an isomorphism of pointed sets

$$A \pitchfork (B \pitchfork X) \cong (A \times B) \pitchfork X,$$

natural in $A, B \in \text{Obj}(\text{Sets})$ and $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

00D7 6. *Commutativity With Homs.* We have natural isomorphisms

$$\begin{aligned} A \pitchfork \text{Sets}_*(X, -) &\cong \text{Sets}_*(A \odot X, -), \\ A \pitchfork \text{Sets}_*(-, Y) &\cong \text{Sets}_*(-, A \pitchfork Y). \end{aligned}$$

00D8 7. *The Cotensor Evaluation Map.* For each $X, Y \in \text{Obj}(\text{Sets}_*)$, we have a map

$$\text{ev}_{X,Y}^{\pitchfork}: X \rightarrow \text{Sets}_*(X, Y) \pitchfork Y,$$

natural in $X, Y \in \text{Obj}(\text{Sets}_*)$, and given by

$$\text{ev}_{X,Y}^{\pitchfork}(x) \stackrel{\text{def}}{=} \left[(f(x))_{f \in \text{Sets}_*(X,Y)} \right]$$

for each $x \in X$.

- 00D9 8. *The Cotensor Coevaluation Map.* For each $X \in \text{Obj}(\text{Sets}_*)$ and each $A \in \text{Obj}(\text{Sets})$, we have a map

$$\text{coev}_{A,X}^{\pitchfork} : A \rightarrow \text{Sets}_*(A \pitchfork X, X),$$

natural in $X \in \text{Obj}(\text{Sets}_*)$ and $A \in \text{Obj}(\text{Sets})$, and given by

$$\text{coev}_{A,X}^{\pitchfork}(a) \stackrel{\text{def}}{=} \llbracket [(x_b)_{b \in A}] \mapsto x_a \rrbracket$$

for each $a \in A$.

Proof. Item 1, Functoriality: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 2, Adjointness I: This is simply a rephrasing of **Definition 4.2.2.1.1**.

Item 3, Adjointness II: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 4, As a Weighted Limit: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 5, Iterated Cotensors: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 6, Commutativity With Homs: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 7, The Cotensor Evaluation Map: This is the special case of ?? of ?? for when $C = \text{Sets}_*$.

Item 8, The Cotensor Coevaluation Map: This is the special case of ?? of ?? for when $C = \text{Sets}_*$. \square

00DA 4.3 The Left Tensor Product of Pointed Sets

00DB 4.3.1 Foundations

Let (X, x_0) and (Y, y_0) be pointed sets.

00DC **Definition 4.3.1.1.1.** The **left tensor product of pointed sets** is the functor¹¹

$$\triangleleft : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

defined as the composition

$$\text{Sets}_* \times \text{Sets}_* \xrightarrow{\text{id} \times \overline{\omega}} \text{Sets}_* \times \text{Sets} \xrightarrow{\beta_{\text{Sets}_*, \text{Sets}}^{\text{Cats}_2}} \text{Sets} \times \text{Sets}_* \xrightarrow{\odot} \text{Sets}_*,$$

where:

- $\overline{\omega} : \text{Sets}_* \rightarrow \text{Sets}$ is the forgetful functor from pointed sets to sets.

¹¹*Further Notation:* Also written $\triangleleft_{\text{Sets}_*}$.

- $\beta_{\text{Sets}_*, \text{Sets}}^{\text{Cats}_2} : \text{Sets}_* \times \text{Sets} \xrightarrow{\cong} \text{Sets} \times \text{Sets}_*$ is the braiding of Cats_2 , i.e. the functor witnessing the isomorphism

$$\text{Sets}_* \times \text{Sets} \cong \text{Sets} \times \text{Sets}_*.$$

- $\odot : \text{Sets} \times \text{Sets}_* \rightarrow \text{Sets}_*$ is the tensor functor of **Item 1** of **Proposition 4.2.1.1.6**.

00DD Remark 4.3.1.1.2. The left tensor product of pointed sets satisfies the following natural bijection:

$$\text{Sets}_*(X \triangleleft Y, Z) \cong \text{Hom}_{\text{Sets}_*}^{\otimes, L}(X \times Y, Z).$$

That is to say, the following data are in natural bijection:

1. Pointed maps $f : X \triangleleft Y \rightarrow Z$.
2. Maps of sets $f : X \times Y \rightarrow Z$ satisfying $f(x_0, y) = z_0$ for each $y \in Y$.

00DE Remark 4.3.1.1.3. The left tensor product of pointed sets may be described as follows:

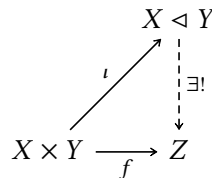
- The left tensor product of (X, x_0) and (Y, y_0) is the pair $((X \triangleleft Y, x_0 \triangleleft y_0), \iota)$ consisting of
 - A pointed set $(X \triangleleft Y, x_0 \triangleleft y_0)$;
 - A left bilinear morphism of pointed sets $\iota : (X \times Y, (x_0, y_0)) \rightarrow X \triangleleft Y$;

satisfying the following universal property:

(UP) Given another such pair $((Z, z_0), f)$ consisting of

- * A pointed set (Z, z_0) ;
- * A left bilinear morphism of pointed sets $f : (X \times Y, (x_0, y_0)) \rightarrow X \triangleleft Y$;

there exists a unique morphism of pointed sets $X \triangleleft Y \xrightarrow{\exists!} Z$ making the diagram



commute.

00DF Construction 4.3.1.1.4. In detail, the **left tensor product of (X, x_0) and (Y, y_0)** is the pointed set $(X \triangleleft Y, [x_0])$ consisting of

- *The Underlying Set.* The set $X \triangleleft Y$ defined by

$$\begin{aligned} X \triangleleft Y &\stackrel{\text{def}}{=} |Y| \odot X \\ &\cong \bigvee_{y \in Y} (X, x_0), \end{aligned}$$

where $|Y|$ denotes the underlying set of (Y, y_0) ;

- *The Underlying Basepoint.* The point $[(y_0, x_0)]$ of $\bigvee_{y \in Y} (X, x_0)$, which is equal to $[(y, x_0)]$ for any $y \in Y$.

00DG Notation 4.3.1.1.5. We write¹² $x \triangleleft y$ for the element $[(y, x)]$ of

$$X \triangleleft Y \cong |Y| \odot X.$$

00DH Remark 4.3.1.1.6. Employing the notation introduced in **Notation 4.3.1.1.5**, we have

$$x_0 \triangleleft y_0 = x_0 \triangleleft y$$

for each $y \in Y$, and

$$x_0 \triangleleft y = x_0 \triangleleft y'$$

for each $y, y' \in Y$.

00DJ Proposition 4.3.1.1.7. Let (X, x_0) and (Y, y_0) be pointed sets.

00DK 1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto X \triangleleft Y$ define functors

$$\begin{aligned} X \triangleleft - &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ - \triangleleft Y &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ -_1 \triangleleft -_2 &: \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*. \end{aligned}$$

In particular, given pointed maps

$$\begin{aligned} f &: (X, x_0) \rightarrow (A, a_0), \\ g &: (Y, y_0) \rightarrow (B, b_0), \end{aligned}$$

the induced map

$$f \triangleleft g: X \triangleleft Y \rightarrow A \triangleleft B$$

is given by

$$[f \triangleleft g](x \triangleleft y) \stackrel{\text{def}}{=} f(x) \triangleleft g(y)$$

for each $x \triangleleft y \in X \triangleleft Y$.

¹²*Further Notation:* Also written $x \triangleleft_{\mathbf{Sets}_*} y$.

00DL 2. *Adjointness I.* We have an adjunction

$$\left(- \triangleleft Y \dashv [Y, -]_{\mathbf{Sets}_*}^{\triangleleft} \right): \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \triangleleft Y} \\ \perp \\ \xleftarrow{[Y, -]_{\mathbf{Sets}_*}^{\triangleleft}} \end{array} \mathbf{Sets}_*$$

witnessed by a bijection of sets

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleleft Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}_*}\left(X, [Y, Z]_{\mathbf{Sets}_*}^{\triangleleft}\right)$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \mathrm{Obj}(\mathbf{Sets}_*)$, where $[X, Y]_{\mathbf{Sets}_*}^{\triangleleft}$ is the pointed set of [Definition 4.3.2.1.1](#).

00DM 3. *Adjointness II.* The functor

$$X \triangleleft -: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

does not admit a right adjoint.

00DN 4. *Adjointness III.* We have a bijection of sets

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleleft Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}_*}(|Y|, \mathbf{Sets}_*(X, Z))$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \mathrm{Obj}(\mathbf{Sets}_*)$.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness I: This follows from [Item 3](#) of [Proposition 4.2.1.1.6](#).

Item 3, Adjointness II: For $X \triangleleft -$ to admit a right adjoint would require it to preserve colimits by ?? of ??. However, we have

$$\begin{aligned} X \triangleleft \mathrm{pt} &\stackrel{\mathrm{def}}{=} |\mathrm{pt}| \odot X \\ &\cong X \\ &\neq \mathrm{pt}, \end{aligned}$$

and thus we see that $X \triangleleft -$ does not have a right adjoint.

Item 4, Adjointness III: This follows from [Item 2](#) of [Proposition 4.2.1.1.6](#). \square

00DP **Remark 4.3.1.1.8.** Here is some intuition on why $X \triangleleft -$ fails to be a left adjoint. [Item 4](#) of [Proposition 4.3.1.1.7](#) states that we have a natural bijection

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleleft Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}_*}(|Y|, \mathbf{Sets}_*(X, Z)),$$

so it would be reasonable to wonder whether a natural bijection of the form

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleleft Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}_*}(Y, \mathbf{Sets}_*(X, Z)),$$

also holds, which would give $X \triangleleft - \dashv \mathbf{Sets}_*(X, -)$. However, such a bijection would require every map

$$f: X \triangleleft Y \rightarrow Z$$

to satisfy

$$f(x \triangleleft y_0) = z_0$$

for each $x \in X$, whereas we are imposing such a basepoint preservation condition only for elements of the form $x_0 \triangleleft y$. Thus $\mathbf{Sets}_*(X, -)$ can't be a right adjoint for $X \triangleleft -$, and as shown by **Item 3** of **Proposition 4.3.1.1.7**, no functor can.¹³

00DQ 4.3.2 The Left Internal Hom of Pointed Sets

Let (X, x_0) and (Y, y_0) be pointed sets.

00DR **Definition 4.3.2.1.1.** The **left internal Hom of pointed sets** is the functor

$$[-, -]_{\mathbf{Sets}_*}^{\triangleleft} : \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

defined as the composition

$$\mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \xrightarrow{\overset{\text{forgetful}}{\text{Set}} \times \text{id}} \mathbf{Sets}^{\text{op}} \times \mathbf{Sets} \xrightarrow{\pitchfork} \mathbf{Sets}_*,$$

where:

- $\overset{\text{forgetful}}{\text{Set}} : \mathbf{Sets}_* \rightarrow \mathbf{Sets}$ is the forgetful functor from pointed sets to sets.
- $\pitchfork : \mathbf{Sets}^{\text{op}} \times \mathbf{Sets} \rightarrow \mathbf{Sets}_*$ is the cotensor functor of **Item 1** of **Proposition 4.2.2.1.4**.

Proof. For a proof that $[-, -]_{\mathbf{Sets}_*}^{\triangleleft}$ is indeed the left internal Hom of \mathbf{Sets}_* with respect to the left tensor product of pointed sets, see **Item 2** of **Proposition 4.3.1.1.7**. \square

00DS **Remark 4.3.2.1.2.** The left internal Hom of pointed sets satisfies the following universal property:

$$\mathbf{Sets}_*(X \triangleleft Y, Z) \cong \mathbf{Sets}_*\left(X, [Y, Z]_{\mathbf{Sets}_*}^{\triangleleft}\right)$$

That is to say, the following data are in bijection:

¹³The functor $\mathbf{Sets}_*(X, -)$ is instead right adjoint to $X \wedge -$, the smash product of pointed sets of **Definition 4.5.1.1.1**. See **Item 2** of **Proposition 4.5.1.1.9**.

1. Pointed maps $f: X \triangleleft Y \rightarrow Z$.
2. Pointed maps $f: X \rightarrow [Y, Z]_{\text{Sets}_*}^{\triangleleft}$.

00DT Remark 4.3.2.1.3. In detail, the **left internal Hom of** (X, x_0) **and** (Y, y_0) is the pointed set $\left([X, Y]_{\text{Sets}_*}^{\triangleleft}, [(y_0)_{x \in X}]\right)$ consisting of

- *The Underlying Set.* The set $[X, Y]_{\text{Sets}_*}^{\triangleleft}$ defined by

$$\begin{aligned} [X, Y]_{\text{Sets}_*}^{\triangleleft} &\stackrel{\text{def}}{=} |X| \wr Y \\ &\cong \bigwedge_{x \in X} (Y, y_0), \end{aligned}$$

where $|X|$ denotes the underlying set of (X, x_0) ;

- *The Underlying Basepoint.* The point $[(y_0)_{x \in X}]$ of $\bigwedge_{x \in X} (Y, y_0)$.

00DU Proposition 4.3.2.1.4. Let (X, x_0) and (Y, y_0) be pointed sets.

00DV 1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto [X, Y]_{\text{Sets}_*}^{\triangleleft}$ define functors

$$\begin{aligned} [X, -]_{\text{Sets}_*}^{\triangleleft} &: \text{Sets}_* \rightarrow \text{Sets}_*, \\ [-, Y]_{\text{Sets}_*}^{\triangleleft} &: \text{Sets}_*^{\text{op}} \rightarrow \text{Sets}_*, \\ [-_1, -_2]_{\text{Sets}_*}^{\triangleleft} &: \text{Sets}_*^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*. \end{aligned}$$

In particular, given pointed maps

$$\begin{aligned} f &: (X, x_0) \rightarrow (A, a_0), \\ g &: (Y, y_0) \rightarrow (B, b_0), \end{aligned}$$

the induced map

$$[f, g]_{\text{Sets}_*}^{\triangleleft} : [A, Y]_{\text{Sets}_*}^{\triangleleft} \rightarrow [X, B]_{\text{Sets}_*}^{\triangleleft}$$

is given by

$$[f, g]_{\text{Sets}_*}^{\triangleleft} \left([(y_a)_{a \in A}] \right) \stackrel{\text{def}}{=} [(g(y_{f(x)}))_{x \in X}]$$

for each $[(y_a)_{a \in A}] \in [A, Y]_{\text{Sets}_*}^{\triangleleft}$.

00DW 2. *Adjointness I.* We have an adjunction

$$\left(- \triangleleft Y \dashv [Y, -]_{\text{Sets}_*}^{\triangleleft} \right) : \text{Sets}_* \begin{array}{c} \xrightarrow{- \triangleleft Y} \\ \perp \\ \xleftarrow{[Y, -]_{\text{Sets}_*}^{\triangleleft}} \end{array} \text{Sets}_*$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Sets}_*}(X \triangleleft Y, Z) \cong \text{Hom}_{\text{Sets}_*}\left(X, [Y, Z]_{\text{Sets}_*}^{\triangleleft}\right)$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$

00DX 3. *Adjointness II.* The functor

$$X \triangleleft -: \text{Sets}_* \rightarrow \text{Sets}_*$$

does not admit a right adjoint.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness I: This is a repetition of *Item 2* of *Proposition 4.3.1.1.7*, and is proved there.

Item 3, Adjointness II: This is a repetition of *Item 3* of *Proposition 4.3.1.1.7*, and is proved there. \square

00DY 4.3.3 The Left Skew Unit

00DZ **Definition 4.3.3.1.1.** The **left skew unit of the left tensor product of pointed sets** is the functor

$$\mathbb{1}_{\text{Sets}_*}^{\triangleleft}: \text{pt} \rightarrow \text{Sets}_*$$

defined by

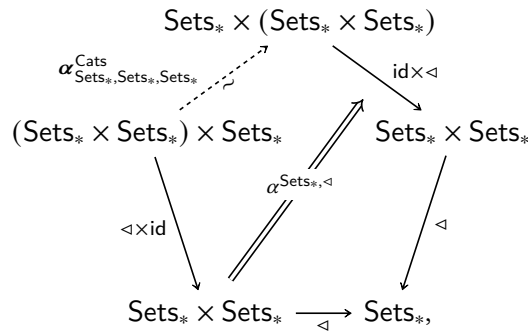
$$\mathbb{1}_{\text{Sets}_*}^{\triangleleft} \stackrel{\text{def}}{=} S^0.$$

00E0 4.3.4 The Left Skew Associator

00E1 **Definition 4.3.4.1.1.** The **skew associator of the left tensor product of pointed sets** is the natural transformation

$$\alpha^{\text{Sets}_*, \triangleleft}: \triangleleft \circ (\triangleleft \times \text{id}_{\text{Sets}_*}) \implies \triangleleft \circ (\text{id}_{\text{Sets}_*} \times \triangleleft) \circ \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}}$$

as in the diagram



whose component

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft} : (X \triangleleft Y) \triangleleft Z \rightarrow X \triangleleft (Y \triangleleft Z)$$

at $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$ is given by

$$\begin{aligned} (X \triangleleft Y) \triangleleft Z &\stackrel{\text{def}}{=} |Z| \odot (X \triangleleft Y) \\ &\stackrel{\text{def}}{=} |Z| \odot (|Y| \odot X) \\ &\cong \bigvee_{z \in Z} |Y| \odot X \\ &\cong \bigvee_{z \in Z} \left(\bigvee_{y \in Y} X \right) \\ &\rightarrow \bigvee_{[(z,y)] \in \bigvee_{z \in Z} Y} X \\ &\cong \bigvee_{[(z,y)] \in |Z| \odot Y} X \\ &\cong ||Z| \odot Y| \odot X \\ &\stackrel{\text{def}}{=} |Y \triangleleft Z| \odot X \\ &\stackrel{\text{def}}{=} X \triangleleft (Y \triangleleft Z), \end{aligned}$$

where the map

$$\bigvee_{z \in Z} \left(\bigvee_{y \in Y} X \right) \rightarrow \bigvee_{(z,y) \in \bigvee_{z \in Z} Y} X$$

is given by $[(z, [(y, x)])] \mapsto [([(z, y)], x)]$.

Proof. (Proven below in a bit.) □

00E2 Remark 4.3.4.1.2. Unwinding the notation for elements, we have

$$\begin{aligned} [(z, [(y, x)])] &\stackrel{\text{def}}{=} [(z, x \triangleleft y)] \\ &\stackrel{\text{def}}{=} (x \triangleleft y) \triangleleft z \end{aligned}$$

and

$$\begin{aligned} [([(z, y)], x)] &\stackrel{\text{def}}{=} [(y \triangleleft z, x)] \\ &\stackrel{\text{def}}{=} x \triangleleft (y \triangleleft z). \end{aligned}$$

So, in other words, $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft}$ acts on elements via

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft} ((x \triangleleft y) \triangleleft z) \stackrel{\text{def}}{=} x \triangleleft (y \triangleleft z)$$

for each $(x \triangleleft y) \triangleleft z \in (X \triangleleft Y) \triangleleft Z$.

00E3 Remark 4.3.4.1.3. Taking $y = y_0$, we see that the morphism $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft}$ acts on elements as

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft}((x \triangleleft y_0) \triangleleft z) \stackrel{\text{def}}{=} x \triangleleft (y_0 \triangleleft z).$$

However, by the definition of \triangleleft , we have $y_0 \triangleleft z = y_0 \triangleleft z'$ for all $z, z' \in Z$, preventing $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft}$ from being non-invertible.

Proof. Firstly, note that, given $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$, the map

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft} : (X \triangleleft Y) \triangleleft Z \rightarrow X \triangleleft (Y \triangleleft Z)$$

is indeed a morphism of pointed sets, as we have

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft}((x_0 \triangleleft y_0) \triangleleft z_0) = x_0 \triangleleft (y_0 \triangleleft z_0).$$

Next, we claim that $\alpha^{\text{Sets}_*, \triangleleft}$ is a natural transformation. We need to show that, given morphisms of pointed sets

$$\begin{aligned} f &: (X, x_0) \rightarrow (X', x'_0), \\ g &: (Y, y_0) \rightarrow (Y', y'_0), \\ h &: (Z, z_0) \rightarrow (Z', z'_0) \end{aligned}$$

the diagram

$$\begin{array}{ccc} (X \triangleleft Y) \triangleleft Z & \xrightarrow{(f \triangleleft g) \triangleleft h} & (X' \triangleleft Y') \triangleleft Z' \\ \alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft} \downarrow & & \downarrow \alpha_{X',Y',Z'}^{\text{Sets}_*, \triangleleft} \\ X \triangleleft (Y \triangleleft Z) & \xrightarrow{f \triangleleft (g \triangleleft h)} & X' \triangleleft (Y' \triangleleft Z') \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} (x \triangleleft y) \triangleleft z & \longmapsto & (f(x) \triangleleft g(y)) \triangleleft h(z) \\ \downarrow & & \downarrow \\ x \triangleleft (y \triangleleft z) & \longmapsto & f(x) \triangleleft (g(y) \triangleleft h(z)) \end{array}$$

and hence indeed commutes, showing $\alpha^{\text{Sets}_*, \triangleleft}$ to be a natural transformation. This finishes the proof. \square

00E4 4.3.5 The Left Skew Left Unitor

00E5 Definition 4.3.5.1.1. The skew left unitor of the left tensor product of pointed sets is the natural transformation

$$\lambda^{\text{Sets}_*, \triangleleft} : \triangleleft \circ (\mathbb{1}^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \lambda_{\text{Sets}_*}^{\text{Cats}_2}$$

whose component

$$\lambda_X^{\text{Sets}_*, \triangleleft} : S^0 \triangleleft X \rightarrow X$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by the composition

$$\begin{aligned} S^0 \triangleleft X &\cong |X| \circ S^0 \\ &\cong \bigvee_{x \in X} S^0 \\ &\rightarrow X, \end{aligned}$$

where $\bigvee_{x \in X} S^0 \rightarrow X$ is the map given by

$$\begin{aligned} [(x, 0)] &\mapsto x_0, \\ [(x, 1)] &\mapsto x. \end{aligned}$$

Proof. (Proven below in a bit.) □

00E6 Remark 4.3.5.1.2. In other words, $\lambda_X^{\text{Sets}_*, \triangleleft}$ acts on elements as

$$\begin{aligned} \lambda_X^{\text{Sets}_*, \triangleleft} (0 \triangleleft x) &\stackrel{\text{def}}{=} x_0, \\ \lambda_X^{\text{Sets}_*, \triangleleft} (1 \triangleleft x) &\stackrel{\text{def}}{=} x \end{aligned}$$

for each $1 \triangleleft x \in S^0 \triangleleft X$.

00E7 Remark 4.3.5.1.3. The morphism $\lambda_X^{\text{Sets}_*, \triangleleft}$ is almost invertible, with its would-be-inverse

$$\phi_X : X \rightarrow S^0 \triangleleft X$$

given by

$$\phi_X(x) \stackrel{\text{def}}{=} 1 \triangleleft x$$

for each $x \in X$. Indeed, we have

$$\begin{aligned} \left[\lambda_X^{\mathbf{Sets}_*, \triangleleft} \circ \phi \right] (x) &= \lambda_X^{\mathbf{Sets}_*, \triangleleft} (\phi(x)) \\ &= \lambda_X^{\mathbf{Sets}_*, \triangleleft} (1 \triangleleft x) \\ &= x \\ &= [\text{id}_X](x) \end{aligned}$$

so that

$$\lambda_X^{\mathbf{Sets}_*, \triangleleft} \circ \phi = \text{id}_X$$

and

$$\begin{aligned} \left[\phi \circ \lambda_X^{\mathbf{Sets}_*, \triangleleft} \right] (1 \triangleleft x) &= \phi \left(\lambda_X^{\mathbf{Sets}_*, \triangleleft} (1 \triangleleft x) \right) \\ &= \phi(x) \\ &= 1 \triangleleft x \\ &= [\text{id}_{S^0 \triangleleft X}](1 \triangleleft x), \end{aligned}$$

but

$$\begin{aligned} \left[\phi \circ \lambda_X^{\mathbf{Sets}_*, \triangleleft} \right] (0 \triangleleft x) &= \phi \left(\lambda_X^{\mathbf{Sets}_*, \triangleleft} (0 \triangleleft x) \right) \\ &= \phi(x_0) \\ &= 1 \triangleleft x_0, \end{aligned}$$

where $0 \triangleleft x \neq 1 \triangleleft x_0$. Thus

$$\phi \circ \lambda_X^{\mathbf{Sets}_*, \triangleleft} \stackrel{?}{=} \text{id}_{S^0 \triangleleft X}$$

holds for all elements in $S^0 \triangleleft X$ except one.

Proof. Firstly, note that, given $(X, x_0) \in \text{Obj}(\mathbf{Sets}_*)$, the map

$$\lambda_X^{\mathbf{Sets}_*, \triangleleft} : S^0 \triangleleft X \rightarrow X$$

is indeed a morphism of pointed sets, as we have

$$\lambda_X^{\mathbf{Sets}_*, \triangleleft} (0 \triangleleft x_0) = x_0.$$

Next, we claim that $\lambda^{\mathbf{Sets}_*, \triangleleft}$ is a natural transformation. We need to show that, given a morphism of pointed sets

$$f : (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc}
 S^0 \triangleleft X & \xrightarrow{\text{id}_{S^0} \triangleleft f} & S^0 \triangleleft Y \\
 \lambda_X^{\text{Sets}_*, \triangleleft} \downarrow & & \downarrow \lambda_Y^{\text{Sets}_*, \triangleleft} \\
 X & \xrightarrow{f} & Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 0 \triangleleft x & & 0 \triangleleft x \mapsto 0 \triangleleft f(x) \\
 \downarrow & & \downarrow \\
 x_0 \mapsto f(x_0) & & y_0
 \end{array}$$

and

$$\begin{array}{ccc}
 1 \triangleleft x \mapsto 1 \triangleleft f(x) & & \\
 \downarrow & & \downarrow \\
 x \mapsto f(x) & &
 \end{array}$$

and hence indeed commutes, showing $\lambda^{\text{Sets}_*, \triangleleft}$ to be a natural transformation. This finishes the proof. \square

00E8 4.3.6 The Left Skew Right Unitor

00E9 Definition 4.3.6.1.1. The **skew right unitor of the left tensor product of pointed sets** is the natural transformation

$$\rho^{\text{Sets}_*, \triangleleft} : \rho_{\text{Sets}_*}^{\text{Cats}_2} \xrightarrow{\sim} \triangleleft \circ (\text{id} \times \mathbb{1}^{\text{Sets}_*}),$$

The diagram shows a commutative square with a diagonal arrow. The top-left node is $\text{Sets}_* \times \text{pt}$, the top-right node is $\text{Sets}_* \times \text{Sets}_*$, and the bottom-right node is Sets_* . A dashed arrow labeled $\rho_{\text{Sets}_*}^{\text{Cats}_2}$ points from $\text{Sets}_* \times \text{pt}$ to Sets_* . A solid arrow labeled $\rho^{\text{Sets}_*, \triangleleft}$ points from $\text{Sets}_* \times \text{pt}$ to Sets_* . A solid arrow labeled $\text{id} \times \mathbb{1}^{\text{Sets}_*}$ points from $\text{Sets}_* \times \text{pt}$ to $\text{Sets}_* \times \text{Sets}_*$. A solid arrow labeled \triangleleft points from $\text{Sets}_* \times \text{Sets}_*$ to Sets_* . A solid arrow labeled $\rho^{\text{Sets}_*, \triangleleft}$ also points from $\text{Sets}_* \times \text{Sets}_*$ to Sets_* .

whose component

$$\rho_X^{\text{Sets}_*, \triangleleft} : X \rightarrow X \triangleleft S^0$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by the composition

$$\begin{aligned} X &\rightarrow X \vee X \\ &\cong |S^0| \odot X \\ &\cong X \triangleleft S^0, \end{aligned}$$

where $X \rightarrow X \vee X$ is the map sending X to the second factor of X in $X \vee X$.

Proof. (Proven below in a bit.) □

00EA Remark 4.3.6.1.2. In other words, $\rho_X^{\text{Sets}_*, \triangleleft}$ acts on elements as

$$\rho_X^{\text{Sets}_*, \triangleleft}(x) \stackrel{\text{def}}{=} [(1, x)]$$

i.e. by

$$\rho_X^{\text{Sets}_*, \triangleleft}(x) \stackrel{\text{def}}{=} x \triangleleft 1$$

for each $x \in X$.

00EB Remark 4.3.6.1.3. The morphism $\rho_X^{\text{Sets}_*, \triangleleft}$ is non-invertible, as it is non-surjective when viewed as a map of sets, since the elements $x \triangleleft 0$ of $X \triangleleft S^0$ with $x \neq x_0$ are outside the image of $\rho_X^{\text{Sets}_*, \triangleleft}$, which sends x to $x \triangleleft 1$.

Proof. Firstly, note that, given $(X, x_0) \in \text{Obj}(\text{Sets}_*)$, the map

$$\rho_X^{\text{Sets}_*, \triangleleft}: X \rightarrow X \triangleleft S^0$$

is indeed a morphism of pointed sets as we have

$$\begin{aligned} \rho_X^{\text{Sets}_*, \triangleleft}(x_0) &= x_0 \triangleleft 1 \\ &= x_0 \triangleleft 0. \end{aligned}$$

Next, we claim that $\rho^{\text{Sets}_*, \triangleleft}$ is a natural transformation. We need to show that, given a morphism of pointed sets

$$f: (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \rho_X^{\text{Sets}_*, \triangleleft} \downarrow & & \downarrow \rho_Y^{\text{Sets}_*, \triangleleft} \\ X \triangleleft S^0 & \xrightarrow{f \triangleleft \text{id}_{S^0}} & Y \triangleleft S^0 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x & \xrightarrow{\quad} & f(x) \\ \downarrow & & \downarrow \\ x \triangleleft 0 & \xrightarrow{\quad} & f(x) \triangleleft 0 \end{array}$$

and hence indeed commutes, showing $\rho^{\text{Sets}_*, \triangleleft}$ to be a natural transformation. This finishes the proof. \square

00EC 4.3.7 The Diagonal

00ED Definition 4.3.7.1.1. The **diagonal of the left tensor product of pointed sets** is the natural transformation

$$\Delta^{\triangleleft} : \text{id}_{\text{Sets}_*} \implies \triangleleft \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2}$$

whose component

$$\Delta_X^{\triangleleft} : (X, x_0) \rightarrow (X \triangleleft X, x_0 \triangleleft x_0)$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by

$$\Delta_X^{\triangleleft}(x) \stackrel{\text{def}}{=} x \triangleleft x$$

for each $x \in X$.

Proof. Being a Morphism of Pointed Sets: We have

$$\Delta_X^{\triangleleft}(x_0) \stackrel{\text{def}}{=} x_0 \triangleleft x_0,$$

and thus Δ_X^{\triangleleft} is a morphism of pointed sets.

Naturality: We need to show that, given a morphism of pointed sets

$$f : (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \Delta_X^{\triangleleft} \downarrow & & \downarrow \Delta_Y^{\triangleleft} \\ X \triangleleft X & \xrightarrow{f \triangleleft f} & Y \triangleleft Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x & \xrightarrow{\quad} & f(x) \\ \downarrow & & \downarrow \\ x \triangleleft x & \xrightarrow{\quad} & f(x) \triangleleft f(x) \end{array}$$

and hence indeed commutes, showing Δ^\triangleleft to be natural. \square

4.3.8 The Left Skew Monoidal Structure on Pointed Sets Associated to \triangleleft

00EE

00EF **Proposition 4.3.8.1.1.** The category \mathbf{Sets}_* admits a left-closed left skew monoidal category structure consisting of

- *The Underlying Category.* The category \mathbf{Sets}_* of pointed sets;
- *The Left Skew Monoidal Product.* The left tensor product functor

$$\triangleleft : \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

of [Definition 4.3.1.1.1](#);

- *The Left Internal Skew Hom.* The left internal Hom functor

$$[-, -]_{\mathbf{Sets}_*}^{\triangleleft} : \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

of [Definition 4.3.2.1.1](#);

- *The Left Skew Monoidal Unit.* The functor

$$\mathbb{1}^{\mathbf{Sets}_*, \triangleleft} : \text{pt} \rightarrow \mathbf{Sets}_*$$

of [Definition 4.3.3.1.1](#);

- *The Left Skew Associators.* The natural transformation

$$\alpha^{\mathbf{Sets}_*, \triangleleft} : \triangleleft \circ (\triangleleft \times \text{id}_{\mathbf{Sets}_*}) \Longrightarrow \triangleleft \circ (\text{id}_{\mathbf{Sets}_*} \times \triangleleft) \circ \alpha_{\mathbf{Sets}_*, \mathbf{Sets}_*, \mathbf{Sets}_*}^{\text{Cats}}$$

of [Definition 4.3.4.1.1](#);

- *The Left Skew Left Unitors.* The natural transformation

$$\lambda^{\mathbf{Sets}_*, \triangleleft} : \triangleleft \circ \left(\mathbb{1}^{\mathbf{Sets}_*} \times \text{id}_{\mathbf{Sets}_*} \right) \xrightarrow{\sim} \lambda_{\mathbf{Sets}_*}^{\text{Cats}_2}$$

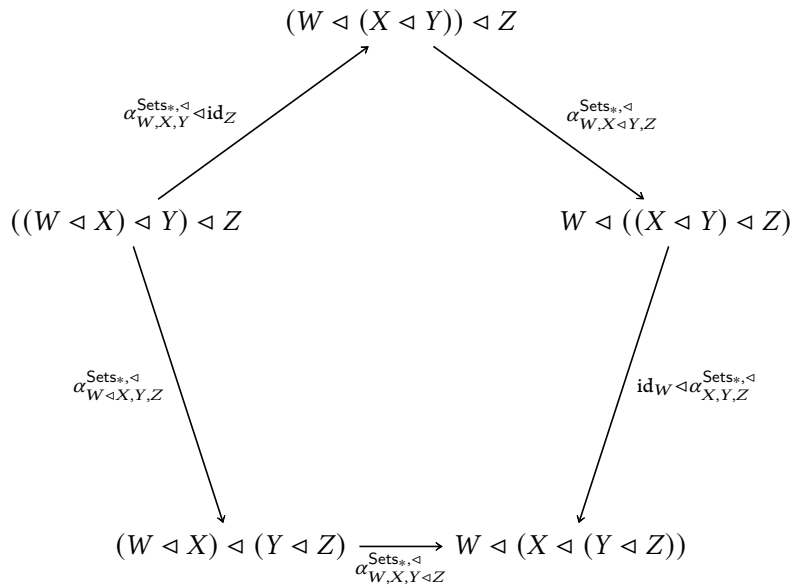
of [Definition 4.3.5.1.1](#);

- *The Left Skew Right Unitors.* The natural transformation

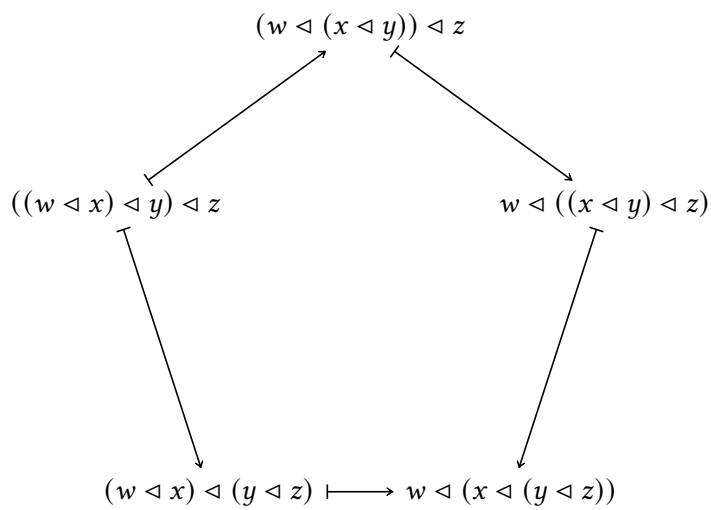
$$\rho^{\text{Sets}_*, \triangleleft} : \rho_{\text{Sets}_*}^{\text{Cats}_2} \xrightarrow{\sim} \triangleleft \circ (\text{id} \times \mathbb{1}^{\text{Sets}_*})$$

of **Definition 4.3.6.1.1.**

Proof. The Pentagon Identity: Let (W, w_0) , (X, x_0) , (Y, y_0) and (Z, z_0) be pointed sets. We have to show that the diagram



commutes. Indeed, this diagram acts on elements as



and thus we see that the pentagon identity is satisfied.

The Left Skew Left Triangle Identity: Let (X, x_0) and (Y, y_0) be pointed sets. We have to show that the diagram

$$\begin{array}{ccc}
 (S^0 \triangleleft X) \triangleleft Y & \xrightarrow{\alpha_{S^0, X, Y}^{\text{Sets}_*, \triangleleft}} & S^0 \triangleleft (X \triangleleft Y) \\
 \searrow \lambda_X^{\text{Sets}_*, \triangleleft} \triangleleft \text{id}_Y & & \downarrow \lambda_{X \triangleleft Y}^{\text{Sets}_*, \triangleleft} \\
 & & X \triangleleft Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 (0 \triangleleft x) \triangleleft y & \longmapsto & 0 \triangleleft (x \triangleleft y) \\
 \searrow & & \downarrow \\
 & & x_0 \triangleleft y = x_0 \triangleleft y_0
 \end{array}$$

and

$$\begin{array}{ccc}
 (1 \triangleleft x) \triangleleft y & \longmapsto & 1 \triangleleft (x \triangleleft y) \\
 \searrow & & \downarrow \\
 & & x \triangleleft y
 \end{array}$$

and hence indeed commutes. Thus the left skew triangle identity is satisfied.

The Left Skew Right Triangle Identity: Let (X, x_0) and (Y, y_0) be pointed sets. We have to show that the diagram

$$\begin{array}{ccc}
 X \triangleleft Y & & \\
 \downarrow \rho_{X \triangleleft Y}^{\text{Sets}_*, \triangleleft} & \searrow \text{id}_X \triangleleft \rho_Y^{\text{Sets}_*, \triangleleft} & \\
 (X \triangleleft Y) \triangleleft S^0 & \xrightarrow{\alpha_{X, Y, S^0}^{\text{Sets}_*, \triangleleft}} & X \triangleleft (Y \triangleleft S^0)
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 x \triangleleft y & & \\
 \downarrow & \searrow & \\
 (x \triangleleft y) \triangleleft 1 & \longmapsto & x \triangleleft (y \triangleleft 1)
 \end{array}$$

and hence indeed commutes. Thus the right skew triangle identity is satisfied.

The Left Skew Middle Triangle Identity: Let (X, x_0) and (Y, y_0) be pointed sets. We have to show that the diagram

$$\begin{array}{ccc}
 X \triangleleft Y & \xlongequal{\quad} & X \triangleleft Y \\
 \rho_X^{\text{Sets}_*, \triangleleft} \triangleleft \text{id}_Y \downarrow & & \uparrow \text{id}_A \triangleleft \lambda_Y^{\text{Sets}_*, \triangleleft} \\
 (X \triangleleft S^0) \triangleleft Y & \xrightarrow{\alpha_{X, S^0, Y}^{\text{Sets}_*, \triangleleft}} & X \triangleleft (S^0 \triangleleft Y)
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 x \triangleleft y & \xrightarrow{\quad} & x \triangleleft y \\
 \downarrow & & \uparrow \\
 (x \triangleleft 1) \triangleleft y & \xrightarrow{\quad} & x \triangleleft (1 \triangleleft y)
 \end{array}$$

and hence indeed commutes. Thus the right skew triangle identity is satisfied.

The Zig-Zag Identity: We have to show that the diagram

$$\begin{array}{ccc}
 S^0 & \xrightarrow{\rho_{S^0}^{\text{Sets}_*, \triangleleft}} & S^0 \triangleleft S^0 \\
 \parallel & & \downarrow \lambda_{S^0}^{\text{Sets}_*, \triangleleft} \\
 & & S^0
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 0 & \xrightarrow{\quad} & 0 \triangleleft 1 \\
 \swarrow & & \downarrow \\
 & & 0
 \end{array}$$

and

$$\begin{array}{ccc}
 1 & \xrightarrow{\quad} & 1 \triangleleft 1 \\
 \swarrow & & \downarrow \\
 & & 1
 \end{array}$$

and hence indeed commutes. Thus the zig-zag identity is satisfied.

Left Skew Monoidal Left-Closedness: This follows from **Item 2** of **Proposition 4.3.1.1.7**. □

4.3.9 Monoids With Respect to the Left Tensor Product of Pointed Sets

00EG

00EH Proposition 4.3.9.1.1. The category of monoids on $(\text{Sets}_*, \triangleleft, S^0)$ is isomorphic to the category of “monoids with left zero”¹⁴ and morphisms between them.

Proof. Monoids on $(\text{Sets}_*, \triangleleft, S^0)$: A monoid on $(\text{Sets}_*, \triangleleft, S^0)$ consists of:

- *The Underlying Object.* A pointed set $(A, 0_A)$.
- *The Multiplication Morphism.* A morphism of pointed sets

$$\mu_A: A \triangleleft A \rightarrow A,$$

determining a left bilinear morphism of pointed sets

$$\begin{aligned} A \times A &\longrightarrow A \\ (a, b) &\longmapsto ab. \end{aligned}$$

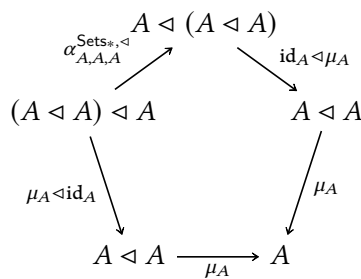
- *The Unit Morphism.* A morphism of pointed sets

$$\eta_A: S^0 \rightarrow A$$

picking an element 1_A of A .

satisfying the following conditions:

1. *Associativity.* The diagram

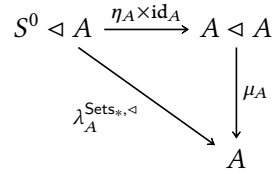


¹⁴A monoid with left zero is defined similarly as the monoids with zero of ???. Succinctly, they are monoids (A, μ_A, η_A) with a special element 0_A satisfying

$$0_A a = 0_A$$

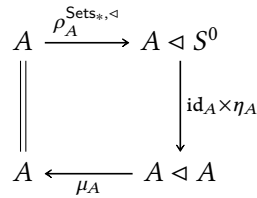
for each $a \in A$.

2. *Left Unitality.* The diagram



commutes.

3. *Right Unitality.* The diagram



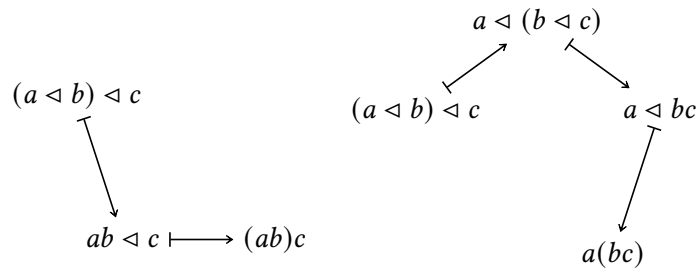
commutes.

Being a left-bilinear morphism of pointed sets, the multiplication map satisfies

$$0_A a = 0_A$$

for each $a \in A$. Now, the associativity, left unitality, and right unitality conditions act on elements as follows:

1. *Associativity.* The associativity condition acts as



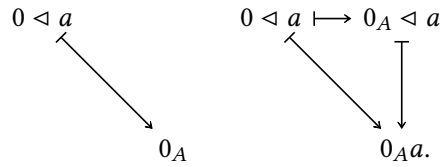
This gives

$$(ab)c = a(bc)$$

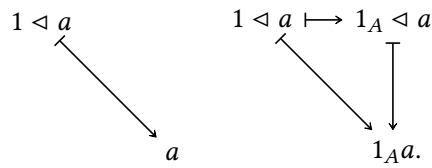
for each $a, b, c \in A$.

2. *Left Unitality.* The left unitality condition acts:

(a) On $0 \triangleleft a$ as



(b) On $1 \triangleleft a$ as

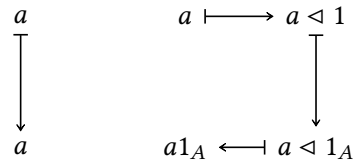


This gives

$$\begin{aligned}
 1_A a &= a, \\
 0_A a &= 0_A
 \end{aligned}$$

for each $a \in A$.

3. *Right Unitality.* The right unitality condition acts as



This gives

$$a 1_A = a$$

for each $a \in A$.

Thus we see that monoids with respect to \triangleleft are exactly monoids with left zero.

Morphisms of Monoids on $(\text{Sets}_, \triangleleft, S^0)$:* A morphism of monoids on $(\text{Sets}_*, \triangleleft, S^0)$ from $(A, \mu_A, \eta_A, 0_A)$ to $(B, \mu_B, \eta_B, 0_B)$ is a morphism of pointed sets

$$f: (A, 0_A) \rightarrow (B, 0_B)$$

satisfying the following conditions:

1. *Compatibility With the Multiplication Morphisms.* The diagram

$$\begin{array}{ccc}
 A \triangleleft A & \xrightarrow{f \triangleleft f} & B \triangleleft B \\
 \mu_A \downarrow & & \downarrow \mu_B \\
 A & \xrightarrow{f} & B
 \end{array}$$

commutes.

2. *Compatibility With the Unit Morphisms.* The diagram

$$\begin{array}{ccc}
 S^0 & \xrightarrow{\eta_A} & A \\
 & \searrow \eta_B & \downarrow f \\
 & & B
 \end{array}$$

commutes.

These act on elements as

$$\begin{array}{ccc}
 a \triangleleft b & & a \triangleleft b \mapsto f(a) \triangleleft f(b) \\
 \downarrow & & \downarrow \\
 ab \mapsto f(ab) & & f(a)f(b)
 \end{array}$$

and

$$\begin{array}{ccc}
 0 & \mapsto & 0_A \\
 \searrow & & \downarrow \\
 & & f(0_A) \\
 & & \downarrow \\
 & & 0_B
 \end{array}$$

and

$$\begin{array}{ccc}
 1 & \mapsto & 1_A \\
 \searrow & & \downarrow \\
 & & f(1_A) \\
 & & \downarrow \\
 & & 1_B
 \end{array}$$

giving

$$\begin{aligned}
 f(ab) &= f(a)f(b), \\
 f(0_A) &= 0_B, \\
 f(1_A) &= 1_B,
 \end{aligned}$$

for each $a, b \in A$, which is exactly a morphism of monoids with left zero.

Identities and Composition: Similarly, the identities and composition of $\text{Mon}(\text{Sets}_*, \triangleleft, S^0)$ can be easily seen to agree with those of monoids with left zero, which finishes the proof. \square

00EJ 4.4 The Right Tensor Product of Pointed Sets

00EK 4.4.1 Foundations

Let (X, x_0) and (Y, y_0) be pointed sets.

00EL **Definition 4.4.1.1.1.** The **right tensor product of pointed sets** is the functor¹⁵

$$\triangleright : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

defined as the composition

$$\text{Sets}_* \times \text{Sets}_* \xrightarrow{\overset{\text{忘}}{\text{id}}} \text{Sets} \times \text{Sets}_* \xrightarrow{\odot} \text{Sets}_*,$$

where:

- $\overset{\text{忘}}{\text{id}} : \text{Sets}_* \rightarrow \text{Sets}$ is the forgetful functor from pointed sets to sets.
- $\odot : \text{Sets} \times \text{Sets}_* \rightarrow \text{Sets}_*$ is the tensor functor of **Item 1** of **Proposition 4.2.1.1.6**.

00EM **Remark 4.4.1.1.2.** The right tensor product of pointed sets satisfies the following natural bijection:

$$\text{Sets}_*(X \triangleright Y, Z) \cong \text{Hom}_{\text{Sets}_*}^{\otimes, \mathbb{R}}(X \times Y, Z).$$

That is to say, the following data are in natural bijection:

1. Pointed maps $f : X \triangleright Y \rightarrow Z$.
2. Maps of sets $f : X \times Y \rightarrow Z$ satisfying $f(x, y_0) = z_0$ for each $x \in X$.

00EN **Remark 4.4.1.1.3.** The right tensor product of pointed sets may be described as follows:

- The right tensor product of (X, x_0) and (Y, y_0) is the pair $((X \triangleright Y, x_0 \triangleright y_0), \iota)$ consisting of

- A pointed set $(X \triangleright Y, x_0 \triangleright y_0)$;

¹⁵*Further Notation:* Also written $\triangleright_{\text{Sets}_*}$.

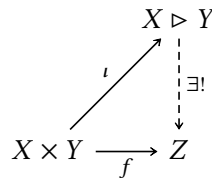
- A right bilinear morphism of pointed sets $\iota: (X \times Y, (x_0, y_0)) \rightarrow X \triangleright Y$;

satisfying the following universal property:

(UP) Given another such pair $((Z, z_0), f)$ consisting of

- * A pointed set (Z, z_0) ;
- * A right bilinear morphism of pointed sets $f: (X \times Y, (x_0, y_0)) \rightarrow X \triangleright Y$;

there exists a unique morphism of pointed sets $X \triangleright Y \xrightarrow{\exists!} Z$ making the diagram



commute.

00EP Construction 4.4.1.1.4. In detail, the **right tensor product of (X, x_0) and (Y, y_0)** is the pointed set $(X \triangleright Y, [y_0])$ consisting of:

- *The Underlying Set.* The set $X \triangleright Y$ defined by

$$\begin{aligned}
 X \triangleright Y &\stackrel{\text{def}}{=} |X| \odot Y \\
 &\cong \bigvee_{x \in X} (Y, y_0),
 \end{aligned}$$

where $|X|$ denotes the underlying set of (X, x_0) .

- *The Underlying Basepoint.* The point $[(x_0, y_0)]$ of $\bigvee_{x \in X} (Y, y_0)$, which is equal to $[(x, y_0)]$ for any $x \in X$.

00EQ Notation 4.4.1.1.5. We write¹⁶ $x \triangleright y$ for the element $[(x, y)]$ of

$$X \triangleright Y \cong |X| \odot Y.$$

00ER Remark 4.4.1.1.6. Employing the notation introduced in **Notation 4.4.1.1.5**, we have

$$x_0 \triangleright y_0 = x \triangleright y_0$$

for each $x \in X$, and

$$x \triangleright y_0 = x' \triangleright y_0$$

for each $x, x' \in X$.

¹⁶Further Notation: Also written $x \triangleright_{\text{Sets}_*} y$.

00ES Proposition 4.4.1.1.7. Let (X, x_0) and (Y, y_0) be pointed sets.

00ET 1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto X \triangleright Y$ define functors

$$\begin{aligned} X \triangleright - &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ - \triangleright Y &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ -_1 \triangleright -_2 &: \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*. \end{aligned}$$

In particular, given pointed maps

$$\begin{aligned} f &: (X, x_0) \rightarrow (A, a_0), \\ g &: (Y, y_0) \rightarrow (B, b_0), \end{aligned}$$

the induced map

$$f \triangleright g: X \triangleright Y \rightarrow A \triangleright B$$

is given by

$$[f \triangleright g](x \triangleright y) \stackrel{\text{def}}{=} f(x) \triangleright g(y)$$

for each $x \triangleright y \in X \triangleright Y$.

00EU 2. *Adjointness I.* We have an adjunction

$$\left(X \triangleright - \dashv [X, -]_{\mathbf{Sets}_*}^{\triangleright} \right): \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \triangleright -} \\ \perp \\ \xleftarrow{[X, -]_{\mathbf{Sets}_*}^{\triangleright}} \end{array} \mathbf{Sets}_*$$

witnessed by a bijection of sets

$$\text{Hom}_{\mathbf{Sets}_*}(X \triangleright Y, Z) \cong \text{Hom}_{\mathbf{Sets}_*}\left(Y, [X, Z]_{\mathbf{Sets}_*}^{\triangleright}\right)$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$, where $[X, Y]_{\mathbf{Sets}_*}^{\triangleright}$ is the pointed set of **Definition 4.4.2.1.1**.

00EV 3. *Adjointness II.* The functor

$$- \triangleright Y: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

does not admit a right adjoint.

00EW 4. *Adjointness III.* We have a bijection of sets

$$\text{Hom}_{\mathbf{Sets}_*}(X \triangleright Y, Z) \cong \text{Hom}_{\mathbf{Sets}_*}(|X|, \mathbf{Sets}_*(Y, Z))$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness I: This follows from **Item 3** of **Proposition 4.2.1.1.6**.

Item 3, Adjointness II: For $- \triangleright Y$ to admit a right adjoint would require it to preserve colimits by ?? of ??. However, we have

$$\begin{aligned} \text{pt} \triangleright X &\stackrel{\text{def}}{=} |\text{pt}| \odot X \\ &\cong X \\ &\neq \text{pt}, \end{aligned}$$

and thus we see that $- \triangleright Y$ does not have a right adjoint.

Item 4, Adjointness III: This follows from **Item 2** of **Proposition 4.2.1.1.6**. \square

00EX Remark 4.4.1.1.8. Here is some intuition on why $- \triangleright Y$ fails to be a left adjoint. **Item 4** of **Proposition 4.3.1.1.7** states that we have a natural bijection

$$\text{Hom}_{\text{Sets}_*}(X \triangleright Y, Z) \cong \text{Hom}_{\text{Sets}}(|X|, \text{Sets}_*(Y, Z)),$$

so it would be reasonable to wonder whether a natural bijection of the form

$$\text{Hom}_{\text{Sets}_*}(X \triangleright Y, Z) \cong \text{Hom}_{\text{Sets}_*}(X, \mathbf{Sets}_*(Y, Z)),$$

also holds, which would give $- \triangleright Y \dashv \mathbf{Sets}_*(Y, -)$. However, such a bijection would require every map

$$f: X \triangleright Y \rightarrow Z$$

to satisfy

$$f(x_0 \triangleright y) = z_0$$

for each $x \in X$, whereas we are imposing such a basepoint preservation condition only for elements of the form $x \triangleright y_0$. Thus $\mathbf{Sets}_*(Y, -)$ can't be a right adjoint for $- \triangleright Y$, and as shown by **Item 3** of **Proposition 4.4.1.1.7**, no functor can.¹⁷

00EY 4.4.2 The Right Internal Hom of Pointed Sets

Let (X, x_0) and (Y, y_0) be pointed sets.

00EZ Definition 4.4.2.1.1. The **right internal Hom of pointed sets** is the functor

$$[-, -]_{\text{Sets}_*}^{\triangleright}: \text{Sets}_*^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*$$

defined as the composition

$$\text{Sets}_*^{\text{op}} \times \text{Sets}_* \xrightarrow{\text{忘} \times \text{id}} \text{Sets}_*^{\text{op}} \times \text{Sets}_* \xrightarrow{\hat{\text{m}}} \text{Sets}_*,$$

where:

¹⁷The functor $\mathbf{Sets}_*(Y, -)$ is instead right adjoint to $- \wedge Y$, the smash product of pointed

- $\overline{} : \mathbf{Sets}_* \rightarrow \mathbf{Sets}$ is the forgetful functor from pointed sets to sets.
- $\pitchfork : \mathbf{Sets}^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$ is the cotensor functor of **Item 1** of **Proposition 4.2.2.1.4**.

Proof. For a proof that $[-, -]_{\mathbf{Sets}_*}^{\triangleright}$ is indeed the right internal Hom of \mathbf{Sets}_* with respect to the right tensor product of pointed sets, see **Item 2** of **Proposition 4.4.1.1.7**. \square

00F0 Remark 4.4.2.1.2. We have

$$[-, -]_{\mathbf{Sets}_*}^{\triangleleft} = [-, -]_{\mathbf{Sets}_*}^{\triangleright}.$$

00F1 Remark 4.4.2.1.3. The right internal Hom of pointed sets satisfies the following universal property:

$$\mathbf{Sets}_*(X \triangleright Y, Z) \cong \mathbf{Sets}_*\left(Y, [X, Z]_{\mathbf{Sets}_*}^{\triangleright}\right)$$

That is to say, the following data are in bijection:

1. Pointed maps $f : X \triangleright Y \rightarrow Z$.
2. Pointed maps $f : Y \rightarrow [X, Z]_{\mathbf{Sets}_*}^{\triangleright}$.

00F2 Remark 4.4.2.1.4. In detail, the **right internal Hom of (X, x_0) and (Y, y_0)** is the pointed set $\left([X, Y]_{\mathbf{Sets}_*}^{\triangleright}, [(y_0)_{x \in X}]\right)$ consisting of

- *The Underlying Set.* The set $[X, Y]_{\mathbf{Sets}_*}^{\triangleright}$ defined by

$$\begin{aligned} [X, Y]_{\mathbf{Sets}_*}^{\triangleright} &\stackrel{\text{def}}{=} |X| \pitchfork Y \\ &\cong \bigwedge_{x \in X} (Y, y_0), \end{aligned}$$

where $|X|$ denotes the underlying set of (X, x_0) ;

- *The Underlying Basepoint.* The point $[(y_0)_{x \in X}]$ of $\bigwedge_{x \in X} (Y, y_0)$.

00F3 Proposition 4.4.2.1.5. Let (X, x_0) and (Y, y_0) be pointed sets.

00F4 1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto [X, Y]_{\mathbf{Sets}_*}^{\triangleright}$ define functors

$$\begin{aligned} [X, -]_{\mathbf{Sets}_*}^{\triangleright} &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ [-, Y]_{\mathbf{Sets}_*}^{\triangleright} &: \mathbf{Sets}_*^{\text{op}} \rightarrow \mathbf{Sets}_*, \\ [-_1, -_2]_{\mathbf{Sets}_*}^{\triangleright} &: \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*. \end{aligned}$$

In particular, given pointed maps

$$\begin{aligned} f &: (X, x_0) \rightarrow (A, a_0), \\ g &: (Y, y_0) \rightarrow (B, b_0), \end{aligned}$$

the induced map

$$[f, g]_{\mathbf{Sets}_*}^{\triangleright} : [A, Y]_{\mathbf{Sets}_*}^{\triangleright} \rightarrow [X, B]_{\mathbf{Sets}_*}^{\triangleright}$$

is given by

$$[f, g]_{\mathbf{Sets}_*}^{\triangleright} \left([(y_a)_{a \in A}] \right) \stackrel{\text{def}}{=} [(g(y_{f(x)}))_{x \in X}]$$

for each $[(y_a)_{a \in A}] \in [A, Y]_{\mathbf{Sets}_*}^{\triangleright}$.

00F5 2. *Adjointness I.* We have an adjunction

$$\left(X \triangleright - \dashv [X, -]_{\mathbf{Sets}_*}^{\triangleright} \right) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \triangleright -} \\ \perp \\ \xleftarrow{[X, -]_{\mathbf{Sets}_*}^{\triangleright}} \end{array} \mathbf{Sets}_*$$

witnessed by a bijection of sets

$$\text{Hom}_{\mathbf{Sets}_*}(X \triangleright Y, Z) \cong \text{Hom}_{\mathbf{Sets}_*}\left(Y, [X, Z]_{\mathbf{Sets}_*}^{\triangleright}\right)$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$, where $[X, Y]_{\mathbf{Sets}_*}^{\triangleright}$ is the pointed set of **Definition 4.4.2.1.1**.

00F6 3. *Adjointness II.* The functor

$$- \triangleright Y : \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

does not admit a right adjoint.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness I: This is a repetition of **Item 2** of **Proposition 4.4.1.1.7**, and is proved there.

Item 3, Adjointness II: This is a repetition of **Item 3** of **Proposition 4.4.1.1.7**, and is proved there. \square

00F7 4.4.3 The Right Skew Unit

sets of **Definition 4.5.1.1.1**. See **Item 2** of **Proposition 4.5.1.1.9**.

00F8 Definition 4.4.3.1.1. The **right skew unit of the right tensor product of pointed sets** is the functor

$$\mathbb{1}^{\text{Sets}_*, \triangleright} : \text{pt} \rightarrow \text{Sets}_*$$

defined by

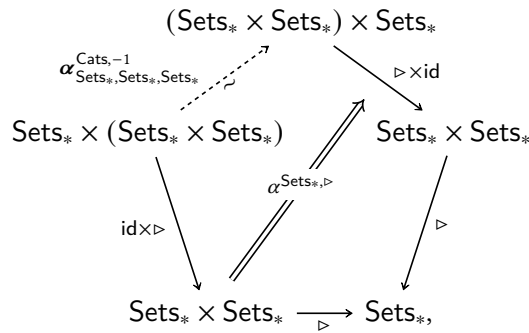
$$\mathbb{1}_{\text{Sets}_*}^{\triangleright} \stackrel{\text{def}}{=} S^0.$$

00F9 4.4.4 The Right Skew Associator

00FA Definition 4.4.4.1.1. The **skew associator of the right tensor product of pointed sets** is the natural transformation

$$\alpha^{\text{Sets}_*, \triangleright} : \triangleright \circ (\text{id}_{\text{Sets}_*} \times \triangleright) \Longrightarrow \triangleright \circ (\triangleright \times \text{id}_{\text{Sets}_*}) \circ \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}, -1}$$

as in the diagram



whose component

$$\alpha_{X, Y, Z}^{\text{Sets}_*, \triangleright} : X \triangleright (Y \triangleright Z) \rightarrow (X \triangleright Y) \triangleright Z$$

at $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$ is given by

$$\begin{aligned}
X \triangleright (Y \triangleright Z) &\stackrel{\text{def}}{=} |X| \odot (Y \triangleright Z) \\
&\stackrel{\text{def}}{=} |X| \odot (|Y| \odot Z) \\
&\cong \bigvee_{x \in X} (|Y| \odot Z) \\
&\cong \bigvee_{x \in X} \left(\bigvee_{y \in Y} Z \right) \\
&\rightarrow \bigvee_{[(x,y)] \in \bigvee_{x \in X} Y} Z \\
&\cong \bigvee_{[(x,y)] \in |X| \odot Y} Z \\
&\cong ||X| \odot Y| \odot Z \\
&\stackrel{\text{def}}{=} |X \triangleright Y| \odot Z \\
&\stackrel{\text{def}}{=} (X \triangleright Y) \triangleright Z,
\end{aligned}$$

where the map

$$\bigvee_{x \in X} \left(\bigvee_{y \in Y} Z \right) \rightarrow \bigvee_{[(x,y)] \in \bigvee_{x \in X} Y} Z$$

is given by $[(x, [(y, z)])] \mapsto [([(x, y)], z)]$.

Proof. (Proven below in a bit.) □

00FB Remark 4.4.4.1.2. Unwinding the notation for elements, we have

$$\begin{aligned}
[(x, [(y, z)])] &\stackrel{\text{def}}{=} [(x, y \triangleright z)] \\
&\stackrel{\text{def}}{=} x \triangleright (y \triangleright z)
\end{aligned}$$

and

$$\begin{aligned}
[([(x, y)], z)] &\stackrel{\text{def}}{=} [(x \triangleright y, z)] \\
&\stackrel{\text{def}}{=} (x \triangleright y) \triangleright z.
\end{aligned}$$

So, in other words, $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright}$ acts on elements via

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright} (x \triangleright (y \triangleright z)) \stackrel{\text{def}}{=} (x \triangleright y) \triangleright z$$

for each $x \triangleright (y \triangleright z) \in X \triangleright (Y \triangleright Z)$.

00FC Remark 4.4.4.1.3. Taking $y = y_0$, we see that the morphism $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright}$ acts on elements as

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright} (x \triangleright (y_0 \triangleright z)) \stackrel{\text{def}}{=} (x \triangleright y_0) \triangleright z.$$

However, by the definition of \triangleright , we have $x \triangleright y_0 = x' \triangleright y_0$ for all $x, x' \in X$, preventing $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright}$ from being non-invertible.

Proof. Firstly, note that, given $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$, the map

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright} : X \triangleright (Y \triangleright Z) \rightarrow (X \triangleright Y) \triangleright Z$$

is indeed a morphism of pointed sets, as we have

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright} (x_0 \triangleright (y_0 \triangleright z_0)) = (x_0 \triangleright y_0) \triangleright z_0.$$

Next, we claim that $\alpha^{\text{Sets}_*, \triangleright}$ is a natural transformation. We need to show that, given morphisms of pointed sets

$$\begin{aligned} f &: (X, x_0) \rightarrow (X', x'_0), \\ g &: (Y, y_0) \rightarrow (Y', y'_0), \\ h &: (Z, z_0) \rightarrow (Z', z'_0) \end{aligned}$$

the diagram

$$\begin{array}{ccc} X \triangleright (Y \triangleright Z) & \xrightarrow{f \triangleright (g \triangleright h)} & X' \triangleright (Y' \triangleright Z') \\ \alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright} \downarrow & & \downarrow \alpha_{X',Y',Z'}^{\text{Sets}_*, \triangleright} \\ (X \triangleright Y) \triangleright Z & \xrightarrow{(f \triangleright g) \triangleright h} & (X' \triangleright Y') \triangleright Z' \end{array}$$

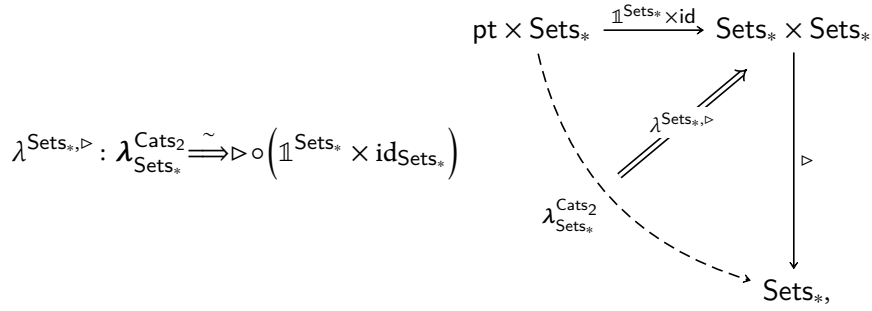
commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x \triangleright (y \triangleright z) & \longmapsto & f(x) \triangleright (g(y) \triangleright h(z)) \\ \downarrow & & \downarrow \\ (x \triangleright y) \triangleright z & \longmapsto & (f(x) \triangleright g(y)) \triangleright h(z) \end{array}$$

and hence indeed commutes, showing $\alpha^{\text{Sets}_*, \triangleright}$ to be a natural transformation. This finishes the proof. \square

00FD 4.4.5 The Right Skew Left Unitor

00FE Definition 4.4.5.1.1. The skew left unitor of the right tensor product of pointed sets is the natural transformation



whose component

$$\lambda_X^{\text{Sets}_*, \triangleright} : X \rightarrow S^0 \triangleright X$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by the composition

$$\begin{aligned} X &\rightarrow X \vee X \\ &\cong |S^0| \odot X \\ &\cong S^0 \triangleright X, \end{aligned}$$

where $X \rightarrow X \vee X$ is the map sending X to the second factor of X in $X \vee X$.

Proof. (Proven below in a bit.) □

00FF Remark 4.4.5.1.2. In other words, $\lambda_X^{\text{Sets}_*, \triangleright}$ acts on elements as

$$\lambda_X^{\text{Sets}_*, \triangleright}(x) \stackrel{\text{def}}{=} [(1, x)]$$

i.e. by

$$\lambda_X^{\text{Sets}_*, \triangleright}(x) \stackrel{\text{def}}{=} 1 \triangleright x$$

for each $x \in X$.

00FG Remark 4.4.5.1.3. The morphism $\lambda_X^{\text{Sets}_*, \triangleright}$ is non-invertible, as it is non-surjective when viewed as a map of sets, since the elements $0 \triangleright x$ of $S^0 \triangleright X$ with $x \neq x_0$ are outside the image of $\lambda_X^{\text{Sets}_*, \triangleright}$, which sends x to $1 \triangleright x$.

Proof. Firstly, note that, given $(X, x_0) \in \text{Obj}(\text{Sets}_*)$, the map

$$\lambda_X^{\text{Sets}_*, \triangleright} : X \rightarrow S^0 \triangleright X$$

is indeed a morphism of pointed sets, as we have

$$\begin{aligned} \lambda_X^{\text{Sets}_*, \triangleright}(x_0) &= 1 \triangleright x_0 \\ &= 0 \triangleright x_0. \end{aligned}$$

Next, we claim that $\lambda^{\text{Sets}_*, \triangleright}$ is a natural transformation. We need to show that, given a morphism of pointed sets

$$f: (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \lambda_X^{\text{Sets}_*, \triangleright} \downarrow & & \downarrow \lambda_Y^{\text{Sets}_*, \triangleright} \\ S^0 \triangleright X & \xrightarrow{\text{id}_{S^0} \triangleright f} & S^0 \triangleright Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x & \xrightarrow{f} & f(x) \\ \downarrow & & \downarrow \\ 1 \triangleright x & \xrightarrow{\text{id}} & 1 \triangleright f(x) \end{array}$$

and hence indeed commutes, showing $\lambda^{\text{Sets}_*, \triangleright}$ to be a natural transformation. This finishes the proof. \square

00FH 4.4.6 The Right Skew Right Unitor

00FJ Definition 4.4.6.1.1. The **skew right unitor of the right tensor product of pointed sets** is the natural transformation

$$\rho^{\text{Sets}_*, \triangleright} : \triangleright \circ (\text{id} \times \mathbb{1}^{\text{Sets}_*}) \xrightarrow{\sim} \rho_{\text{Sets}_*}^{\text{Cats}_2}$$

whose component

$$\rho_X^{\text{Sets}_*, \triangleright} : X \triangleright S^0 \rightarrow X$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by the composition

$$\begin{aligned} X \triangleright S^0 &\cong |X| \odot S^0 \\ &\cong \bigvee_{x \in X} S^0 \\ &\rightarrow X, \end{aligned}$$

where $\bigvee_{x \in X} S^0 \rightarrow X$ is the map given by

$$\begin{aligned} [(x, 0)] &\mapsto x_0, \\ [(x, 1)] &\mapsto x. \end{aligned}$$

Proof. (Proven below in a bit.) □

00FK Remark 4.4.6.1.2. In other words, $\rho_X^{\text{Sets}_*, \triangleright}$ acts on elements as

$$\begin{aligned} \rho_X^{\text{Sets}_*, \triangleright}(x \triangleright 0) &\stackrel{\text{def}}{=} x_0, \\ \rho_X^{\text{Sets}_*, \triangleright}(x \triangleright 1) &\stackrel{\text{def}}{=} x \end{aligned}$$

for each $x \triangleright 1 \in X \triangleright S^0$.

00FL Remark 4.4.6.1.3. The morphism $\rho_X^{\text{Sets}_*, \triangleright}$ is almost invertible, with its would-be-inverse

$$\phi_X: X \rightarrow X \triangleright S^0$$

given by

$$\phi_X(x) \stackrel{\text{def}}{=} x \triangleright 1$$

for each $x \in X$. Indeed, we have

$$\begin{aligned} \left[\rho_X^{\text{Sets}_*, \triangleright} \circ \phi \right](x) &= \rho_X^{\text{Sets}_*, \triangleright}(\phi(x)) \\ &= \rho_X^{\text{Sets}_*, \triangleright}(x \triangleright 1) \\ &= x \\ &= [\text{id}_X](x) \end{aligned}$$

so that

$$\rho_X^{\text{Sets}_*, \triangleright} \circ \phi = \text{id}_X$$

and

$$\begin{aligned} \left[\phi \circ \rho_X^{\text{Sets}_*, \triangleright} \right](x \triangleright 1) &= \phi\left(\rho_X^{\text{Sets}_*, \triangleright}(x \triangleright 1)\right) \\ &= \phi(x) \\ &= x \triangleright 1 \\ &= [\text{id}_{X \triangleright S^0}](x \triangleright 1), \end{aligned}$$

but

$$\begin{aligned} \left[\phi \circ \rho_X^{\text{Sets}_*, \triangleright} \right] (x \triangleright 0) &= \phi \left(\rho_X^{\text{Sets}_*, \triangleright} (x \triangleright 0) \right) \\ &= \phi(x_0) \\ &= 1 \triangleright x_0, \end{aligned}$$

where $x \triangleright 0 \neq 1 \triangleright x_0$. Thus

$$\phi \circ \rho_X^{\text{Sets}_*, \triangleright} \stackrel{?}{=} \text{id}_{X \triangleright S^0}$$

holds for all elements in $X \triangleright S^0$ except one.

Proof. Firstly, note that, given $(X, x_0) \in \text{Obj}(\text{Sets}_*)$, the map

$$\rho_X^{\text{Sets}_*, \triangleright} : X \triangleright S^0 \rightarrow X$$

is indeed a morphism of pointed sets as we have

$$\rho_X^{\text{Sets}_*, \triangleright} (x_0 \triangleright 0) = x_0.$$

Next, we claim that $\rho^{\text{Sets}_*, \triangleright}$ is a natural transformation. We need to show that, given a morphism of pointed sets

$$f: (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc} X \triangleright S^0 & \xrightarrow{f \triangleright \text{id}_{S^0}} & Y \triangleright S^0 \\ \rho_X^{\text{Sets}_*, \triangleright} \downarrow & & \downarrow \rho_Y^{\text{Sets}_*, \triangleright} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x \triangleright 0 & & x \triangleright 0 \longmapsto f(x) \triangleright 0 \\ \downarrow & & \downarrow \\ x_0 & \longmapsto & f(x_0) \\ & & y_0 \end{array}$$

and

$$\begin{array}{ccc} x \triangleright 1 & \longmapsto & f(x) \triangleright 1 \\ \downarrow & & \downarrow \\ x & \longmapsto & f(x) \end{array}$$

and hence indeed commutes, showing $\rho^{\text{Sets}_*, \triangleright}$ to be a natural transformation. This finishes the proof. \square

00FM 4.4.7 The Diagonal

00FN Definition 4.4.7.1.1. The **diagonal of the right tensor product of pointed sets** is the natural transformation

$$\Delta^\triangleright : \text{id}_{\text{Sets}_*} \implies \triangleright \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2}$$

whose component

$$\Delta_X^\triangleright : (X, x_0) \rightarrow (X \triangleright X, x_0 \triangleright x_0)$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by

$$\Delta_X^\triangleright(x) \stackrel{\text{def}}{=} x \triangleright x$$

for each $x \in X$.

Proof. Being a Morphism of Pointed Sets: We have

$$\Delta_X^\triangleright(x_0) \stackrel{\text{def}}{=} x_0 \triangleright x_0,$$

and thus Δ_X^\triangleright is a morphism of pointed sets.

Naturality: We need to show that, given a morphism of pointed sets

$$f : (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \Delta_X^\triangleright \downarrow & & \downarrow \Delta_Y^\triangleright \\ X \triangleright X & \xrightarrow{f \triangleright f} & Y \triangleright Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x & \longmapsto & f(x) \\ \downarrow & & \downarrow \\ x \triangleright x & \longmapsto & f(x) \triangleright f(x) \end{array}$$

and hence indeed commutes, showing Δ^\triangleright to be natural. □

4.4.8 The Right Skew Monoidal Structure on Pointed Sets Associated to \triangleright

00FP

00FQ **Proposition 4.4.8.1.1.** The category \mathbf{Sets}_* admits a right-closed right skew monoidal category structure consisting of

- *The Underlying Category.* The category \mathbf{Sets}_* of pointed sets;
- *The Right Skew Monoidal Product.* The right tensor product functor

$$\triangleright : \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

of **Definition 4.4.1.1.1**;

- *The Right Internal Skew Hom.* The right internal Hom functor

$$[-, -]_{\mathbf{Sets}_*}^{\triangleright} : \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

of **Definition 4.4.2.1.1**;

- *The Right Skew Monoidal Unit.* The functor

$$\mathbb{1}^{\mathbf{Sets}_*, \triangleright} : \text{pt} \rightarrow \mathbf{Sets}_*$$

of **Definition 4.4.3.1.1**;

- *The Right Skew Associators.* The natural transformation

$$\alpha^{\mathbf{Sets}_*, \triangleright} : \triangleright \circ (\text{id}_{\mathbf{Sets}_*} \times \triangleright) \Longrightarrow \triangleright \circ (\triangleright \times \text{id}_{\mathbf{Sets}_*}) \circ \alpha_{\mathbf{Sets}_*, \mathbf{Sets}_*, \mathbf{Sets}_*}^{\mathbf{Cats}, -1}$$

of **Definition 4.4.4.1.1**;

- *The Right Skew Left Unitors.* The natural transformation

$$\lambda^{\mathbf{Sets}_*, \triangleright} : \lambda_{\mathbf{Sets}_*}^{\mathbf{Cats}_2} \xrightarrow{\sim} \triangleright \circ (\mathbb{1}^{\mathbf{Sets}_*} \times \text{id}_{\mathbf{Sets}_*})$$

of **Definition 4.4.5.1.1**;

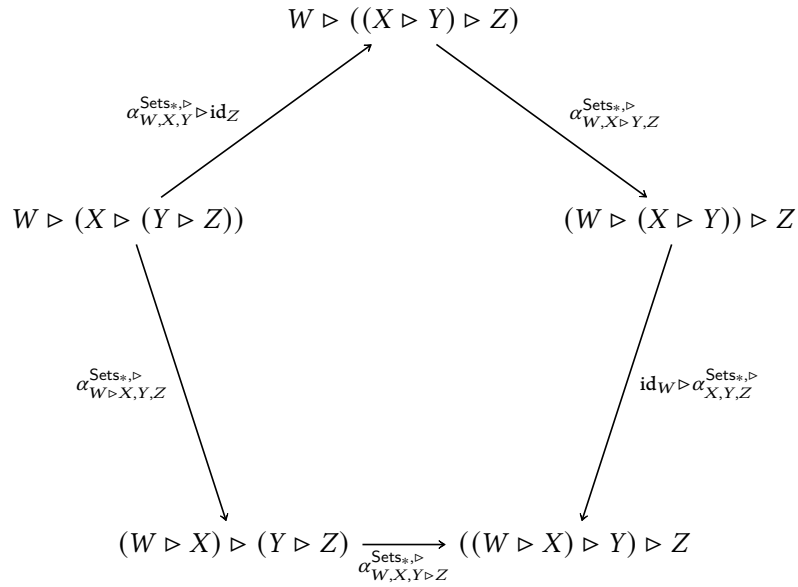
- *The Right Skew Right Unitors.* The natural transformation

$$\rho^{\mathbf{Sets}_*, \triangleright} : \triangleright \circ (\text{id} \times \mathbb{1}^{\mathbf{Sets}_*}) \xrightarrow{\sim} \rho_{\mathbf{Sets}_*}^{\mathbf{Cats}_2}$$

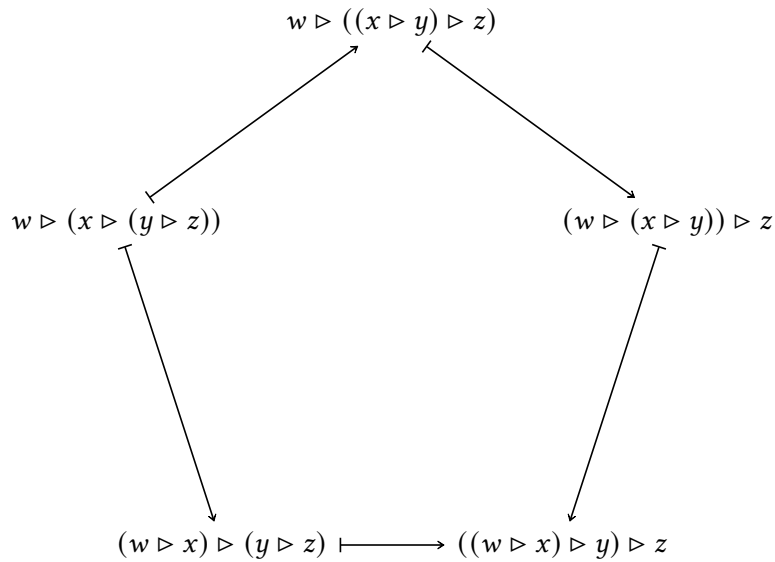
of **Definition 4.4.6.1.1**.

Proof. The Pentagon Identity: Let (W, w_0) , (X, x_0) , (Y, y_0) and (Z, z_0) be

pointed sets. We have to show that the diagram



commutes. Indeed, this diagram acts on elements as



and thus we see that the pentagon identity is satisfied.

The Right Skew Left Triangle Identity: Let (X, x_0) and (Y, y_0) be pointed sets.

We have to show that the diagram

$$\begin{array}{ccc}
 X \triangleright Y & & \\
 \lambda_{X \triangleright Y}^{\text{Sets}_*, \triangleright} \downarrow & \searrow \lambda_X^{\text{Sets}_*, \triangleright} \triangleright \text{id}_Y & \\
 S^0 \triangleright (X \triangleright Y) & \xrightarrow{\alpha_{S^0, X, Y}^{\text{Sets}_*, \triangleright}} & (S^0 \triangleright X) \triangleright Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 x \triangleright y & & \\
 \downarrow & \searrow & \\
 1 \triangleright (x \triangleright y) & \mapsto & (1 \triangleright x) \triangleright y
 \end{array}$$

and hence indeed commutes. Thus the left skew triangle identity is satisfied.

The Right Skew Right Triangle Identity: Let (X, x_0) and (Y, y_0) be pointed sets. We have to show that the diagram

$$\begin{array}{ccc}
 X \triangleright (Y \triangleright S^0) & \xrightarrow{\text{id}_X \triangleright \rho_Y^{\text{Sets}_*, \triangleright}} & (X \triangleright Y) \triangleright S^0 \\
 \searrow \alpha_{S^0, X, Y}^{\text{Sets}_*, \triangleright} & & \downarrow \rho_{X \triangleright Y}^{\text{Sets}_*, \triangleright} \\
 & & X \triangleright Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 x \triangleright (y \triangleright 0) & \mapsto & (x \triangleright y) \triangleright 0 \\
 \searrow & & \downarrow \\
 & & x \triangleright y_0 = x_0 \triangleright y_0
 \end{array}$$

and

$$\begin{array}{ccc}
 x \triangleright (y \triangleright 1) & \mapsto & (x \triangleright y) \triangleright 1 \\
 \searrow & & \downarrow \\
 & & x \triangleright y
 \end{array}$$

and hence indeed commutes. Thus the right skew triangle identity is satisfied.

The Right Skew Middle Triangle Identity: Let (X, x_0) and (Y, y_0) be pointed

sets. We have to show that the diagram

$$\begin{array}{ccc}
 X \triangleright Y & \xlongequal{\quad} & X \triangleright Y \\
 \text{id}_X \triangleright \lambda_Y^{\text{Sets}_*, \triangleright} \downarrow & & \uparrow \rho_X^{\text{Sets}_*, \triangleright} \triangleright \text{id}_Y \\
 X \triangleright (S^0 \triangleright Y) & \xrightarrow{\alpha_{X, S^0, Y}^{\text{Sets}_*, \triangleright}} & (X \triangleright S^0) \triangleright Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 x \triangleright y & \xrightarrow{\quad} & x \triangleright y \\
 \downarrow & & \uparrow \\
 x \triangleright (1 \triangleright y) & \xrightarrow{\quad} & (x \triangleright 1) \triangleright y
 \end{array}$$

and hence indeed commutes. Thus the right skew triangle identity is satisfied.

The Zig-Zag Identity: We have to show that the diagram

$$\begin{array}{ccc}
 S^0 & \xrightarrow{\lambda_{S^0}^{\text{Sets}_*, \triangleright}} & S^0 \triangleright S^0 \\
 \parallel & & \downarrow \rho_{S^0}^{\text{Sets}_*, \triangleright} \\
 & & S^0
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 0 & \xrightarrow{\quad} & 1 \triangleright 0 \\
 \swarrow & & \downarrow \\
 & & 0
 \end{array}$$

and

$$\begin{array}{ccc}
 1 & \xrightarrow{\quad} & 1 \triangleright 1 \\
 \swarrow & & \downarrow \\
 & & 1
 \end{array}$$

and hence indeed commutes. Thus the zig-zag identity is satisfied.

Right Skew Monoidal Right-Closedness: This follows from **Item 2** of **Proposition 4.4.1.1.7**. □

4.4.9 Monoids With Respect to the Right Tensor Product of Pointed Sets

00FR

00FS Proposition 4.4.9.1.1. The category of monoids on $(\text{Sets}_*, \triangleright, S^0)$ is isomorphic to the category of “monoids with right zero”¹⁸ and morphisms between them.

Proof. Monoids on $(\text{Sets}_*, \triangleright, S^0)$: A monoid on $(\text{Sets}_*, \triangleright, S^0)$ consists of:

- *The Underlying Object.* A pointed set $(A, 0_A)$.
- *The Multiplication Morphism.* A morphism of pointed sets

$$\mu_A: A \triangleright A \rightarrow A,$$

determining a right bilinear morphism of pointed sets

$$\begin{aligned} A \times A &\longrightarrow A \\ (a, b) &\longmapsto ab. \end{aligned}$$

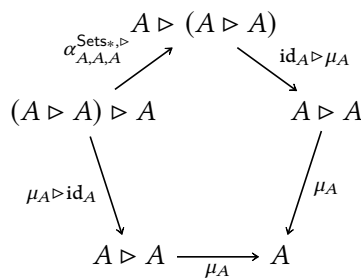
- *The Unit Morphism.* A morphism of pointed sets

$$\eta_A: S^0 \rightarrow A$$

picking an element 1_A of A .

satisfying the following conditions:

1. *Associativity.* The diagram

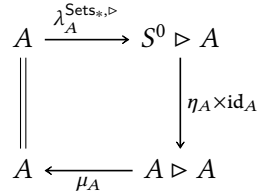


¹⁸A monoid with right zero is defined similarly as the monoids with zero of ???. Succinctly, they are monoids (A, μ_A, η_A) with a special element 0_A satisfying

$$0_A a = 0_A$$

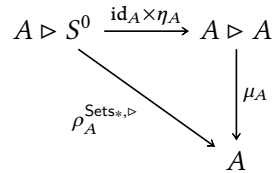
for each $a \in A$.

2. *Left Unitality.* The diagram



commutes.

3. *Right Unitality.* The diagram



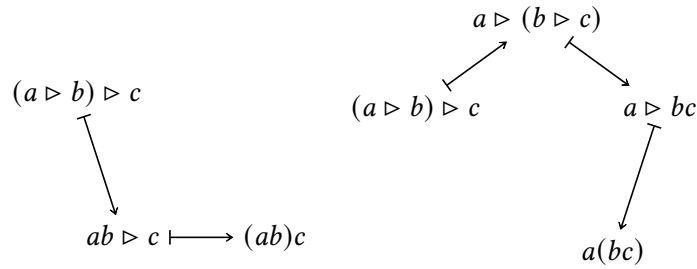
commutes.

Being a right-bilinear morphism of pointed sets, the multiplication map satisfies

$$0_A a = 0_A$$

for each $a \in A$. Now, the associativity, left unitality, and right unitality conditions act on elements as follows:

1. *Associativity.* The associativity condition acts as

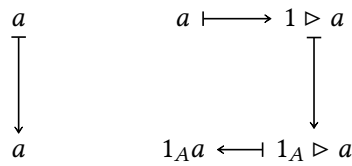


This gives

$$(ab)c = a(bc)$$

for each $a, b, c \in A$.

2. *Left Unitality.* The left unitality condition acts as



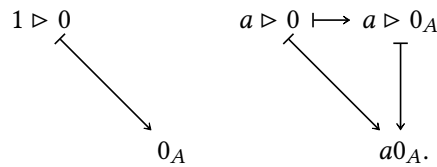
This gives

$$1_A a = a$$

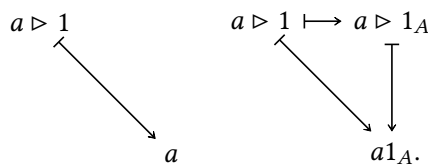
for each $a \in A$.

3. *Right Unitality.* The right unitality condition acts:

(a) On $1 \triangleright 0$ as



(b) On $a \triangleright 1$ as



This gives

$$\begin{aligned} a 1_A &= a, \\ a 0_A &= 0_A \end{aligned}$$

for each $a \in A$.

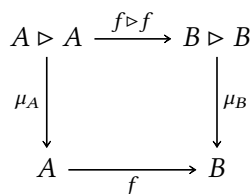
Thus we see that monoids with respect to \triangleright are exactly monoids with right zero.

Morphisms of Monoids on $(\text{Sets}_, \triangleright, S^0)$:* A morphism of monoids on $(\text{Sets}_*, \triangleright, S^0)$ from $(A, \mu_A, \eta_A, 0_A)$ to $(B, \mu_B, \eta_B, 0_B)$ is a morphism of pointed sets

$$f: (A, 0_A) \rightarrow (B, 0_B)$$

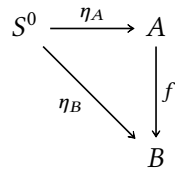
satisfying the following conditions:

1. *Compatibility With the Multiplication Morphisms.* The diagram



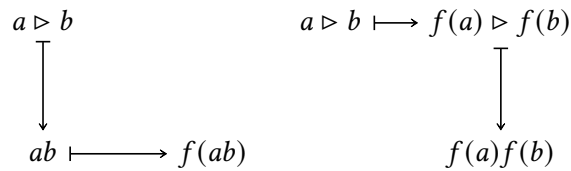
commutes.

2. *Compatibility With the Unit Morphisms.* The diagram

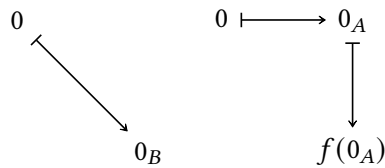


commutes.

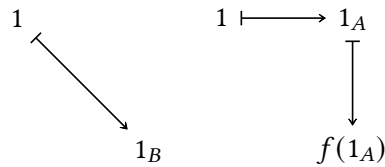
These act on elements as



and



and



giving

$$\begin{aligned}
 f(ab) &= f(a)f(b), \\
 f(0_A) &= 0_B, \\
 f(1_A) &= 1_B,
 \end{aligned}$$

for each $a, b \in A$, which is exactly a morphism of monoids with right zero.

Identities and Composition: Similarly, the identities and composition of $\text{Mon}(\text{Sets}_*, \triangleright, S^0)$ can be easily seen to agree with those of monoids with right zero, which finishes the proof. \square

00FT 4.5 The Smash Product of Pointed Sets

00FU 4.5.1 Foundations

Let (X, x_0) and (Y, y_0) be pointed sets.

00FV Definition 4.5.1.1.1. The **smash product of (X, x_0) and (Y, y_0)** ¹⁹ is the pointed set $X \wedge Y$ ²⁰ satisfying the bijection

$$\text{Sets}_*(X \wedge Y, Z) \cong \text{Hom}_{\text{Sets}_*}^{\otimes}(X \times Y, Z),$$

naturally in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$.

00FW Remark 4.5.1.1.2. That is to say, the smash product of pointed sets is defined so as to induce a bijection between the following data:

- Pointed maps $f: X \wedge Y \rightarrow Z$.
- Maps of sets $f: X \times Y \rightarrow Z$ satisfying

$$f(x_0, y) = z_0,$$

$$f(x, y_0) = z_0$$

for each $x \in X$ and each $y \in Y$.

00FX Remark 4.5.1.1.3. The smash product of pointed sets may be described as follows:

- The smash product of (X, x_0) and (Y, y_0) is the pair $((X \wedge Y, x_0 \wedge y_0), \iota)$ consisting of
 - A pointed set $(X \wedge Y, x_0 \wedge y_0)$;
 - A bilinear morphism of pointed sets $\iota: (X \times Y, (x_0, y_0)) \rightarrow X \wedge Y$;

satisfying the following universal property:

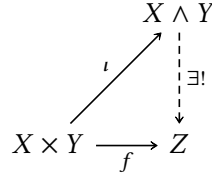
(UP) Given another such pair $((Z, z_0), f)$ consisting of

- * A pointed set (Z, z_0) ;
- * A bilinear morphism of pointed sets $f: (X \times Y, (x_0, y_0)) \rightarrow X \wedge Y$;

¹⁹*Further Terminology:* In the context of monoids with zero as models for \mathbb{F}_1 -algebras, the smash product $X \wedge Y$ is also called the **tensor product of \mathbb{F}_1 -modules of (X, x_0) and (Y, y_0)** or the **tensor product of (X, x_0) and (Y, y_0) over \mathbb{F}_1** .

²⁰*Further Notation:* In the context of monoids with zero as models for \mathbb{F}_1 -algebras, the

there exists a unique morphism of pointed sets $X \wedge Y \xrightarrow{\exists!} Z$ making the diagram



commute.

00FY Construction 4.5.1.1.4. Concretely, the **smash product of (X, x_0) and (Y, y_0)** is the pointed set $(X \wedge Y, x_0 \wedge y_0)$ consisting of

- *The Underlying Set.* The set $X \wedge Y$ defined by

$$X \wedge Y \cong (X \times Y) / \sim_R,$$

where \sim_R is the equivalence relation on $X \times Y$ obtained by declaring

$$\begin{aligned}
 (x_0, y) &\sim_R (x_0, y'), \\
 (x, y_0) &\sim_R (x', y_0)
 \end{aligned}$$

for each $x, x' \in X$ and each $y, y' \in Y$;

- *The Basepoint.* The element $[(x_0, y_0)]$ of $X \wedge Y$ given by the equivalence class of (x_0, y_0) under the equivalence relation \sim on $X \times Y$.

Proof. By **Item 6 of Proposition 7.5.2.1.3**, we have a natural bijection

$$\text{Sets}_*(X \wedge Y, Z) \cong \text{Hom}_{\text{Sets}}^R(X \times Y, Z).$$

Now, by definition, $\text{Hom}_{\text{Sets}}^R(X \times Y, Z)$ is the set

$$\text{Hom}_{\text{Sets}}^R(X \times Y, Z) \stackrel{\text{def}}{=} \left\{ f \in \text{Hom}_{\text{Sets}}(X \times Y, Z) \left| \begin{array}{l} \text{for each } x, y \in X, \text{ if} \\ (x, y) \sim_R (x', y'), \text{ then} \\ f(x, y) = f(x', y') \end{array} \right. \right\}.$$

However, the condition $(x, y) \sim_R (x', y')$ only holds when:

1. We have $x = x'$ and $y = y'$.
2. The following conditions are satisfied:

smash product $X \wedge Y$ is also denoted $X \otimes_{\mathbb{F}_1} Y$.

(a) We have $x = x_0$ or $y = y_0$.

(b) We have $x' = x_0$ or $y' = y_0$.

So, given $f \in \text{Hom}_{\text{Sets}}(X \times Y, Z)$ with a corresponding $\bar{f}: X \wedge Y \rightarrow Z$, the latter case above implies

$$\begin{aligned} f(x_0, y) &= f(x, y_0) \\ &= f(x_0, y_0), \end{aligned}$$

and since $\bar{f}: X \wedge Y \rightarrow Z$ is a pointed map, we have

$$\begin{aligned} f(x_0, y_0) &= \bar{f}(x_0, y_0) \\ &= z_0. \end{aligned}$$

Thus the elements f in $\text{Hom}_{\text{Sets}}(X \times Y, Z)$ are precisely those functions $f: X \times Y \rightarrow Z$ satisfying the equalities

$$\begin{aligned} f(x_0, y) &= z_0, \\ f(x, y_0) &= z_0 \end{aligned}$$

for each $x \in X$ and each $y \in Y$, giving an equality

$$\text{Hom}_{\text{Sets}}^R(X \times Y, Z) = \text{Hom}_{\text{Sets}_*}^{\otimes}(X \times Y, Z)$$

of sets, which when composed with our earlier isomorphism

$$\text{Sets}_*(X \wedge Y, Z) \cong \text{Hom}_{\text{Sets}}^R(X \times Y, Z)$$

gives our desired natural bijection, finishing the proof. \square

00FZ Remark 4.5.1.1.5. It is also somewhat common to write

$$X \wedge Y \stackrel{\text{def}}{=} \frac{X \times Y}{X \vee Y},$$

identifying $X \vee Y$ with the subspace $(\{x_0\} \times Y) \cup (X \times \{y_0\})$ of $X \times Y$, and having the quotient be defined by declaring $(x, y) \sim (x', y')$ iff we have $(x, y), (x', y') \in X \vee Y$.

00G0 Notation 4.5.1.1.6. We write $x \wedge y$ for the element $[(x, y)]$ of

$$X \wedge Y \cong X \times Y / \sim.$$

00G1 Remark 4.5.1.1.7. Employing the notation introduced in **Notation 4.5.1.1.6**, we have

$$\begin{aligned}x_0 \wedge y_0 &= x \wedge y_0, \\ &= x_0 \wedge y\end{aligned}$$

for each $x \in X$ and each $y \in Y$, and

$$\begin{aligned}x \wedge y_0 &= x' \wedge y_0, \\ x_0 \wedge y &= x_0 \wedge y'\end{aligned}$$

for each $x, x' \in X$ and each $y, y' \in Y$.

00G2 Example 4.5.1.1.8. Here are some examples of smash products of pointed sets.

00G3 1. *Smashing With pt.* For any pointed set X , we have isomorphisms of pointed sets

$$\begin{aligned}\text{pt} \wedge X &\cong \text{pt}, \\ X \wedge \text{pt} &\cong \text{pt}.\end{aligned}$$

00G4 2. *Smashing With S^0 .* For any pointed set X , we have isomorphisms of pointed sets

$$\begin{aligned}S^0 \wedge X &\cong X, \\ X \wedge S^0 &\cong X.\end{aligned}$$

00G5 Proposition 4.5.1.1.9. Let (X, x_0) and (Y, y_0) be pointed sets.

00G6 1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto X \wedge Y$ define functors

$$\begin{aligned}X \wedge -: \text{Sets}_* &\rightarrow \text{Sets}_*, \\ - \wedge Y: \text{Sets}_* &\rightarrow \text{Sets}_*, \\ -_1 \wedge -_2: \text{Sets}_* \times \text{Sets}_* &\rightarrow \text{Sets}_*.\end{aligned}$$

In particular, given pointed maps

$$\begin{aligned}f: (X, x_0) &\rightarrow (A, a_0), \\ g: (Y, y_0) &\rightarrow (B, b_0),\end{aligned}$$

the induced map

$$f \wedge g: X \wedge Y \rightarrow A \wedge B$$

is given by

$$[f \wedge g](x \wedge y) \stackrel{\text{def}}{=} f(x) \wedge g(y)$$

for each $x \wedge y \in X \wedge Y$.

00G7 2. *Adjointness.* We have adjunctions

$$(X \wedge - \dashv \mathbf{Sets}_*(X, -)) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*$$

$$(- \wedge Y \dashv \mathbf{Sets}_*(Y, -)) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*$$

witnessed by bijections

$$\begin{aligned} \text{Hom}_{\mathbf{Sets}_*}(X \wedge Y, Z) &\cong \text{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(Y, Z)), \\ \text{Hom}_{\mathbf{Sets}_*}(X \wedge Y, Z) &\cong \text{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(A, Z)), \end{aligned}$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

00G8 3. *Enriched Adjointness.* We have \mathbf{Sets}_* -enriched adjunctions

$$(X \wedge - \dashv \mathbf{Sets}_*(X, -)) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*$$

$$(- \wedge Y \dashv \mathbf{Sets}_*(Y, -)) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*$$

witnessed by isomorphisms of pointed sets

$$\begin{aligned} \mathbf{Sets}_*(X \wedge Y, Z) &\cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(Y, Z)), \\ \mathbf{Sets}_*(X \wedge Y, Z) &\cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(A, Z)), \end{aligned}$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

00G9 4. *As a Pushout.* We have an isomorphism

$$X \wedge Y \cong \text{pt} \coprod_{X \vee Y} (X \times Y)$$

$$\begin{array}{ccc} X \wedge Y & \longleftarrow & X \times Y \\ \uparrow \ulcorner & & \uparrow \lrcorner \\ \text{pt} & \longleftarrow & X \vee Y \end{array}$$

natural in $X, Y \in \text{Obj}(\text{Sets}_*)$, where the pushout is taken in Sets , and the embedding $\iota: X \vee Y \hookrightarrow X \times Y$ is defined following [Remark 4.5.1.1.5](#).

00GA 5. *Distributivity Over Wedge Sums.* We have isomorphisms of pointed sets

$$\begin{aligned} X \wedge (Y \vee Z) &\cong (X \wedge Y) \vee (X \wedge Z), \\ (X \vee Y) \wedge Z &\cong (X \wedge Z) \vee (Y \wedge Z), \end{aligned}$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$.

Proof. Item 1, Functoriality: The map $f \wedge g$ comes from [Item 4 of Proposition 7.5.2.1.3](#) via the map

$$f \wedge g: X \times Y \rightarrow A \wedge B$$

sending (x, y) to $f(x) \wedge g(y)$, which we need to show satisfies

$$[f \wedge g](x, y) = [f \wedge g](x', y')$$

for each $(x, y), (x', y') \in X \times Y$ with $(x, y) \sim_R (x', y')$, where \sim_R is the relation constructing $X \wedge Y$ as

$$X \wedge Y \cong (X \times Y) / \sim_R$$

in [Construction 4.5.1.1.4](#). The condition defining \sim is that at least one of the following conditions is satisfied:

1. We have $x = x'$ and $y = y'$;
2. Both of the following conditions are satisfied:
 - (a) We have $x = x_0$ or $y = y_0$.
 - (b) We have $x' = x_0$ or $y' = y_0$.

We have five cases:

1. In the first case, we clearly have

$$[f \wedge g](x, y) = [f \wedge g](x', y')$$

since $x = x'$ and $y = y'$.

2. If $x = x_0$ and $x' = x_0$, we have

$$\begin{aligned} [f \wedge g](x_0, y) &\stackrel{\text{def}}{=} f(x_0) \wedge g(y) \\ &= a_0 \wedge g(y) \\ &= a_0 \wedge g(y') \\ &= f(x_0) \wedge g(y') \\ &\stackrel{\text{def}}{=} [f \wedge g](x_0, y'). \end{aligned}$$

3. If $x = x_0$ and $y' = y_0$, we have

$$\begin{aligned} [f \wedge g](x_0, y) &\stackrel{\text{def}}{=} f(x_0) \wedge g(y) \\ &= a_0 \wedge g(y) \\ &= a_0 \wedge b_0 \\ &= f(x') \wedge b_0 \\ &= f(x') \wedge g(y_0) \\ &\stackrel{\text{def}}{=} [f \wedge g](x', y_0). \end{aligned}$$

4. If $y = y_0$ and $x' = x_0$, we have

$$\begin{aligned} [f \wedge g](x, y_0) &\stackrel{\text{def}}{=} f(x) \wedge g(y_0) \\ &= f(x) \wedge b_0 \\ &= a_0 \wedge b_0 \\ &= a_0 \wedge g(y') \\ &= f(x_0) \wedge g(y') \\ &\stackrel{\text{def}}{=} [f \wedge g](x_0, y'). \end{aligned}$$

5. If $y = y_0$ and $y' = y_0$, we have

$$\begin{aligned} [f \wedge g](x, y_0) &\stackrel{\text{def}}{=} f(x) \wedge g(y_0) \\ &= f(x) \wedge b_0 \\ &= f(x') \wedge b_0 \\ &= f(x) \wedge g(y_0) \\ &\stackrel{\text{def}}{=} [f \wedge g](x', y_0). \end{aligned}$$

Thus $f \wedge g$ is well-defined. Next, we claim that \wedge preserves identities and composition:

- *Preservation of Identities.* We have

$$\begin{aligned} [\text{id}_X \wedge \text{id}_Y](x \wedge y) &\stackrel{\text{def}}{=} \text{id}_X(x) \wedge \text{id}_Y(y) \\ &= x \wedge y \\ &= [\text{id}_{X \wedge Y}](x \wedge y) \end{aligned}$$

for each $x \wedge y \in X \wedge Y$, and thus

$$\text{id}_X \wedge \text{id}_Y = \text{id}_{X \wedge Y}.$$

- *Preservation of Composition.* Given pointed maps

$$\begin{aligned} f: (X, x_0) &\rightarrow (X', x'_0), \\ h: (X', x'_0) &\rightarrow (X'', x''_0), \\ g: (Y, y_0) &\rightarrow (Y', y'_0), \\ k: (Y', y'_0) &\rightarrow (Y'', y''_0), \end{aligned}$$

we have

$$\begin{aligned} [(h \circ f) \wedge (k \circ g)](x \wedge y) &\stackrel{\text{def}}{=} h(f(x)) \wedge k(g(y)) \\ &\stackrel{\text{def}}{=} [h \wedge k](f(x) \wedge g(y)) \\ &\stackrel{\text{def}}{=} [h \wedge k]([f \wedge g](x \wedge y)) \\ &\stackrel{\text{def}}{=} [(h \wedge k) \circ (f \wedge g)](x \wedge y) \end{aligned}$$

for each $x \wedge y \in X \wedge Y$, and thus

$$(h \circ f) \wedge (k \circ g) = (h \wedge k) \circ (f \wedge g).$$

This finishes the proof.

Item 2, Adjointness: We prove only the adjunction $- \wedge Y \dashv \mathbf{Sets}_*(Y, -)$, witnessed by a natural bijection

$$\text{Hom}_{\mathbf{Sets}_*}(X \wedge Y, Z) \cong \text{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(Y, Z)),$$

as the proof of the adjunction $X \wedge - \dashv \mathbf{Sets}_*(X, -)$ is similar. We claim we have a bijection

$$\text{Hom}_{\mathbf{Sets}_*}^{\otimes}(X \times Y, Z) \cong \text{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(Y, Z))$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$, implying the desired adjunction. Indeed, this bijection is a restriction of the bijection

$$\text{Sets}(X \times Y, Z) \cong \text{Sets}(X, \text{Sets}(Y, Z))$$

of *Item 2* of [Proposition 2.1.3.1.2](#):

- A map

$$\xi: X \times Y \rightarrow Z$$

in $\text{Hom}_{\mathbf{Sets}_*}^{\otimes}(X \times Y, Z)$ gets sent to the pointed map

$$\begin{aligned} \xi^\dagger: (X, x_0) &\rightarrow (\mathbf{Sets}_*(Y, Z), \Delta_{z_0}), \\ x &\longmapsto (\xi_x^\dagger: Y \rightarrow Z), \end{aligned}$$

where $\xi_x^\dagger: Y \rightarrow Z$ is the map defined by

$$\xi_x^\dagger(y) \stackrel{\text{def}}{=} \xi(x, y)$$

for each $y \in Y$, where:

- The map ξ^\dagger is indeed pointed, as we have

$$\begin{aligned} \xi_{x_0}^\dagger(y) &\stackrel{\text{def}}{=} \xi(x_0, y) \\ &\stackrel{\text{def}}{=} z_0 \end{aligned}$$

for each $y \in Y$. Thus $\xi_{x_0}^\dagger = \Delta_{z_0}$ and ξ^\dagger is pointed.

- The map ξ_x^\dagger indeed lies in $\mathbf{Sets}_*(Y, Z)$, as we have

$$\begin{aligned} \xi_x^\dagger(y_0) &\stackrel{\text{def}}{=} \xi(x, y_0) \\ &\stackrel{\text{def}}{=} z_0. \end{aligned}$$

- Conversely, a map

$$\begin{aligned} \xi: (X, x_0) &\rightarrow (\mathbf{Sets}_*(Y, Z), \Delta_{z_0}), \\ x &\longmapsto (\xi_x: Y \rightarrow Z), \end{aligned}$$

in $\text{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(Y, Z))$ gets sent to the map

$$\xi^\dagger: X \times Y \rightarrow Z$$

defined by

$$\xi^\dagger(x, y) \stackrel{\text{def}}{=} \xi_x(y)$$

for each $(x, y) \in X \times Y$, which indeed lies in $\text{Hom}_{\mathbf{Sets}_*}^{\otimes}(X \times Y, Z)$, as:

- *Left Bilinearity.* We have

$$\begin{aligned} \xi^\dagger(x_0, y) &\stackrel{\text{def}}{=} \xi_{x_0}(y) \\ &\stackrel{\text{def}}{=} \Delta_{z_0}(y) \\ &\stackrel{\text{def}}{=} z_0 \end{aligned}$$

for each $y \in Y$, since $\xi_{x_0} = \Delta_{z_0}$ as ξ is assumed to be a pointed map.

– *Right Bilinearity.* We have

$$\xi^\dagger(x, y_0) \stackrel{\text{def}}{=} \xi_x(y_0) \\ \stackrel{\text{def}}{=} z_0$$

for each $x \in X$, since $\xi_x \in \mathbf{Sets}_*(Y, Z)$ is a morphism of pointed sets.

This finishes the proof.

Item 3, Enriched Adjointness: This follows from *Item 2* and ?? of ??.

Item 4, As a Pushout: Following the description of *Remark 2.2.4.1.2*, we have

$$\text{pt} \coprod_{X \vee Y} (X \times Y) \cong (\text{pt} \times (X \times Y)) / \sim,$$

where \sim identifies the element \star in pt with all elements of the form (x_0, y) and (x, y_0) in $X \times Y$. Thus *Item 4* of *Proposition 7.5.2.1.3* coupled with *Remark 4.5.1.1.7* then gives us a well-defined map

$$\text{pt} \coprod_{X \vee Y} (X \times Y) \rightarrow X \wedge Y$$

via $[(\star, (x, y))] \mapsto x \wedge y$, with inverse

$$X \wedge Y \rightarrow \text{pt} \coprod_{X \vee Y} (X \times Y)$$

given by $x \wedge y \mapsto [(\star, (x, y))]$.

Item 5, Distributivity Over Wedge Sums: This follows from *Proposition 4.5.9.1.1*, ?? of ??, and the fact that \vee is the coproduct in \mathbf{Sets}_* (*Definition 3.3.3.1.1*). \square

00GB 4.5.2 The Internal Hom of Pointed Sets

Let (X, x_0) and (Y, y_0) be pointed sets.

00GC Definition 4.5.2.1.1. The **internal Hom**²¹ of pointed sets from (X, x_0) to (Y, y_0) is the pointed set $\mathbf{Sets}_*((X, x_0), (Y, y_0))$ ²² consisting of:

- *The Underlying Set.* The set $\mathbf{Sets}_*((X, x_0), (Y, y_0))$ of morphisms of pointed sets from (X, x_0) to (Y, y_0) .
- *The Basepoint.* The element

$$\Delta_{y_0} : (X, x_0) \rightarrow (Y, y_0)$$

²¹The pointed set $\mathbf{Sets}_*(X, Y)$ is the internal **Hom** of \mathbf{Sets}_* with respect to the smash product of *Definition 4.5.1.1.1*; see *Item 2* of *Proposition 4.5.1.1.9*.

²²*Further Notation:* Also written $\mathbf{Homs}_{\mathbf{Sets}_*}(X, Y)$.

of $\mathbf{Sets}_*((X, x_0), (Y, y_0))$ given by

$$\Delta_{y_0}(x) \stackrel{\text{def}}{=} y_0$$

for each $x \in X$.

Proof. For a proof that \mathbf{Sets}_* is indeed the internal Hom of \mathbf{Sets}_* with respect to the smash product of pointed sets, see **Item 2** of **Proposition 4.5.1.1.9**. \square

00GD **Proposition 4.5.2.1.2.** Let (X, x_0) and (Y, y_0) be pointed sets.

00GE 1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto \mathbf{Sets}_*(X, Y)$ define functors

$$\begin{aligned} \mathbf{Sets}_*(X, -) &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ \mathbf{Sets}_*(-, Y) &: \mathbf{Sets}_*^{\text{op}} \rightarrow \mathbf{Sets}_*, \\ \mathbf{Sets}_*(-, -) &: \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*. \end{aligned}$$

In particular, given pointed maps

$$\begin{aligned} f &: (X, x_0) \rightarrow (A, a_0), \\ g &: (Y, y_0) \rightarrow (B, b_0), \end{aligned}$$

the induced map

$$\mathbf{Sets}_*(f, g) : \mathbf{Sets}_*(A, Y) \rightarrow \mathbf{Sets}_*(X, B)$$

is given by

$$[\mathbf{Sets}_*(f, g)](\phi) \stackrel{\text{def}}{=} g \circ \phi \circ f$$

for each $\phi \in \mathbf{Sets}_*(A, Y)$.

00GF 2. *Adjointness.* We have adjunctions

$$\begin{aligned} (X \wedge - \dashv \mathbf{Sets}_*(X, -)) &: \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*, \\ (- \wedge Y \dashv \mathbf{Sets}_*(Y, -)) &: \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*, \end{aligned}$$

witnessed by bijections

$$\begin{aligned} \text{Hom}_{\mathbf{Sets}_*}(X \wedge Y, Z) &\cong \text{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(Y, Z)), \\ \text{Hom}_{\mathbf{Sets}_*}(X \wedge Y, Z) &\cong \text{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(A, Z)), \end{aligned}$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

00GG 3. *Enriched Adjointness.* We have \mathbf{Sets}_* -enriched adjunctions

$$(X \wedge - \dashv \mathbf{Sets}_*(X, -)) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*$$

$$(- \wedge Y \dashv \mathbf{Sets}_*(Y, -)) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*$$

witnessed by isomorphisms of pointed sets

$$\mathbf{Sets}_*(X \wedge Y, Z) \cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(Y, Z)),$$

$$\mathbf{Sets}_*(X \wedge Y, Z) \cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(A, Z)),$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

Proof. Item 1, Functoriality: This follows from **Item 1** of **Proposition 2.3.5.1.2** and from the equalities

$$g \circ \Delta_{y_0} = \Delta_{z_0},$$

$$\Delta_{y_0} \circ f = \Delta_{y_0}$$

for morphisms $f: (K, k_0) \rightarrow (X, x_0)$ and $g: (Y, y_0) \rightarrow (Z, z_0)$, which guarantee pre- and postcomposition by morphisms of pointed sets to also be morphisms of pointed sets.

Item 2, Adjointness: This is a repetition of **Item 2** of **Proposition 4.5.1.1.9**, and is proved there.

Item 3, Enriched Adjointness: This is a repetition of **Item 3** of **Proposition 4.5.1.1.9**, and is proved there. \square

00GH 4.5.3 The Monoidal Unit

00GJ **Definition 4.5.3.1.1.** The **monoidal unit of the smash product of pointed sets** is the functor

$$\mathbb{1}^{\mathbf{Sets}_*} : \text{pt} \rightarrow \mathbf{Sets}_*$$

defined by

$$\mathbb{1}_{\mathbf{Sets}_*} \stackrel{\text{def}}{=} S^0.$$

00GK 4.5.4 The Associator

00GL **Definition 4.5.4.1.1.** The **associator of the smash product of pointed sets** is the natural isomorphism

$$\alpha^{\mathbf{Sets}_*} : \wedge \circ (\wedge \times \text{id}_{\mathbf{Sets}_*}) \xrightarrow{\sim} \wedge \circ (\text{id}_{\mathbf{Sets}_*} \times \wedge) \circ \alpha_{\mathbf{Sets}_*, \mathbf{Sets}_*, \mathbf{Sets}_*}^{\text{Cats}}$$

as in the diagram

$$\begin{array}{ccc}
 & \text{Sets}_* \times (\text{Sets}_* \times \text{Sets}_*) & \\
 \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}} \nearrow & & \searrow \text{id} \times \wedge \\
 (\text{Sets}_* \times \text{Sets}_*) \times \text{Sets}_* & & \text{Sets}_* \times \text{Sets}_* \\
 \wedge \times \text{id} \searrow & \alpha_{\text{Sets}_*} \nearrow & \searrow \wedge \\
 \text{Sets}_* \times \text{Sets}_* & \xrightarrow{\wedge} & \text{Sets}_*
 \end{array}$$

whose component

$$\alpha_{X,Y,Z}^{\text{Sets}_*}: (X \wedge Y) \wedge Z \xrightarrow{\cong} X \wedge (Y \wedge Z)$$

at $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$ is given by

$$\alpha_{X,Y,Z}^{\text{Sets}_*}((x \wedge y) \wedge z) \stackrel{\text{def}}{=} x \wedge (y \wedge z)$$

for each $(x \wedge y) \wedge z \in (X \wedge Y) \wedge Z$.

Proof. Well-Definedness: Let $[(x, y), z] = [(x', y'), z']$ be an element in $(X \wedge Y) \wedge Z$. Then either:

1. We have $x = x', y = y',$ and $z = z'$.
2. Both of the following conditions are satisfied:
 - (a) We have $x = x_0$ or $y = y_0$ or $z = z_0$.
 - (b) We have $x' = x_0$ or $y' = y_0$ or $z' = z_0$.

In the first case, $\alpha_{X,Y,Z}^{\text{Sets}_*}$ clearly sends both elements to the same element in $X \wedge (Y \wedge Z)$. Meanwhile, in the latter case both elements are equal to the basepoint $(x_0 \wedge y_0) \wedge z_0$ of $(X \wedge Y) \wedge Z$, which gets sent to the basepoint $x_0 \wedge (y_0 \wedge z_0)$ of $X \wedge (Y \wedge Z)$.

Being a Morphism of Pointed Sets: As just mentioned, we have

$$\alpha_{X,Y,Z}^{\text{Sets}_*}((x_0 \wedge y_0) \wedge z_0) \stackrel{\text{def}}{=} x_0 \wedge (y_0 \wedge z_0),$$

and thus $\alpha_{X,Y,Z}^{\text{Sets}_*}$ is a morphism of pointed sets.

Invertibility: Clearly, the inverse of $\alpha_{X,Y,Z}^{\text{Sets}_*}$ is given by the morphism

$$\alpha_{X,Y,Z}^{\text{Sets}_*, -1}: X \wedge (Y \wedge Z) \xrightarrow{\cong} (X \wedge Y) \wedge Z$$

defined by

$$\alpha_{X,Y,Z}^{\text{Sets}_*, -1}(x \wedge (y \wedge z)) \stackrel{\text{def}}{=} (x \wedge y) \wedge z$$

for each $x \wedge (y \wedge z) \in X \wedge (Y \wedge Z)$.

Naturality: We need to show that, given morphisms of pointed sets

$$\begin{aligned} f &: (X, x_0) \rightarrow (X', x'_0), \\ g &: (Y, y_0) \rightarrow (Y', y'_0), \\ h &: (Z, z_0) \rightarrow (Z', z'_0) \end{aligned}$$

the diagram

$$\begin{array}{ccc} (X \wedge Y) \wedge Z & \xrightarrow{(f \wedge g) \wedge h} & (X' \wedge Y') \wedge Z' \\ \alpha_{X,Y,Z}^{\text{Sets}_*} \downarrow & & \downarrow \alpha_{X',Y',Z'}^{\text{Sets}_*} \\ X \wedge (Y \wedge Z) & \xrightarrow{f \wedge (g \wedge h)} & X' \wedge (Y' \wedge Z') \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} (x \wedge y) \wedge z & \longmapsto & (f(x) \wedge g(y)) \wedge h(z) \\ \downarrow & & \downarrow \\ x \wedge (y \wedge z) & \longmapsto & f(x) \wedge (g(y) \wedge h(z)) \end{array}$$

and hence indeed commutes, showing α^{Sets_*} to be a natural transformation.

Being a Natural Isomorphism: Since α^{Sets_*} is natural and $\alpha^{\text{Sets}_*, -1}$ is a componentwise inverse to α^{Sets_*} , it follows from **Item 2 of Proposition 8.8.6.1.2** that $\alpha^{\text{Sets}_*, -1}$ is also natural. Thus α^{Sets_*} is a natural isomorphism. \square

00GM 4.5.5 The Left Unitor

00GN Definition 4.5.5.1.1. The left unitor of the smash product of pointed sets is the natural isomorphism

$$\lambda^{\text{Sets}_*} : \wedge \circ (\mathbb{1}_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \lambda_{\text{Sets}_*}^{\text{Cats}_2}$$

The diagram consists of three nodes: $\text{pt} \times \text{Sets}_*$ at the top left, $\text{Sets}_* \times \text{Sets}_*$ at the top right, and $\text{Sets}_{*,*}$ at the bottom right. A solid arrow labeled $\mathbb{1}_{\text{Sets}_*} \times \text{id}$ points from $\text{pt} \times \text{Sets}_*$ to $\text{Sets}_* \times \text{Sets}_*$. A solid arrow labeled \wedge points from $\text{Sets}_* \times \text{Sets}_*$ to $\text{Sets}_{*,*}$. A dashed arrow labeled $\lambda_{\text{Sets}_*}^{\text{Cats}_2}$ points from $\text{pt} \times \text{Sets}_*$ to $\text{Sets}_{*,*}$. Two diagonal arrows, one solid and one dashed, both labeled λ^{Sets_*} , connect $\text{pt} \times \text{Sets}_*$ and $\text{Sets}_* \times \text{Sets}_*$.

whose component

$$\lambda_X^{\text{Sets}_*} : S^0 \wedge X \xrightarrow{\cong} X$$

at $X \in \text{Obj}(\text{Sets}_*)$ is given by

$$\begin{aligned} 0 \wedge x &\mapsto x_0, \\ 1 \wedge x &\mapsto x. \end{aligned}$$

Proof. Well-Definedness: Let $[(x, y)] = [(x', y')]$ be an element in $S^0 \wedge X$. Then either:

1. We have $x = x'$ and $y = y'$.
2. Both of the following conditions are satisfied:
 - (a) We have $x = 0$ or $y = x_0$.
 - (b) We have $x' = 0$ or $y' = x_0$.

In the first case, $\lambda_X^{\text{Sets}_*}$ clearly sends both elements to the same element in X . Meanwhile, in the latter case both elements are equal to the basepoint $0 \wedge x_0$ of $S^0 \wedge X$, which gets sent to the basepoint x_0 of X .

Being a Morphism of Pointed Sets: As just mentioned, we have

$$\lambda_X^{\text{Sets}_*}(0 \wedge x_0) \stackrel{\text{def}}{=} x_0,$$

and thus $\lambda_X^{\text{Sets}_*}$ is a morphism of pointed sets.

Invertibility: The inverse of $\lambda_X^{\text{Sets}_*}$ is the morphism

$$\lambda_X^{\text{Sets}_*, -1} : X \xrightarrow{\cong} S^0 \wedge X$$

defined by

$$\lambda_X^{\text{Sets}_*, -1}(x) \stackrel{\text{def}}{=} 1 \wedge x$$

for each $x \in X$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned} \left[\lambda_X^{\text{Sets}_*, -1} \circ \lambda_X^{\text{Sets}_*} \right] (0 \wedge x) &= \lambda_X^{\text{Sets}_*, -1} \left(\lambda_X^{\text{Sets}_*} (0 \wedge x) \right) \\ &= \lambda_X^{\text{Sets}_*, -1}(x_0) \\ &= 1 \wedge x_0 \\ &= 0 \wedge x, \end{aligned}$$

and

$$\begin{aligned} \left[\lambda_X^{\text{Sets}_*, -1} \circ \lambda_X^{\text{Sets}_*} \right] (1 \wedge x) &= \lambda_X^{\text{Sets}_*, -1} \left(\lambda_X^{\text{Sets}_*} (1 \wedge x) \right) \\ &= \lambda_X^{\text{Sets}_*, -1} (x) \\ &= 1 \wedge x \end{aligned}$$

for each $x \in X$, and thus we have

$$\lambda_X^{\text{Sets}_*, -1} \circ \lambda_X^{\text{Sets}_*} = \text{id}_{S^0 \wedge X}.$$

• *Invertibility II.* We have

$$\begin{aligned} \left[\lambda_X^{\text{Sets}_*} \circ \lambda_X^{\text{Sets}_*, -1} \right] (x) &= \lambda_X^{\text{Sets}_*} \left(\lambda_X^{\text{Sets}_*, -1} (x) \right) \\ &= \lambda_X^{\text{Sets}_*, -1} (1 \wedge x) \\ &= x \end{aligned}$$

for each $x \in X$, and thus we have

$$\lambda_X^{\text{Sets}_*} \circ \lambda_X^{\text{Sets}_*, -1} = \text{id}_X.$$

This shows $\lambda_X^{\text{Sets}_*}$ to be invertible.

Naturality: We need to show that, given a morphism of pointed sets

$$f: (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc} S^0 \wedge X & \xrightarrow{\text{id}_{S^0} \wedge f} & S^0 \wedge Y \\ \lambda_X^{\text{Sets}_*} \downarrow & & \downarrow \lambda_Y^{\text{Sets}_*} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} 0 \wedge x & & 0 \wedge x \longmapsto 0 \wedge f(x) \\ \downarrow & & \downarrow \\ x_0 & \longmapsto & f(x_0) \\ & & y_0 \end{array}$$

and

$$\begin{array}{ccc} 1 \wedge x & \longmapsto & 1 \wedge f(x) \\ \downarrow & & \downarrow \\ x & \longmapsto & f(x) \end{array}$$

and hence indeed commutes, showing $\lambda^{\mathbf{Sets}_*}$ to be a natural transformation. *Being a Natural Isomorphism:* Since $\lambda^{\mathbf{Sets}_*}$ is natural and $\lambda^{\mathbf{Sets}_*, -1}$ is a componentwise inverse to $\lambda^{\mathbf{Sets}_*}$, it follows from **Item 2 of Proposition 8.8.6.1.2** that $\lambda^{\mathbf{Sets}_*, -1}$ is also natural. Thus $\lambda^{\mathbf{Sets}_*}$ is a natural isomorphism. \square

00GP 4.5.6 The Right Unitor

00GQ Definition 4.5.6.1.1. The **right unitor of the smash product of pointed sets** is the natural isomorphism

$$\rho^{\mathbf{Sets}_*} : \wedge \circ (\text{id} \times \mathbb{1}^{\mathbf{Sets}_*}) \xrightarrow{\sim} \rho_{\mathbf{Sets}_*}^{\mathbf{Cats}_2}$$

whose component

$$\rho_X^{\mathbf{Sets}_*} : X \wedge S^0 \xrightarrow{\cong} X$$

at $X \in \text{Obj}(\mathbf{Sets}_*)$ is given by

$$\begin{aligned} x \wedge 0 &\mapsto x_0, \\ x \wedge 1 &\mapsto x. \end{aligned}$$

Proof. Well-Definedness: Let $[(x, y)] = [(x', y')]$ be an element in $X \wedge S^0$. Then either:

1. We have $x = x'$ and $y = y'$.
2. Both of the following conditions are satisfied:
 - (a) We have $x = x_0$ or $y = 0$.
 - (b) We have $x' = x_0$ or $y' = 0$.

In the first case, $\rho_X^{\text{Sets}_*}$ clearly sends both elements to the same element in X . Meanwhile, in the latter case both elements are equal to the basepoint $x_0 \wedge 0$ of $X \wedge S^0$, which gets sent to the basepoint x_0 of X .

Being a Morphism of Pointed Sets: As just mentioned, we have

$$\rho_X^{\text{Sets}_*}(x_0 \wedge 0) \stackrel{\text{def}}{=} x_0,$$

and thus $\rho_X^{\text{Sets}_*}$ is a morphism of pointed sets.

Invertibility: The inverse of $\rho_X^{\text{Sets}_*}$ is the morphism

$$\rho_X^{\text{Sets}_{**,-1}}: X \xrightarrow{\cong} X \wedge S^0$$

defined by

$$\rho_X^{\text{Sets}_{**,-1}}(x) \stackrel{\text{def}}{=} x \wedge 1$$

for each $x \in X$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned} \left[\rho_X^{\text{Sets}_{**,-1}} \circ \rho_X^{\text{Sets}_*} \right] (x \wedge 0) &= \rho_X^{\text{Sets}_{**,-1}} \left(\rho_X^{\text{Sets}_*}(x \wedge 0) \right) \\ &= \rho_X^{\text{Sets}_{**,-1}}(x_0) \\ &= x_0 \wedge 1 \\ &= x \wedge 0, \end{aligned}$$

and

$$\begin{aligned} \left[\rho_X^{\text{Sets}_{**,-1}} \circ \rho_X^{\text{Sets}_*} \right] (x \wedge 1) &= \rho_X^{\text{Sets}_{**,-1}} \left(\rho_X^{\text{Sets}_*}(x \wedge 1) \right) \\ &= \rho_X^{\text{Sets}_{**,-1}}(x) \\ &= x \wedge 1 \end{aligned}$$

for each $x \in X$, and thus we have

$$\rho_X^{\text{Sets}_{**,-1}} \circ \rho_X^{\text{Sets}_*} = \text{id}_{X \wedge S^0}.$$

- *Invertibility II.* We have

$$\begin{aligned} \left[\rho_X^{\text{Sets}_*} \circ \rho_X^{\text{Sets}_{**,-1}} \right] (x) &= \rho_X^{\text{Sets}_*} \left(\rho_X^{\text{Sets}_{**,-1}}(x) \right) \\ &= \rho_X^{\text{Sets}_*}(x \wedge 1) \\ &= x \end{aligned}$$

for each $x \in X$, and thus we have

$$\rho_X^{\text{Sets}_*} \circ \rho_X^{\text{Sets}_{**,-1}} = \text{id}_X.$$

at $X, Y \in \text{Obj}(\text{Sets}_*)$ is defined by

$$\sigma_{X,Y}^{\text{Sets}_*}(x \wedge y) \stackrel{\text{def}}{=} y \wedge x$$

for each $x \wedge y \in X \wedge Y$.

Proof. Well-Definedness: Let $[(x, y)] = [(x', y')]$ be an element in $X \wedge Y$. Then either:

1. We have $x = x'$ and $y = y'$.
2. Both of the following conditions are satisfied:
 - (a) We have $x = x_0$ or $y = y_0$.
 - (b) We have $x' = x_0$ or $y' = y_0$.

In the first case, $\sigma_X^{\text{Sets}_*}$ clearly sends both elements to the same element in X . Meanwhile, in the latter case both elements are equal to the basepoint $x_0 \wedge y_0$ of $X \wedge Y$, which gets sent to the basepoint $y_0 \wedge x_0$ of $Y \wedge X$.

Being a Morphism of Pointed Sets: As just mentioned, we have

$$\sigma_X^{\text{Sets}_*}(x_0 \wedge y_0) \stackrel{\text{def}}{=} y_0 \wedge x_0,$$

and thus $\sigma_X^{\text{Sets}_*}$ is a morphism of pointed sets.

Invertibility: Clearly, the inverse of $\sigma_{X,Y}^{\text{Sets}_*}$ is given by the morphism

$$\sigma_{X,Y}^{\text{Sets}_*,-1}: Y \wedge X \xrightarrow{\cong} X \wedge Y$$

defined by

$$\sigma_{X,Y}^{\text{Sets}_*,-1}(y \wedge x) \stackrel{\text{def}}{=} x \wedge y$$

for each $y \wedge x \in Y \wedge X$.

Naturality: We need to show that, given morphisms of pointed sets

$$\begin{aligned} f: (X, x_0) &\rightarrow (A, a_0), \\ g: (Y, y_0) &\rightarrow (B, b_0) \end{aligned}$$

the diagram

$$\begin{array}{ccc} X \wedge Y & \xrightarrow{f \wedge g} & A \wedge B \\ \sigma_{X,Y}^{\text{Sets}_*} \downarrow & & \downarrow \sigma_{A,B}^{\text{Sets}_*} \\ Y \wedge X & \xrightarrow{g \wedge f} & B \wedge A \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x \wedge y & \longmapsto & f(x) \wedge g(y) \\ \downarrow & & \downarrow \\ y \wedge x & \longmapsto & g(y) \wedge f(x) \end{array}$$

and hence indeed commutes, showing $\sigma^{\mathbf{Sets}_*}$ to be a natural transformation. *Being a Natural Isomorphism:* Since $\sigma^{\mathbf{Sets}_*}$ is natural and $\sigma^{\mathbf{Sets}_*, -1}$ is a componentwise inverse to $\sigma^{\mathbf{Sets}_*}$, it follows from **Item 2 of Proposition 8.8.6.1.2** that $\sigma^{\mathbf{Sets}_*, -1}$ is also natural. Thus $\sigma^{\mathbf{Sets}_*}$ is a natural isomorphism. \square

00GT 4.5.8 The Diagonal

00GU Definition 4.5.8.1.1. The **diagonal of the smash product of pointed sets** is the natural transformation

$$\Delta^\wedge : \text{id}_{\mathbf{Sets}_*} \implies \wedge \circ \Delta_{\mathbf{Sets}_*}^{\text{Cats}_2}$$

whose component

$$\Delta_X^\wedge : (X, x_0) \rightarrow (X \wedge X, x_0 \wedge x_0)$$

at $(X, x_0) \in \text{Obj}(\mathbf{Sets}_*)$ is given by the composition

$$\begin{aligned} (X, x_0) &\xrightarrow{\Delta_X^\wedge} (X \times X, (x_0, x_0)) \\ &\longrightarrow ((X \times X)/\sim, [(x_0, x_0)]) \\ &\stackrel{\text{def}}{=} (X \wedge X, x_0 \wedge x_0) \end{aligned}$$

in \mathbf{Sets}_* , and thus by

$$\Delta_X^\wedge(x) \stackrel{\text{def}}{=} x \wedge x$$

for each $x \in X$.

Proof. Being a Morphism of Pointed Sets: We have

$$\Delta_X^\wedge(x_0) \stackrel{\text{def}}{=} x_0 \wedge x_0,$$

and thus Δ_X^\wedge is a morphism of pointed sets.

Naturality: We need to show that, given a morphism of pointed sets

$$f: (X, x_0) \rightarrow (Y, y_0),$$

the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \Delta_X^\wedge \downarrow & & \downarrow \Delta_Y^\wedge \\ X \wedge X & \xrightarrow{f \wedge f} & Y \wedge Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x & \longmapsto & f(x) \\ \downarrow & & \downarrow \\ x \wedge x & \longmapsto & f(x) \wedge f(x) \end{array}$$

and hence indeed commutes, showing Δ^\wedge to be natural. □

00GV Proposition 4.5.8.1.2. Let $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

00GW 1. *Monoidality.* The diagonal

$$\Delta^\wedge: \text{id}_{\text{Sets}_*} \implies \wedge \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2},$$

of the smash product of pointed sets is a monoidal natural transformation:

00GX (a) *Compatibility With Strong Monoidality Constraints.* For each $(X, x_0), (Y, y_0) \in \text{Obj}(\text{Sets}_*)$, the diagram

$$\begin{array}{ccc} X \wedge Y & \xrightarrow{\Delta_X^\wedge \wedge \Delta_Y^\wedge} & (X \wedge X) \wedge (Y \wedge Y) \\ & \searrow \Delta_{X \wedge Y}^\wedge & \downarrow \wr \\ & & (X \wedge Y) \wedge (X \wedge Y) \end{array}$$

commutes.

00GY (b) *Compatibility With Strong Unitality Constraints.* The diagrams

$$\begin{array}{ccc} S^0 & \xrightarrow{\Delta_{S^0}^\wedge} & S^0 \wedge S^0 \\ \parallel & & \downarrow \lambda_{S^0}^{\text{Sets}_*} \\ & & S^0 \end{array} \quad \begin{array}{ccc} S^0 & \xrightarrow{\Delta_{S^0}^\wedge} & S^0 \wedge S^0 \\ \parallel & & \downarrow \rho_{S^0}^{\text{Sets}_*} \\ & & S^0 \end{array}$$

commute, i.e. we have

$$\begin{aligned} \Delta_{S^0}^\wedge &= \lambda_{S^0}^{\text{Sets}_*, -1} \\ &= \rho_{S^0}^{\text{Sets}_*, -1}, \end{aligned}$$

where we recall that the equalities

$$\begin{aligned} \lambda_{S^0}^{\text{Sets}_*} &= \rho_{S^0}^{\text{Sets}_*}, \\ \lambda_{S^0}^{\text{Sets}_*, -1} &= \rho_{S^0}^{\text{Sets}_*, -1} \end{aligned}$$

are always true in any monoidal category by ?? of ??.

00GZ 2. *The Diagonal of the Unit.* The component

$$\Delta_{S^0}^\wedge : S^0 \xrightarrow{\cong} S^0 \wedge S^0$$

of Δ^\wedge at S^0 is an isomorphism.

Proof. **Item 1, Monoidality:** We claim that Δ^\wedge is indeed monoidal:

1. **Item 1a: Compatibility With Strong Monoidality Constraints:** We need to show that the diagram

$$\begin{array}{ccc} X \wedge Y & \xrightarrow{\Delta_X^\wedge \wedge \Delta_Y^\wedge} & (X \wedge X) \wedge (Y \wedge Y) \\ & \searrow \Delta_{X \wedge Y}^\wedge & \downarrow \wr \\ & & (X \wedge Y) \wedge (X \wedge Y) \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x \wedge y & \xrightarrow{\quad} & (x \wedge x) \wedge (y \wedge y) \\ & \searrow & \downarrow \\ & & (x \wedge y) \wedge (x \wedge y) \end{array}$$

and hence indeed commutes.

2. **Item 1b: Compatibility With Strong Unitality Constraints:** As shown in the proof of **Definition 4.5.5.1.1**, the inverse of the left unitor of Sets_* with respect to the smash product of pointed sets at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by

$$\lambda_X^{\text{Sets}_*, -1}(x) \stackrel{\text{def}}{=} 1 \wedge x$$

for each $x \in X$, so when $X = S^0$, we have

$$\begin{aligned}\lambda_{S^0}^{\text{Sets}_*^{-1}}(0) &\stackrel{\text{def}}{=} 1 \wedge 0, \\ \lambda_{S^0}^{\text{Sets}_*^{-1}}(1) &\stackrel{\text{def}}{=} 1 \wedge 1.\end{aligned}$$

But since $1 \wedge 0 = 0 \wedge 0$ and

$$\begin{aligned}\Delta_{S^0}^\wedge(0) &\stackrel{\text{def}}{=} 0 \wedge 0, \\ \Delta_{S^0}^\wedge(1) &\stackrel{\text{def}}{=} 1 \wedge 1,\end{aligned}$$

it follows that we indeed have $\Delta_{S^0}^\wedge = \lambda_{S^0}^{\text{Sets}_*^{-1}}$.

This finishes the proof.

Item 2, The Diagonal of the Unit: This follows from [Item 1](#) and the invertibility of the left/right unitor of Sets_* with respect to \wedge , proved in the proof of [Definition 4.5.5.1.1](#) for the left unitor or the proof of [Definition 4.5.6.1.1](#) for the right unitor. \square

00H0 4.5.9 The Monoidal Structure on Pointed Sets Associated to \wedge

00H1 **Proposition 4.5.9.1.1.** The category Sets_* admits a closed monoidal category with diagonals structure consisting of

- *The Underlying Category.* The category Sets_* of pointed sets;
- *The Monoidal Product.* The smash product functor

$$\wedge : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

of [Item 1](#) of [Proposition 4.5.1.1.9](#);

- *The Internal Hom.* The internal Hom functor

$$\mathbf{Sets}_* : \text{Sets}_*^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*$$

of [Item 1](#) of [Proposition 4.5.2.1.2](#);

- *The Monoidal Unit.* The functor

$$\mathbb{1}^{\text{Sets}_*} : \text{pt} \rightarrow \text{Sets}_*$$

of [Definition 4.5.3.1.1](#);

- *The Associators.* The natural isomorphism

$$\alpha^{\text{Sets}_*} : \wedge \circ (\wedge \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \wedge \circ (\text{id}_{\text{Sets}_*} \times \wedge) \circ \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}}$$

of [Definition 4.5.4.1.1](#);

- *The Left Unitors.* The natural isomorphism

$$\lambda^{\mathbf{Sets}_*} : \wedge \circ (\mathbb{1}^{\mathbf{Sets}_*} \times \text{id}_{\mathbf{Sets}_*}) \xrightarrow{\sim} \lambda_{\mathbf{Sets}_*}^{\mathbf{Cats}_2}$$

of [Definition 4.5.5.1.1](#);

- *The Right Unitors.* The natural isomorphism

$$\rho^{\mathbf{Sets}_*} : \wedge \circ (\text{id} \times \mathbb{1}^{\mathbf{Sets}_*}) \xrightarrow{\sim} \rho_{\mathbf{Sets}_*}^{\mathbf{Cats}_2}$$

of [Definition 4.5.6.1.1](#);

- *The Symmetry.* The natural isomorphism

$$\sigma^{\mathbf{Sets}_*} : \wedge \xrightarrow{\sim} \wedge \circ \sigma_{\mathbf{Sets}_*, \mathbf{Sets}_*}^{\mathbf{Cats}_2}$$

of [Definition 4.5.7.1.1](#);

- *The Diagonals.* The monoidal natural transformation

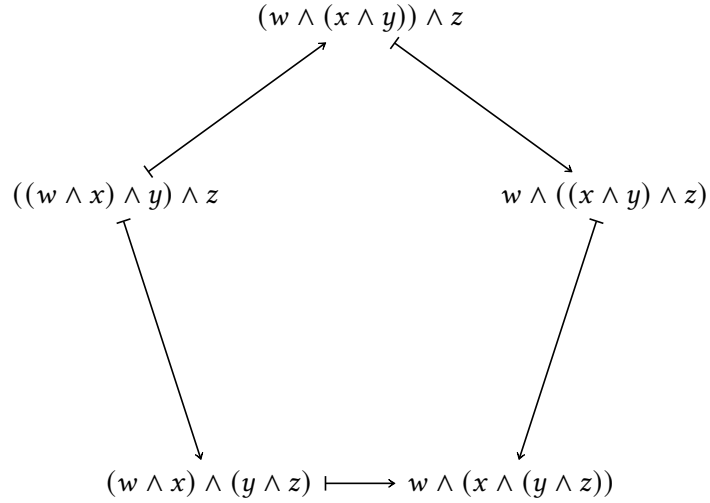
$$\Delta^\wedge : \text{id}_{\mathbf{Sets}_*} \Longrightarrow \wedge \circ \Delta_{\mathbf{Sets}_*}^{\mathbf{Cats}_2}$$

of [Definition 4.5.8.1.1](#).

Proof. The Pentagon Identity: Let (W, w_0) , (X, x_0) , (Y, y_0) and (Z, z_0) be pointed sets. We have to show that the diagram

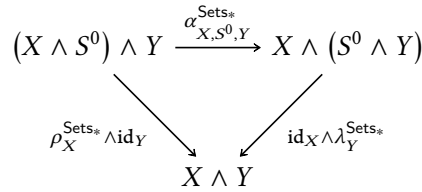
$$\begin{array}{ccc}
 & (W \wedge (X \wedge Y)) \wedge Z & \\
 \alpha_{W, X, Y}^{\mathbf{Sets}_*} \wedge \text{id}_Z \nearrow & & \searrow \alpha_{W, X \wedge Y, Z}^{\mathbf{Sets}_*} \\
 ((W \wedge X) \wedge Y) \wedge Z & & W \wedge ((X \wedge Y) \wedge Z) \\
 \alpha_{W \wedge X, Y, Z}^{\mathbf{Sets}_*} \searrow & & \swarrow \text{id}_W \wedge \alpha_{X, Y, Z}^{\mathbf{Sets}_*} \\
 (W \wedge X) \wedge (Y \wedge Z) & \xrightarrow{\alpha_{W, X, Y \wedge Z}^{\mathbf{Sets}_*}} & W \wedge (X \wedge (Y \wedge Z))
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

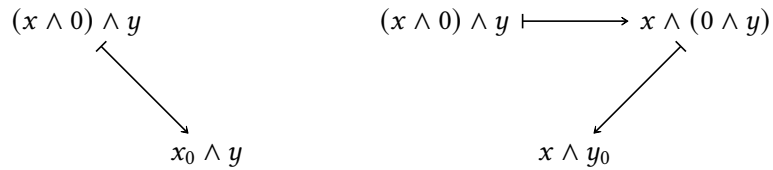


and thus we see that the pentagon identity is satisfied.

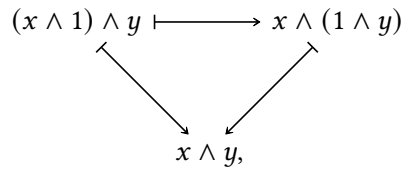
The Triangle Identity: Let (X, x_0) and (Y, y_0) be pointed sets. We have to show that the diagram



commutes. Indeed, this diagram acts on elements as

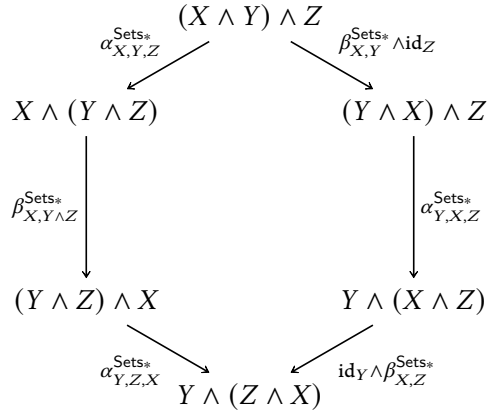


and

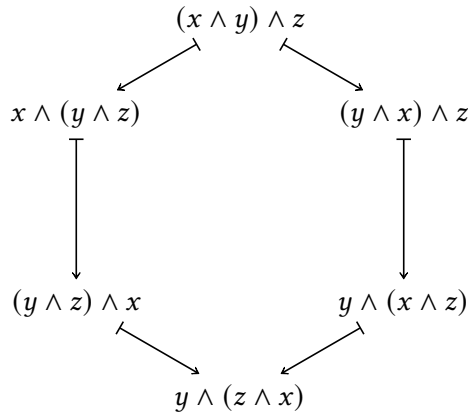


and thus we see that the triangle identity is satisfied.

The Left Hexagon Identity: Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets. We have to show that the diagram



commutes. Indeed, this diagram acts on elements as



and thus we see that the left hexagon identity is satisfied.

The Right Hexagon Identity: Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

We have to show that the diagram

$$\begin{array}{ccc}
 & (X \wedge (Y \wedge Z)) & \\
 \begin{array}{c} \left(\alpha_{X,Y,Z}^{\text{Sets}_*} \right)^{-1} \\ \swarrow \end{array} & & \searrow \begin{array}{c} \text{id}_X \wedge \beta_{Y,Z}^{\text{Sets}_*} \\ \end{array} \\
 (X \wedge Y) \wedge Z & & X \wedge (Z \wedge Y) \\
 \downarrow \begin{array}{c} \beta_{X \wedge Y, Z}^{\text{Sets}_*} \\ \end{array} & & \downarrow \begin{array}{c} \left(\alpha_{X,Z,Y}^{\text{Sets}_*} \right)^{-1} \\ \end{array} \\
 Z \wedge (X \wedge Y) & & (X \wedge Z) \wedge Y \\
 \swarrow \begin{array}{c} \left(\alpha_{Z,X,Y}^{\text{Sets}_*} \right)^{-1} \\ \end{array} & & \swarrow \begin{array}{c} \beta_{X,Z}^{\text{Sets}_*} \wedge \text{id}_Y \\ \end{array} \\
 & (Z \wedge X) \wedge Y &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 & x \wedge (y \wedge z) & \\
 \swarrow & & \searrow \\
 (x \wedge y) \wedge z & & x \wedge (z \wedge y) \\
 \downarrow & & \downarrow \\
 z \wedge (x \wedge y) & & (x \wedge z) \wedge y \\
 \swarrow & & \swarrow \\
 & (z \wedge x) \wedge y &
 \end{array}$$

and thus we see that the right hexagon identity is satisfied.

Monoidal Closedness: This follows from **Item 2** of **Proposition 4.5.1.1.9**.

Existence of Monoidal Diagonals: This follows from **Items 1** and **2** of **Proposition 4.5.8.1.2**. □

4.5.10 Universal Properties of the Smash Product of Pointed Sets

00H2

I

00H3 **Theorem 4.5.10.1.1.** The symmetric monoidal structure on the category Sets_* is uniquely determined by the following requirements:

1. *Two-Sided Preservation of Colimits.* The smash product

$$\wedge : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

of Sets_* preserves colimits separately in each variable.

2. *The Unit Object Is S^0 .* We have $\mathbb{1}_{\text{Sets}_*} = S^0$.

Proof. Omitted. \square

4.5.11 Universal Properties of the Smash Product of Pointed Sets II

00H4

00H5 **Theorem 4.5.11.1.1.** The symmetric monoidal structure on the category Sets_* is the unique symmetric monoidal structure on Sets_* such that the free pointed set functor

$$(-)^+ : \text{Sets} \rightarrow \text{Sets}_*$$

admits a symmetric monoidal structure.

Proof. See [GGN15, Theorem 5.1]. \square

4.5.12 Monoids With Respect to the Smash Product of Pointed Sets

00H6

00H7 **Proposition 4.5.12.1.1.** The category of monoids on $(\text{Sets}_*, \wedge, S^0)$ is isomorphic to the category of monoids with zero and morphisms between them.

Proof. See ??, in particular ??, ??, and ??. \square

4.5.13 Comonoids With Respect to the Smash Product of Pointed Sets

00H8

00H9 **Proposition 4.5.13.1.1.** The symmetric monoidal functor

$$((-)^+, (-)^{+, \times}, (-)_{\mathbb{1}}^{+, \times}) : (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}_*, \wedge, S^0),$$

of [Item 4](#) of [Proposition 3.4.1.1.2](#) lifts to an equivalence of categories

$$\begin{aligned} \text{CoMon}(\text{Sets}_*, \wedge, S^0) &\stackrel{\text{eq.}}{\cong} \text{CoMon}(\text{Sets}, \times, \text{pt}) \\ &\cong \text{Sets}. \end{aligned}$$

Proof. See [PS19, Lemma 2.4]. \square

00HA 4.6 Miscellany

00HB 4.6.1 The Smash Product of a Family of Pointed Sets

Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

00HC Definition 4.6.1.1.1. The **smash product of the family** $\{(X_i, x_0^i)\}_{i \in I}$ is the pointed set $\bigwedge_{i \in I} X_i$ consisting of:

- *The Underlying Set.* The set $\bigwedge_{i \in I} X_i$ defined by

$$\bigwedge_{i \in I} X_i \stackrel{\text{def}}{=} \left(\prod_{i \in I} X_i \right) / \sim,$$

where \sim is the equivalence relation on $\prod_{i \in I} X_i$ obtained by declaring

$$(x_i)_{i \in I} \sim (y_i)_{i \in I}$$

if there exist $i_0 \in I$ such that $x_{i_0} = x_0$ and $y_{i_0} = y_0$, for each $(x_i)_{i \in I}, (y_i)_{i \in I} \in \prod_{i \in I} X_i$.

- *The Basepoint.* The element $[(x_0)_{i \in I}]$ of $\bigwedge_{i \in I} X_i$.

Appendices

4.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets

Relations

5. Relations

6. Constructions With Relations

7. Equivalence Relations and Apartness Relations

Category Theory

8. Categories

Bicategories

9. Types of Morphisms in Bicategories

Part II

Relations

Chapter 5

Relations

00HD This chapter contains some material about relations. Notably, we discuss and explore:

1. The definition of relations ([Section 5.1.1](#)).
2. How relations may be viewed as decategorification of profunctors ([Section 5.1.2](#)).
3. The various kind of categories that relations form, namely:
 - (a) A category ([Section 5.2.1](#)).
 - (b) A monoidal category ([Section 5.2.2](#)).
 - (c) A 2-category ([Section 5.2.3](#)).
 - (d) A double category ([Section 5.2.4](#)).
4. The various categorical properties of the 2-category of relations, including:
 - (a) The self-duality of \mathbf{Rel} and \mathbf{Rel} ([Proposition 5.3.1.1.1](#)).
 - (b) Identifications of equivalences and isomorphisms in \mathbf{Rel} with bijections ([Proposition 5.3.2.1.1](#)).
 - (c) Identifications of adjunctions in \mathbf{Rel} with functions ([Proposition 5.3.3.1.1](#)).
 - (d) Identifications of monads in \mathbf{Rel} with preorders ([Proposition 5.3.4.1.1](#)).
 - (e) Identifications of comonads in \mathbf{Rel} with subsets ([Proposition 5.3.5.1.1](#)).
 - (f) A description of the monoids and comonoids in \mathbf{Rel} with respect to the Cartesian product ([Remark 5.3.6.1.1](#)).
 - (g) Characterisations of monomorphisms in \mathbf{Rel} ([Proposition 5.3.7.1.1](#)).

- (h) Characterisations of 2-categorical notions of monomorphisms in **Rel** ([Proposition 5.3.8.1.1](#)).
 - (i) Characterisations of epimorphisms in **Rel** ([Proposition 5.3.9.1.1](#)).
 - (j) Characterisations of 2-categorical notions of epimorphisms in **Rel** ([Proposition 5.3.10.1.1](#)).
 - (k) The partial co/completeness of **Rel** ([Proposition 5.3.11.1.1](#)).
 - (l) The existence or non-existence of Kan extensions and Kan lifts in **Rel** ([Remark 5.3.12.1.1](#)).
 - (m) The closedness of **Rel** ([Proposition 5.3.13.1.1](#)).
 - (n) The identification of **Rel** with the category of free algebras of the powerset monad on **Sets** ([Proposition 5.3.14.1.1](#)).
5. A description of two notions of “skew composition” on $\mathbf{Rel}(A, B)$, giving rise to left and right skew monoidal structures analogous to the left skew monoidal structure on $\mathbf{Fun}(C, \mathcal{D})$ appearing in the definition of a relative monad ([Sections 5.4](#) and [5.5](#)).

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00HE 5.1 Relations

00HF 5.1.1 Foundations

Let A and B be sets.

00HG **Definition 5.1.1.1.1.** A relation $R: A \dashrightarrow B$ from A to B ^{1,2} is a subset R of $A \times B$.

00HH **Notation 5.1.1.1.2.** Let $R: A \dashrightarrow B$ be a relation.

¹Further Terminology: Also called a **multivalued function from A to B** , a **relation over A and B** , **relation on A and B** , a **binary relation over A and B** , or a **binary relation on A and B** .

²Further Terminology: When $A = B$, we also call $R \subset A \times A$ a **relation on A** .

00HJ 1. Given elements $a \in A$ and $b \in B$ and a relation $R: A \dashrightarrow B$, we write $a \sim_R b$ to mean $(a, b) \in R$.

00HK 2. Viewing R as a function

$$R: A \times B \rightarrow \{t, f\}$$

via [Remark 5.1.1.1.4](#), we write R_a^b for the value of R at (a, b) .³

00HL **Definition 5.1.1.1.3.** Let A and B be sets.

00HM 1. The **set of relations from A to B** is the set $\text{Rel}(A, B)$ defined by

$$\text{Rel}(A, B) \stackrel{\text{def}}{=} \{\text{Relations from } A \text{ to } B\}.$$

00HN 2. The **poset of relations from A to B** is the poset

$$\mathbf{Rel}(A, B) \stackrel{\text{def}}{=} (\text{Rel}(A, B), \subset)$$

consisting of:

- *The Underlying Set.* The set $\text{Rel}(A, B)$ of [Item 1](#).
- *The Partial Order.* The partial order

$$\subset: \text{Rel}(A, B) \times \text{Rel}(A, B) \rightarrow \{\text{true}, \text{false}\}$$

on $\text{Rel}(A, B)$ given by inclusion of relations.

00HP 3. The **category of relations from A to B** is the posetal category $\mathbf{Rel}(A, B)$ ⁴ associated to the poset $\mathbf{Rel}(A, B)$ of [Item 2](#) via [Definition 8.1.3.1.1](#).

00HQ **Remark 5.1.1.1.4.** A relation from A to B is equivalently:⁵

00HR 1. A subset of $A \times B$.

00HS 2. A function from $A \times B$ to $\{\text{true}, \text{false}\}$.

00HT 3. A function from A to $\mathcal{P}(B)$.

³The choice R_a^b in place of R_b^a is to keep the notation consistent with the notation we will later employ for profunctors.

⁴Here we choose to slightly abuse notation by writing $\mathbf{Rel}(A, B)$ (instead of e.g. $\mathbf{Rel}(A, B)_{\text{pos}}$) for the posetal category of relations from A to B , even though the same notation is used for the poset of relations from A to B .

⁵*Intuition:* In particular, we may think of a relation $R: A \rightarrow \mathcal{P}(B)$ from A to B as a multivalued function from A to B (including the possibility of a given $a \in A$ having no value at all).

- 00HU 4. A function from B to $\mathcal{P}(A)$.
- 00HV 5. A cocontinuous morphism of posets from $(\mathcal{P}(A), \subset)$ to $(\mathcal{P}(B), \subset)$.

That is: we have bijections of sets

$$\begin{aligned} \text{Rel}(A, B) &\stackrel{\text{def}}{=} \mathcal{P}(A \times B), \\ &\cong \text{Hom}_{\text{Sets}}(A \times B, \{\text{true}, \text{false}\}), \\ &\cong \text{Hom}_{\text{Sets}}(A, \mathcal{P}(B)), \\ &\cong \text{Hom}_{\text{Sets}}(B, \mathcal{P}(A)), \\ &\cong \text{Hom}_{\text{Pos}}^{\text{cocont}}(\mathcal{P}(A), \mathcal{P}(B)), \end{aligned}$$

natural in $A, B \in \text{Obj}(\text{Sets})$.

Proof. We claim that **Items 1 to 5** are indeed equivalent:

- **Item 1** \iff **Item 2**: This is a special case of **Items 1 and 2** of **Proposition 2.4.3.1.6**.
- **Item 2** \iff **Item 3**: This follows from the bijections

$$\begin{aligned} \text{Hom}_{\text{Sets}}(A \times B, \{\text{true}, \text{false}\}) &\cong \text{Hom}_{\text{Sets}}(A, \text{Hom}_{\text{Sets}}(B, \{\text{true}, \text{false}\})) \\ &\cong \text{Hom}_{\text{Sets}}(A, \mathcal{P}(B)), \end{aligned}$$

where the last bijection is from **Items 1 and 2** of **Proposition 2.4.3.1.6**.

- **Item 2** \iff **Item 4**: This follows from the bijections

$$\begin{aligned} \text{Hom}_{\text{Sets}}(A \times B, \{\text{true}, \text{false}\}) &\cong \text{Hom}_{\text{Sets}}(B, \text{Hom}_{\text{Sets}}(A, \{\text{true}, \text{false}\})) \\ &\cong \text{Hom}_{\text{Sets}}(B, \mathcal{P}(A)), \end{aligned}$$

where again the last bijection is from **Items 1 and 2** of **Proposition 2.4.3.1.6**.

- **Item 2** \iff **Item 5**: This follows from the universal property of the powerset $\mathcal{P}(X)$ of a set X as the free cocompletion of X via the characteristic embedding

$$\chi_X: X \hookrightarrow \mathcal{P}(X)$$

of X into $\mathcal{P}(X)$, **Item 2** of **Proposition 2.4.3.1.8**.

In particular, the bijection

$$\text{Rel}(A, B) \cong \text{Hom}_{\text{Pos}}^{\text{cocont}}(\mathcal{P}(A), \mathcal{P}(B))$$

is given by taking a relation $R: A \dashv\vdash B$, passing to its associated function $f: A \rightarrow \mathcal{P}(B)$ from A to B and then extending f from A to all of $\mathcal{P}(A)$ by taking its left Kan extension along χ_X .

This coincides with the direct image function $f_*: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$ of [Definition 2.4.4.1.1](#).

This finishes the proof. \square

00HW Proposition 5.1.1.1.5. Let A and B be sets and let $R, S: A \dashv\vdash B$ be relations.

00HX 1. *End Formula for the Set of Inclusions of Relations.* We have

$$\mathrm{Hom}_{\mathbf{Rel}(A,B)}(R, S) \cong \int_{a \in A} \int_{b \in B} \mathrm{Hom}_{\{t,f\}}(R_a^b, S_a^b).$$

Proof. Item 1, End Formula for the Set of Inclusions of Relations: Unwinding the expression inside the end on the right hand side, we have

$$\int_{a \in A} \int_{b \in B} \mathrm{Hom}_{\{t,f\}}(R_a^b, S_a^b) \cong \begin{cases} \mathrm{pt} & \text{if, for each } a \in A \text{ and each } b \in B, \\ & \text{we have } \mathrm{Hom}_{\{t,f\}}(R_a^b, S_a^b) \cong \mathrm{pt} \\ \emptyset & \text{otherwise.} \end{cases}$$

Since we have $\mathrm{Hom}_{\{t,f\}}(R_a^b, S_a^b) = \{\mathrm{true}\} \cong \mathrm{pt}$ exactly when $R_a^b = \mathrm{false}$ or $R_a^b = S_a^b = \mathrm{true}$, we get

$$\int_{a \in A} \int_{b \in B} \mathrm{Hom}_{\{t,f\}}(R_a^b, S_a^b) \cong \begin{cases} \mathrm{pt} & \text{if, for each } a \in A \text{ and each } b \in B, \\ & \text{if } a \sim_R b, \text{ then } a \sim_S b, \\ \emptyset & \text{otherwise.} \end{cases}$$

On the left hand-side, we have

$$\mathrm{Hom}_{\mathbf{Rel}(A,B)}(R, S) \cong \begin{cases} \mathrm{pt} & \text{if } R \subset S, \\ \emptyset & \text{otherwise.} \end{cases}$$

It is then clear that the conditions for each set to evaluate to pt (up to isomorphism) are equivalent, implying that those two sets are isomorphic. \square

00HY 5.1.2 Relations as Decategorifications of Profunctors

00HZ Remark 5.1.2.1.1. The notion of a relation is a decategorification of that of a profunctor:

1. A profunctor from a category C to a category \mathcal{D} is a functor

$$\mathbf{p}: \mathcal{D}^{\mathrm{op}} \times C \rightarrow \mathbf{Sets}.$$

2. A relation on sets A and B is a function

$$R: A \times B \rightarrow \{\text{true}, \text{false}\}.$$

Here we notice that:

- The opposite X^{op} of a set X is itself, as $(-)^{\text{op}}: \text{Cats} \rightarrow \text{Cats}$ restricts to the identity endofunctor on Sets.
- The values that profunctors and relations take are analogous:

- A category is enriched over the category

$$\text{Sets} \stackrel{\text{def}}{=} \text{Cats}_0$$

of sets, with profunctors taking values on it.

- A set is enriched over the set

$$\{\text{true}, \text{false}\} \stackrel{\text{def}}{=} \text{Cats}_{-1}$$

of classical truth values, with relations taking values on it.

00J0 Remark 5.1.2.1.2. Extending **Remark 5.1.2.1.1**, the equivalent definitions of relations in **Remark 5.1.1.4** are also related to the corresponding ones for profunctors (??), which state that a profunctor $p: C \dashv\vdash D$ is equivalently:

- 00J1** 1. A functor $p: D^{\text{op}} \times C \rightarrow \text{Sets}$.
- 00J2** 2. A functor $p: C \rightarrow \text{PSh}(D)$.
- 00J3** 3. A functor $p: D^{\text{op}} \rightarrow \text{Fun}(C, \text{Sets})$.
- 00J4** 4. A colimit-preserving functor $p: \text{PSh}(C) \rightarrow \text{PSh}(D)$.

Indeed:

- The equivalence between **Items 1** and **2** (and also that between **Items 1** and **3**, which is proved analogously) is an instance of currying, both for profunctors as well as for relations, using the isomorphisms

$$\begin{aligned} \text{Sets}(A \times B, \{\text{true}, \text{false}\}) &\cong \text{Sets}(A, \text{Sets}(B, \{\text{true}, \text{false}\})) \\ &\cong \text{Sets}(A, \mathcal{P}(B)), \\ \text{Fun}(D^{\text{op}} \times C, \text{Sets}) &\cong \text{Fun}(C, \text{Fun}(D^{\text{op}}, \text{Sets})) \\ &\cong \text{Fun}(C, \text{PSh}(D)). \end{aligned}$$

- The equivalence between **Items 1** and **3** follows from the universal properties of:

- The powerset $\mathcal{P}(X)$ of a set X as the free cocompletion of X via the characteristic embedding

$$\chi_{(-)} : X \hookrightarrow \mathcal{P}(X)$$

of X into $\mathcal{P}(X)$, as stated and proved in **Item 2** of **Proposition 2.4.3.1.8**.

- The category $\text{PSh}(C)$ of presheaves on a category C as the free cocompletion of C via the Yoneda embedding

$$\mathcal{Y} : C \hookrightarrow \text{PSh}(C)$$

of C into $\text{PSh}(C)$, as stated and proved in ?? of ??.

00J5 5.1.3 Examples of Relations

00J6 Example 5.1.3.1.1. The **trivial relation on A and B** is the relation \sim_{triv} defined equivalently as follows:

1. As a subset of $A \times B$, we have

$$\sim_{\text{triv}} \stackrel{\text{def}}{=} A \times B.$$

2. As a function from $A \times B$ to $\{\text{true}, \text{false}\}$, the relation \sim_{triv} is the constant function

$$\Delta_{\text{true}} : A \times B \rightarrow \{\text{true}, \text{false}\}$$

from $A \times B$ to $\{\text{true}, \text{false}\}$ taking the value true.

3. As a function from A to $\mathcal{P}(B)$, the relation \sim_{triv} is the function

$$\Delta_{\text{true}} : A \rightarrow \mathcal{P}(B)$$

defined by

$$\Delta_{\text{true}}(a) \stackrel{\text{def}}{=} B$$

for each $a \in A$.

4. Lastly, it is the unique relation R on A and B such that we have $a \sim_R b$ for each $a \in A$ and each $b \in B$.

00J7 Example 5.1.3.1.2. The **cotrivial relation on A and B** is the relation \sim_{cotriv} defined equivalently as follows:

1. As a subset of $A \times B$, we have

$$\sim_{\text{cotriv}} \stackrel{\text{def}}{=} \emptyset.$$

2. As a function from $A \times B$ to $\{\text{true}, \text{false}\}$, the relation \sim_{cotriv} is the constant function

$$\Delta_{\text{false}}: A \times B \rightarrow \{\text{true}, \text{false}\}$$

from $A \times B$ to $\{\text{true}, \text{false}\}$ taking the value false.

3. As a function from A to $\mathcal{P}(B)$, the relation \sim_{cotriv} is the function

$$\Delta_{\text{false}}: A \rightarrow \mathcal{P}(B)$$

defined by

$$\Delta_{\text{false}}(a) \stackrel{\text{def}}{=} \emptyset$$

for each $a \in A$.

4. Lastly, it is the unique relation R on A and B such that we have $a \not\sim_R b$ for each $a \in A$ and each $b \in B$.

00J8 Example 5.1.3.1.3. The characteristic relation

$$\chi_X(-1, -2): X \times X \rightarrow \{\text{t}, \text{f}\}$$

on X of [Item 3](#) of [Definition 2.4.1.1.1](#), defined by

$$\chi_X(x, y) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x = y, \\ \text{false} & \text{if } x \neq y \end{cases}$$

for each $x, y \in X$, is another example of a relation.

00J9 Example 5.1.3.1.4. Square roots are examples of relations:

1. *Square Roots in \mathbb{R} .* The assignment $x \mapsto \sqrt{x}$ defines a relation

$$\sqrt{-}: \mathbb{R} \rightarrow \mathcal{P}(\mathbb{R})$$

from \mathbb{R} to itself, being explicitly given by

$$\sqrt{x} \stackrel{\text{def}}{=} \begin{cases} 0 & \text{if } x = 0, \\ \{-\sqrt{|x|}, \sqrt{|x|}\} & \text{if } x \neq 0. \end{cases}$$

2. *Square Roots in \mathbb{Q} .* Square roots in \mathbb{Q} are similar to square roots in \mathbb{R} , though now additionally it may also occur that $\sqrt{\cdot}: \mathbb{Q} \rightarrow \mathcal{P}(\mathbb{Q})$ sends a rational number x (e.g. 2) to the empty set (since $\sqrt{2} \notin \mathbb{Q}$).

00JA Example 5.1.3.1.5. The complex logarithm defines a relation

$$\log: \mathbb{C} \rightarrow \mathcal{P}(\mathbb{C})$$

from \mathbb{C} to itself, where we have

$$\log(a + bi) \stackrel{\text{def}}{=} \left\{ \log\left(\sqrt{a^2 + b^2}\right) + i \arg(a + bi) + (2\pi i)k \mid k \in \mathbb{Z} \right\}$$

for each $a + bi \in \mathbb{C}$.

00JB Example 5.1.3.1.6. See [Wik24] for more examples of relations, such as antiderivation, inverse trigonometric functions, and inverse hyperbolic functions.

00JC 5.1.4 Functional Relations

Let A and B be sets.

00JD Definition 5.1.4.1.1. A relation $R: A \rightarrow B$ is **functional** if, for each $a \in A$, the set $R(a)$ is either empty or a singleton.

00JE Proposition 5.1.4.1.2. Let $R: A \rightarrow B$ be a relation.

00JF 1. *Characterisations.* The following conditions are equivalent:

00JG (a) The relation R is functional.

00JH (b) We have $R \diamond R^\dagger \subset \chi_B$.

Proof. Item 1, Characterisations: We claim that **Items 1a** and **1b** are indeed equivalent:

- **Item 1a** \implies **Item 1b**: Let $(b, b') \in B \times B$. We need to show that

$$[R \diamond R^\dagger](b, b') \preceq_{\{t, f\}} \chi_B(b, b'),$$

i.e. that if there exists some $a \in A$ such that $b \sim_{R^\dagger} a$ and $a \sim_R b'$, then $b = b'$. But since $b \sim_{R^\dagger} a$ is the same as $a \sim_R b$, we have both $a \sim_R b$ and $a \sim_R b'$ at the same time, which implies $b = b'$ since R is functional.

- **Item 1b** \implies **Item 1a**: Suppose that we have $a \sim_R b$ and $a \sim_R b'$ for $b, b' \in B$. We claim that $b = b'$:

1. Since $a \sim_R b$, we have $b \sim_{R^\dagger} a$.
2. Since $R \diamond R^\dagger \subset \chi_B$, we have

$$[R \diamond R^\dagger](b, b') \preceq_{\{t,f\}} \chi_B(b, b'),$$

and since $b \sim_{R^\dagger} a$ and $a \sim_R b'$, it follows that $[R \diamond R^\dagger](b, b') = \text{true}$, and thus $\chi_B(b, b') = \text{true}$ as well, i.e. $b = b'$.

This finishes the proof. \square

00JJ 5.1.5 Total Relations

Let A and B be sets.

00JK Definition 5.1.5.1.1. A relation $R: A \rightarrow B$ is **total** if, for each $a \in A$, we have $R(a) \neq \emptyset$.

00JL Proposition 5.1.5.1.2. Let $R: A \rightarrow B$ be a relation.

00JM 1. *Characterisations.* The following conditions are equivalent:

- 00JN** (a) The relation R is total.
- 00JP** (b) We have $\chi_A \subset R^\dagger \diamond R$.

Proof. Item 1, Characterisations: We claim that **Items 1a** and **1b** are indeed equivalent:

- **Item 1a** \implies **Item 1b**: We have to show that, for each $(a, a') \in A$, we have

$$\chi_A(a, a') \preceq_{\{t,f\}} [R^\dagger \diamond R](a, a'),$$

i.e. that if $a = a'$, then there exists some $b \in B$ such that $a \sim_R b$ and $b \sim_{R^\dagger} a'$ (i.e. $a \sim_R b$ again), which follows from the totality of R .

- **Item 1b** \implies **Item 1a**: Given $a \in A$, since $\chi_A \subset R^\dagger \diamond R$, we must have

$$\{a\} \subset [R^\dagger \diamond R](a),$$

implying that there must exist some $b \in B$ such that $a \sim_R b$ and $b \sim_{R^\dagger} a$ (i.e. $a \sim_R b$) and thus $R(a) \neq \emptyset$, as $b \in R(a)$.

This finishes the proof. \square

00JQ 5.2 Categories of Relations

00JR 5.2.1 The Category of Relations

00JS **Definition 5.2.1.1.1.** The **category of relations** is the category Rel where

- *Objects.* The objects of Rel are sets.
- *Morphisms.* For each $A, B \in \text{Obj}(\text{Sets})$, we have

$$\text{Rel}(A, B) \stackrel{\text{def}}{=} \text{Rel}(A, B).$$

- *Identities.* For each $A \in \text{Obj}(\text{Rel})$, the unit map

$$\mathbb{1}_A^{\text{Rel}} : \text{pt} \rightarrow \text{Rel}(A, A)$$

of Rel at A is defined by

$$\text{id}_A^{\text{Rel}} \stackrel{\text{def}}{=} \chi_A(-1, -2),$$

where $\chi_A(-1, -2)$ is the characteristic relation of A of **Item 3 of Definition 2.4.1.1.1.**

- *Composition.* For each $A, B, C \in \text{Obj}(\text{Rel})$, the composition map

$$\circ_{A,B,C}^{\text{Rel}} : \text{Rel}(B, C) \times \text{Rel}(A, B) \rightarrow \text{Rel}(A, C)$$

of Rel at (A, B, C) is defined by

$$S \circ_{A,B,C}^{\text{Rel}} R \stackrel{\text{def}}{=} S \diamond R$$

for each $(S, R) \in \text{Rel}(B, C) \times \text{Rel}(A, B)$, where $S \diamond R$ is the composition of S and R of **Definition 6.3.12.1.1.**

00JT 5.2.2 The Closed Symmetric Monoidal Category of Relations

00JU 5.2.2.1 The Monoidal Product

00JV **Definition 5.2.2.1.1.** The **monoidal product** of Rel is the functor

$$\times : \text{Rel} \times \text{Rel} \rightarrow \text{Rel}$$

where

- *Action on Objects.* For each $A, B \in \text{Obj}(\text{Rel})$, we have

$$\times(A, B) \stackrel{\text{def}}{=} A \times B,$$

where $A \times B$ is the Cartesian product of sets of **Definition 2.1.3.1.1.**

- *Action on Morphisms.* For each $(A, C), (B, D) \in \text{Obj}(\text{Rel} \times \text{Rel})$, the action on morphisms

$$\times_{(A,C),(B,D)} : \text{Rel}(A, B) \times \text{Rel}(C, D) \rightarrow \text{Rel}(A \times C, B \times D)$$

of \times is given by sending a pair of morphisms (R, S) of the form

$$\begin{aligned} R &: A \rightarrow B, \\ S &: C \rightarrow D \end{aligned}$$

to the relation

$$R \times S : A \times C \rightarrow B \times D$$

of **Definition 6.3.9.1.1.**

00JW 5.2.2.2 The Monoidal Unit

00JX Definition 5.2.2.2.1. The **monoidal unit** of Rel is the functor

$$\mathbb{1}^{\text{Rel}} : \text{pt} \rightarrow \text{Rel}$$

picking the set

$$\mathbb{1}_{\text{Rel}} \stackrel{\text{def}}{=} \text{pt}$$

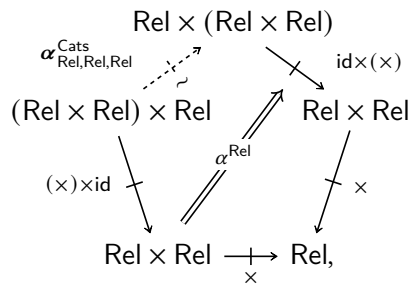
of Rel .

00JY 5.2.2.3 The Associator

00JZ Definition 5.2.2.3.1. The **associator** of Rel is the natural isomorphism

$$\alpha^{\text{Rel}} : \times \circ ((\times) \times \text{id}) \xrightarrow{\sim} \times \circ (\text{id} \times (\times)) \circ \alpha_{\text{Rel}, \text{Rel}, \text{Rel}}^{\text{Cats}}$$

as in the diagram



whose component

$$\alpha_{A,B,C}^{\text{Rel}} : (A \times B) \times C \rightarrow A \times (B \times C)$$

at $A, B, C \in \text{Obj}(\text{Rel})$ is the relation defined by declaring

$$((a, b), c) \sim_{\alpha_{A,B,C}^{\text{Rel}}} (a', (b', c'))$$

iff $a = a', b = b',$ and $c = c'.$

00K0 5.2.2.4 The Left Unitor

00K1 Definition 5.2.2.4.1. The **left unitor** of Rel is the natural isomorphism

$$\lambda^{\text{Rel}} : \times \circ (\mathbb{1}^{\text{Rel}} \times \text{id}) \xrightarrow{\sim} \lambda_{\text{Rel}}^{\text{Cats}_2},$$

whose component

$$\lambda_A^{\text{Rel}} : \mathbb{1}_{\text{Rel}} \times A \rightarrow A$$

at A is defined by declaring

$$(\star, a) \sim_{\lambda_A^{\text{Rel}}} b$$

iff $a = b.$

00K2 5.2.2.5 The Right Unitor

00K3 Definition 5.2.2.5.1. The **right unitor** of Rel is the natural isomorphism

$$\rho^{\text{Rel}} : \times \circ (\text{id} \times \mathbb{1}^{\text{Rel}}) \xrightarrow{\sim} \rho_{\text{Rel}}^{\text{Cats}_2},$$

whose component

$$\rho_A^{\text{Rel}} : A \times \mathbb{1}_{\text{Rel}} \rightarrow A$$

at A is defined by declaring

$$(a, \star) \sim_{\rho_A^{\text{Rel}}} b$$

iff $a = b.$

00K4 5.2.2.6 The Symmetry

00K5 Definition 5.2.2.6.1. The **symmetry of Rel** is the natural isomorphism

$$\sigma^{\text{Rel}} : \times \implies \times \circ \sigma_{\text{Rel,Rel}}^{\text{Cats}_2}$$

whose component

$$\sigma_{A,B}^{\text{Rel}} : A \times B \rightarrow B \times A$$

at (A, B) is defined by declaring

$$(a, b) \sim_{\sigma_{A,B}^{\text{Rel}}} (b', a')$$

iff $a = a'$ and $b = b'$.

00K6 5.2.2.7 The Internal Hom

00K7 Definition 5.2.2.7.1. The **internal Hom of Rel** is the functor

$$\text{Rel} : \text{Rel}^{\text{op}} \times \text{Rel} \rightarrow \text{Rel}$$

defined

- On objects by sending $A, B \in \text{Obj}(\text{Rel})$ to the set $\text{Rel}(A, B)$ of **Item 1** of **Definition 5.1.1.1.3**.
- On morphisms by pre/post-composition defined as in **Definition 6.3.12.1.1**.

00K8 Proposition 5.2.2.7.2. Let $A, B, C \in \text{Obj}(\text{Rel})$.

00K9 1. *Adjointness.* We have adjunctions

$$(A \times - \dashv \text{Rel}(A, -)) : \text{Rel} \begin{array}{c} \xrightarrow{A \times -} \\ \perp \\ \xleftarrow{\text{Rel}(A, -)} \end{array} \text{Rel},$$

$$(- \times B \dashv \text{Rel}(B, -)) : \text{Rel} \begin{array}{c} \xrightarrow{- \times B} \\ \perp \\ \xleftarrow{\text{Rel}(B, -)} \end{array} \text{Rel},$$

witnessed by bijections

$$\begin{aligned} \text{Rel}(A \times B, C) &\cong \text{Rel}(A, \text{Rel}(B, C)), \\ \text{Rel}(A \times B, C) &\cong \text{Rel}(B, \text{Rel}(A, C)), \end{aligned}$$

natural in $A, B, C \in \text{Obj}(\text{Rel})$.

Proof. Item 1, Adjointness: Indeed, we have

$$\begin{aligned} \text{Rel}(A \times B, C) &\stackrel{\text{def}}{=} \text{Sets}(A \times B \times C, \{\text{true}, \text{false}\}) \\ &\stackrel{\text{def}}{=} \text{Rel}(A, B \times C) \\ &\stackrel{\text{def}}{=} \text{Rel}(A, \text{Rel}(B, C)), \end{aligned}$$

and similarly for the bijection $\text{Rel}(A \times B, C) \cong \text{Rel}(B, \text{Rel}(A, C))$. \square

00KA 5.2.2.8 The Closed Symmetric Monoidal Category of Relations

00KB **Proposition 5.2.2.8.1.** The category Rel admits a closed symmetric monoidal category structure consisting of⁶

- *The Underlying Category.* The category Rel of sets and relations of [Definition 5.2.1.1.1](#).
- *The Monoidal Product.* The functor

$$\times: \text{Rel} \times \text{Rel} \rightarrow \text{Rel}$$

of [Definition 5.2.2.1.1](#).

- *The Internal Hom.* The internal Hom functor

$$\mathbf{Rel}: \text{Rel}^{\text{op}} \times \text{Rel} \rightarrow \text{Rel}$$

of [Definition 5.2.2.7.1](#).

- *The Monoidal Unit.* The functor

$$\mathbb{1}^{\text{Rel}}: \text{pt} \rightarrow \text{Rel}$$

of [Definition 5.2.2.2.1](#).

- *The Associators.* The natural isomorphism

$$\alpha^{\text{Rel}}: \times \circ (\times \times \text{id}_{\text{Rel}}) \xrightarrow{\sim} \times \circ (\text{id}_{\text{Rel}} \times \times) \circ \alpha_{\text{Rel}, \text{Rel}, \text{Rel}}^{\text{Cats}}$$

of [Definition 5.2.2.3.1](#).

- *The Left Unitors.* The natural isomorphism

$$\lambda^{\text{Rel}}: \times \circ (\mathbb{1}^{\text{Rel}} \times \text{id}_{\text{Rel}}) \xrightarrow{\sim} \lambda_{\text{Rel}}^{\text{Cats}_2}$$



⁶ **Warning:** This is not a Cartesian monoidal structure, as the product on Rel is in fact

of [Definition 5.2.2.4.1](#).

- *The Right Unitors.* The natural isomorphism

$$\rho^{\mathbf{Rel}}: \times \circ (\text{id} \times \mathbb{1}^{\mathbf{Rel}}) \xrightarrow{\sim} \rho_{\mathbf{Rel}}^{\mathbf{Cats}_2}$$

of [Definition 5.2.2.5.1](#).

- *The Symmetry.* The natural isomorphism

$$\sigma^{\mathbf{Rel}}: \times \xrightarrow{\sim} \times \circ \sigma_{\mathbf{Rel}, \mathbf{Rel}}^{\mathbf{Cats}_2}$$

of [Definition 5.2.2.6.1](#).

Proof. Omitted. □

00KC 5.2.3 The 2-Category of Relations

00KD **Definition 5.2.3.1.1.** The **2-category of relations** is the locally posetal 2-category \mathbf{Rel} where

- *Objects.* The objects of \mathbf{Rel} are sets.
- *Hom-Objects.* For each $A, B \in \text{Obj}(\mathbf{Sets})$, we have

$$\begin{aligned} \text{Hom}_{\mathbf{Rel}}(A, B) &\stackrel{\text{def}}{=} \mathbf{Rel}(A, B) \\ &\stackrel{\text{def}}{=} (\mathbf{Rel}(A, B), \subset). \end{aligned}$$

- *Identities.* For each $A \in \text{Obj}(\mathbf{Rel})$, the unit map

$$\mathbb{1}_A^{\mathbf{Rel}}: \text{pt} \rightarrow \mathbf{Rel}(A, A)$$

of \mathbf{Rel} at A is defined by

$$\text{id}_A^{\mathbf{Rel}} \stackrel{\text{def}}{=} \chi_A(-_1, -_2),$$

where $\chi_A(-_1, -_2)$ is the characteristic relation of A of [Item 3 of Definition 2.4.1.1.1](#).

given by the disjoint union of sets; see ??.

END TEXTDBEND

- *Composition.* For each $A, B, C \in \text{Obj}(\mathbf{Rel})$, the composition map⁷

$$\circ_{A,B,C}^{\mathbf{Rel}}: \mathbf{Rel}(B, C) \times \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(A, C)$$

of \mathbf{Rel} at (A, B, C) is defined by

$$S \circ_{A,B,C}^{\mathbf{Rel}} R \stackrel{\text{def}}{=} S \diamond R$$

for each $(S, R) \in \mathbf{Rel}(B, C) \times \mathbf{Rel}(A, B)$, where $S \diamond R$ is the composition of S and R of [Definition 6.3.12.1.1](#).

00KE 5.2.4 The Double Category of Relations

00KF 5.2.4.1 The Double Category of Relations

00KG Definition 5.2.4.1.1. The **double category of relations** is the locally posetal double category $\mathbf{Rel}^{\text{dbl}}$ where

- *Objects.* The objects of $\mathbf{Rel}^{\text{dbl}}$ are sets.
- *Vertical Morphisms.* The vertical morphisms of $\mathbf{Rel}^{\text{dbl}}$ are maps of sets $f: A \rightarrow B$.
- *Horizontal Morphisms.* The horizontal morphisms of $\mathbf{Rel}^{\text{dbl}}$ are relations $R: A \dashrightarrow X$.
- *2-Morphisms.* A 2-cell

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ f \downarrow & \Downarrow \alpha & \downarrow g \\ X & \xrightarrow{S} & Y \end{array}$$

of $\mathbf{Rel}^{\text{dbl}}$ is either non-existent or an inclusion of relations of the form

$$R \subset S \circ (f \times g), \quad \begin{array}{ccc} A \times B & \xrightarrow{R} & \{\text{true}, \text{false}\} \\ f \times g \downarrow & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ X \times Y & \xrightarrow{S} & \{\text{true}, \text{false}\}. \end{array}$$

⁷Note that this is indeed a morphism of posets: given relations $R_1, R_2 \in \mathbf{Rel}(A, B)$ and

- *Horizontal Identities.* The horizontal unit functor of Rel^{dbl} is the functor of [Definition 5.2.4.2.1](#).
- *Vertical Identities.* For each $A \in \text{Obj}(\text{Rel}^{\text{dbl}})$, we have

$$\text{id}_A^{\text{Rel}^{\text{dbl}}} \stackrel{\text{def}}{=} \text{id}_A.$$

- *Identity 2-Morphisms.* For each horizontal morphism $R: A \dashv\vdash B$ of Rel^{dbl} , the identity 2-morphism

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ \text{id}_A \downarrow & \parallel & \downarrow \text{id}_B \\ & \text{id}_R & \\ & \downarrow & \\ A & \xrightarrow{R} & B \end{array}$$

of R is the identity inclusion

$$\begin{array}{ccc} B \times A & \xrightarrow{R} & \{\text{true}, \text{false}\} \\ \text{id}_B \times \text{id}_A \downarrow & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ B \times A & \xrightarrow{R} & \{\text{true}, \text{false}\}. \end{array}$$

- *Horizontal Composition.* The horizontal composition functor of Rel^{dbl} is the functor of [Definition 5.2.4.3.1](#).
- *Vertical Composition of 1-Morphisms.* For each composable pair $A \xrightarrow{F} B \xrightarrow{G} C$ of vertical morphisms of Rel^{dbl} , i.e. maps of sets, we have

$$g \circ^{\text{Rel}^{\text{dbl}}} f \stackrel{\text{def}}{=} g \circ f.$$

- *Vertical Composition of 2-Morphisms.* The vertical composition of 2-morphisms in Rel^{dbl} is defined as in [Definition 5.2.4.4.1](#).
- *Associators.* The associators of Rel^{dbl} is defined as in [Definition 5.2.4.5.1](#).
- *Left Unitors.* The left unitors of Rel^{dbl} is defined as in [Definition 5.2.4.6.1](#).
- *Right Unitors.* The right unitors of Rel^{dbl} is defined as in [Definition 5.2.4.7.1](#).

00KH 5.2.4.2 Horizontal Identities

00KJ Definition 5.2.4.2.1. The **horizontal unit functor** of Rel^{dbl} is the functor

$$\mathbb{1}^{\text{Rel}^{\text{dbl}}} : \text{Rel}_0^{\text{dbl}} \rightarrow \text{Rel}_1^{\text{dbl}}$$

of Rel^{dbl} is the functor where

- *Action on Objects.* For each $A \in \text{Obj}(\text{Rel}_0^{\text{dbl}})$, we have

$$\mathbb{1}_A \stackrel{\text{def}}{=} \chi_A(-1, -2).$$

- *Action on Morphisms.* For each vertical morphism $f : A \rightarrow B$ of Rel^{dbl} , i.e. each map of sets f from A to B , the identity 2-morphism

$$\begin{array}{ccc} A & \xrightarrow{\mathbb{1}_A} & A \\ f \downarrow & \parallel & \downarrow f \\ B & \xrightarrow{\mathbb{1}_B} & B \end{array}$$

of f is the inclusion

$$\begin{array}{ccc} A \times A & \xrightarrow{\chi_A(-1, -2)} & \{\text{true}, \text{false}\} \\ f \times f \downarrow & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ B \times B & \xrightarrow{\chi_B(-1, -2)} & \{\text{true}, \text{false}\} \end{array}$$

of **Item 1 of Proposition 2.4.1.1.3.**

00KK 5.2.4.3 Horizontal Composition

00KL Definition 5.2.4.3.1. The **horizontal composition functor** of Rel^{dbl} is the functor

$$\odot^{\text{Rel}^{\text{dbl}}} : \text{Rel}_1^{\text{dbl}} \times_{\text{Rel}_0^{\text{dbl}}} \text{Rel}_1^{\text{dbl}} \rightarrow \text{Rel}_1^{\text{dbl}}$$

of Rel^{dbl} is the functor where

$S_1, S_2 \in \mathbf{Rel}(B, C)$ such that

$$\begin{aligned} R_1 &\subset R_2, \\ S_1 &\subset S_2, \end{aligned}$$

- *Action on Objects.* For each composable pair $A \xrightarrow{R} B \xrightarrow{S} C$ of horizontal morphisms of Rel^{dbl} , we have

$$S \circ R \stackrel{\text{def}}{=} S \diamond R,$$

where $S \diamond R$ is the composition of R and S of **Definition 6.3.12.1.1**.

- *Action on Morphisms.* For each horizontally composable pair

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ f \downarrow & \Downarrow \alpha & \downarrow g \\ X & \xrightarrow{T} & Y \end{array} \quad \begin{array}{ccc} B & \xrightarrow{S} & C \\ g \downarrow & \Downarrow \beta & \downarrow h \\ Y & \xrightarrow{U} & Z \end{array}$$

of 2-morphisms of Rel^{dbl} , i.e. for each pair

$$\begin{array}{ccc} A \times B & \xrightarrow{R} & \{\text{true}, \text{false}\} \\ f \times g \downarrow & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ X \times Y & \xrightarrow{T} & \{\text{true}, \text{false}\} \end{array} \quad \begin{array}{ccc} B \times C & \xrightarrow{S} & \{\text{true}, \text{false}\} \\ g \times h \downarrow & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ Y \times Z & \xrightarrow{U} & \{\text{true}, \text{false}\} \end{array}$$

of inclusions of relations, the horizontal composition

$$\begin{array}{ccc} A & \xrightarrow{S \circ R} & C \\ f \downarrow & \Downarrow \beta \circ \alpha & \downarrow h \\ X & \xrightarrow{U \circ T} & Z \end{array}$$

of α and β is the inclusion of relations⁸

$$(U \circ T) \circ (f \times h) \subset (S \circ R) \quad \begin{array}{ccc} A \times C & \xrightarrow{S \circ R} & \{\text{true}, \text{false}\} \\ f \times h \downarrow & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ X \times Z & \xrightarrow{U \circ T} & \{\text{true}, \text{false}\}. \end{array}$$

we have also $S_1 \diamond R_1 \subset S_2 \diamond R_2$.

⁸This is justified by noting that, given $(a, c) \in A \times C$, the statement

- We have $a \sim_{(U \circ T) \circ (f \times h)} c$, i.e. $f(a) \sim_{U \circ T} h(c)$, i.e. there exists some $y \in Y$ such that:

00KM 5.2.4.4 Vertical Composition of 2-Morphisms

00KN Definition 5.2.4.4.1. The **vertical composition** in Rel^{dbl} is defined as follows: for each vertically composable pair

$$\begin{array}{ccc}
 A & \xrightarrow{R} & X \\
 \downarrow f & \Downarrow \alpha & \downarrow g \\
 B & \xrightarrow{S} & Y
 \end{array}
 \quad
 \begin{array}{ccc}
 B & \xrightarrow{S} & Y \\
 \downarrow h & \Downarrow \beta & \downarrow k \\
 C & \xrightarrow{T} & Z
 \end{array}$$

of 2-morphisms of Rel^{dbl} , i.e. for each each pair

$$\begin{array}{ccc}
 A \times X & \xrightarrow{R} & \{\text{true}, \text{false}\} \\
 \downarrow f \times g & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\
 B \times Y & \xrightarrow{S} & \{\text{true}, \text{false}\}
 \end{array}
 \quad
 \begin{array}{ccc}
 B \times Y & \xrightarrow{S} & \{\text{true}, \text{false}\} \\
 \downarrow h \times k & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\
 C \times Z & \xrightarrow{T} & \{\text{true}, \text{false}\}
 \end{array}$$

of inclusions of relations, we define the vertical composition

$$\begin{array}{ccc}
 A & \xrightarrow{R} & X \\
 \downarrow h \circ f & \Downarrow \beta \circ \alpha & \downarrow k \circ g \\
 C & \xrightarrow{T} & Z
 \end{array}$$

1. We have $f(a) \sim_T y$;
2. We have $y \sim_U h(c)$;

is implied by the statement

- We have $a \sim_{S \circ R} c$, i.e. there exists some $b \in B$ such that:
 1. We have $a \sim_R b$;
 2. We have $b \sim_S c$;

since:

- If $a \sim_R b$, then $f(a) \sim_T g(b)$, as $T \circ (f \times g) \subset R$;
- If $b \sim_S c$, then $g(b) \sim_U h(c)$, as $U \circ (g \times h) \subset S$.

of α and β as the inclusion of relations

$$T \circ [(h \circ f) \times (k \circ g)] \subset R, \quad \begin{array}{ccc} A \times X & \xrightarrow{R} & \{\text{true}, \text{false}\} \\ \downarrow (h \circ f) \times (k \circ g) & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ C \times Z & \xrightarrow{T} & \{\text{true}, \text{false}\} \end{array}$$

given by the pasting of inclusions⁹

$$\begin{array}{ccc} A \times X & \xrightarrow{R} & \{\text{true}, \text{false}\} \\ \downarrow f \times g & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ B \times Y & \xrightarrow{S} & \{\text{true}, \text{false}\} \\ \downarrow h \times k & \subset & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ C \times Z & \xrightarrow{T} & \{\text{true}, \text{false}\}. \end{array}$$

00KP 5.2.4.5 The Associators

00KQ Definition 5.2.4.5.1. For each composable triple

$$A \xrightarrow{R} B \xrightarrow{S} C \xrightarrow{T} D$$

of horizontal morphisms of Rel^{dbl} , the component

$$\alpha_{T,S,R}^{\text{Rel}^{\text{dbl}}} : (T \odot S) \odot R \xrightarrow{\sim} T \odot (S \odot R), \quad \begin{array}{ccccccc} A & \xrightarrow{R} & B & \xrightarrow{S} & C & \xrightarrow{T} & D \\ \downarrow \text{id}_A & & \downarrow \alpha_{T,S,R}^{\text{Rel}^{\text{dbl}}} & & \downarrow \text{id}_D & & \\ A & \xrightarrow{R} & B & \xrightarrow{S} & C & \xrightarrow{T} & D \end{array}$$

⁹This is justified by noting that, given $(a, x) \in A \times X$, the statement

- We have $h(f(a)) \sim_T k(g(x))$;

is implied by the statement

- We have $a \sim_R x$;

since

- If $a \sim_R x$, then $f(a) \sim_S g(x)$, as $S \circ (f \times g) \subset R$;
- If $b \sim_S y$, then $h(b) \sim_T k(y)$, as $T \circ (h \times k) \subset S$, and thus, in particular:
 - If $f(a) \sim_S g(x)$, then $h(f(a)) \sim_T k(g(x))$.

of the associator of Rel^{dbl} at (R, S, T) is the identity inclusion¹⁰

$$(T \diamond S) \diamond R = T \diamond (S \diamond R)$$

$$\begin{array}{ccc} A \times B & \xrightarrow{(T \diamond S) \diamond R} & \{\text{true}, \text{false}\} \\ \parallel & \cong & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ A \times B & \xrightarrow{T \diamond (S \diamond R)} & \{\text{true}, \text{false}\}. \end{array}$$

00KR 5.2.4.6 The Left Unitors

00KS Definition 5.2.4.6.1. For each horizontal morphism $R: A \rightarrow B$ of Rel^{dbl} , the component

$$\lambda_R^{\text{Rel}^{\text{dbl}}} : \mathbb{1}_B \odot R \xrightarrow{\sim} R,$$

$$\begin{array}{ccccc} A & \xrightarrow{R} & B & \xrightarrow{\mathbb{1}_B} & B \\ \text{id}_A \downarrow & & \lambda_R^{\text{Rel}^{\text{dbl}}} \downarrow & & \downarrow \text{id}_B \\ A & \xrightarrow{R} & B & & B \end{array}$$

of the left unitor of Rel^{dbl} at R is the identity inclusion¹¹

$$R = \chi_B \diamond R,$$

$$\begin{array}{ccc} A \times B & \xrightarrow{\chi_B \diamond R} & \{\text{true}, \text{false}\} \\ \parallel & \cong & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ A \times B & \xrightarrow{R} & \{\text{true}, \text{false}\}. \end{array}$$

00KT 5.2.4.7 The Right Unitors

00KU Definition 5.2.4.7.1. For each horizontal morphism $R: A \rightarrow B$ of Rel^{dbl} , the component

$$\rho_R^{\text{Rel}^{\text{dbl}}} : R \odot \mathbb{1}_A \xrightarrow{\sim} R,$$

$$\begin{array}{ccccc} A & \xrightarrow{\mathbb{1}_A} & A & \xrightarrow{R} & B \\ \text{id}_A \downarrow & & \rho_R^{\text{Rel}^{\text{dbl}}} \downarrow & & \downarrow \text{id}_B \\ A & \xrightarrow{R} & B & & B \end{array}$$

¹⁰This is justified by **Item 2** of **Proposition 6.3.12.1.3**.

¹¹This is justified by **Item 3** of **Proposition 6.3.12.1.3**.

of the right unitor of Rel^{dbl} at R is the identity inclusion¹²

$$R = R \diamond \chi_A, \quad \begin{array}{ccc} A \times B & \xrightarrow{R \diamond \chi_A} & \{\text{true}, \text{false}\} \\ \parallel & \cong & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ A \times B & \xrightarrow{R} & \{\text{true}, \text{false}\}. \end{array}$$

00KV 5.3 Properties of the 2-Category of Relations

00KW 5.3.1 Self-Duality

00KX **Proposition 5.3.1.1.1.** The (2-)category of relations is self-dual:

00KY 1. *Self-Duality I.* We have an isomorphism

$$\text{Rel}^{\text{op}} \cong^{\text{eq.}} \text{Rel}$$

of categories.

00KZ 2. *Self-Duality II.* We have a 2-isomorphism

$$\text{Rel}^{\text{op}} \cong^{\text{eq.}} \text{Rel}$$

of 2-categories.

Proof. Item 1, Self-Duality I: We claim that the functor

$$F: \text{Rel}^{\text{op}} \rightarrow \text{Rel}$$

given by the identity on objects and by $R \mapsto R^\dagger$ on morphisms is an isomorphism of categories.

By **Item 1 of Proposition 8.5.8.1.3**, it suffices to show that F is bijective on objects (which is clear) and fully faithful. Indeed, the map

$$(-)^\dagger: \text{Rel}(A, B) \rightarrow \text{Rel}(B, A)$$

defined by the assignment $R \mapsto R^\dagger$ is a bijection by **Item 5 of Proposition 6.3.11.1.3**, showing F to be fully faithful.

Item 2, Self-Duality II: We claim that the 2-functor

$$F: \text{Rel}^{\text{op}} \rightarrow \text{Rel}$$

given by the identity on objects, by $R \mapsto R^\dagger$ on morphisms, and by preserving inclusions on 2-morphisms via **Item 1 of Proposition 6.3.11.1.3**, is an isomorphism of categories.

By ?? of ??, it suffices to show that F is:

¹²This is justified by **Item 3 of Proposition 6.3.12.1.3**.

- Bijective on objects, which is clear.
- Bijective on 1-morphisms, which was shown in [Item 1](#).
- Bijective on 2-morphisms, which follows from [Item 1](#) of [Proposition 6.3.11.1.3](#).

Thus F is indeed a 2-isomorphism of categories. \square

00L0 5.3.2 Isomorphisms and Equivalences in \mathbf{Rel}

Let $R: A \dashrightarrow B$ be a relation from A to B .

00L1 **Proposition 5.3.2.1.1.** The following conditions are equivalent:

00L2 1. The relation $R: A \dashrightarrow B$ is an equivalence in \mathbf{Rel} , i.e.:

(\star) There exists a relation $R^{-1}: B \dashrightarrow A$ from B to A together with isomorphisms

$$\begin{aligned} R^{-1} \diamond R &\cong \chi_A, \\ R \diamond R^{-1} &\cong \chi_B. \end{aligned}$$

00L3 2. The relation $R: A \dashrightarrow B$ is an isomorphism in \mathbf{Rel} , i.e.:

(\star) There exists a relation $R^{-1}: B \dashrightarrow A$ from B to A such that we have

$$\begin{aligned} R^{-1} \diamond R &= \chi_A, \\ R \diamond R^{-1} &= \chi_B. \end{aligned}$$

00L4 3. There exists a bijection $f: A \xrightarrow{\cong} B$ with $R = \text{Gr}(f)$.

Proof. We claim that [Items 1](#) to [3](#) are indeed equivalent:

- [Item 1](#) \iff [Item 2](#): This follows from the fact that \mathbf{Rel} is locally posetal, so that natural isomorphisms and equalities of 1-morphisms in \mathbf{Rel} coincide.
- [Item 2](#) \implies [Item 3](#): The equalities in [Item 2](#) imply $R \dashv R^{-1}$, and thus by [Proposition 5.3.3.1.1](#), there exists a function $f_R: A \rightarrow B$ associated to R , where, for each $a \in A$, the image $f_R(a)$ of a by f_R is the unique element of $R(a)$, which implies $R = \text{Gr}(f_R)$ in particular. Furthermore, we have $R^{-1} = f_R^{-1}$ (as in [Definition 6.3.2.1.1](#)). The conditions from

Item 2 then become the following:

$$\begin{aligned} f_R^{-1} \diamond f_R &= \chi_A, \\ f_R \diamond f_R^{-1} &= \chi_B. \end{aligned}$$

All that is left is to show then is that f_R is a bijection:

- *The Function f_R Is Injective.* Let $a, b \in A$ and suppose that $f_R(a) = f_R(b)$. Since $a \sim_R f_R(a)$ and $f_R(a) = f_R(b) \sim_{R^{-1}} b$, the condition $f_R^{-1} \diamond f_R = \chi_A$ implies that $a = b$, showing f_R to be injective.
 - *The Function f_R Is Surjective.* Let $b \in B$. Applying the condition $f_R \diamond f_R^{-1} = \chi_B$ to (b, b) , it follows that there exists some $a \in A$ such that $f_R^{-1}(b) = a$ and $f_R(a) = b$. This shows f_R to be surjective.
- **Item 3** \implies **Item 2**: By **Item 2** of **Proposition 6.3.1.1.2**, we have an adjunction $\text{Gr}(f) \dashv f^{-1}$, giving inclusions

$$\begin{aligned} \chi_A &\subset f^{-1} \diamond \text{Gr}(f), \\ \text{Gr}(f) \diamond f^{-1} &\subset \chi_B. \end{aligned}$$

We claim the reverse inclusions are also true:

- $f^{-1} \diamond \text{Gr}(f) \subset \chi_A$: This is equivalent to the statement that if $f(a) = b$ and $f^{-1}(b) = a'$, then $a = a'$, which follows from the injectivity of f .
- $\chi_B \subset \text{Gr}(f) \diamond f^{-1}$: This is equivalent to the statement that given $b \in B$ there exists some $a \in A$ such that $f^{-1}(b) = a$ and $f(a) = b$, which follows from the surjectivity of f .

This finishes the proof. □

00L5 5.3.3 Adjunctions in Rel

Let A and B be sets.

00L6 Proposition 5.3.3.1.1. We have a natural bijection

$$\left\{ \begin{array}{l} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\} \cong \left\{ \begin{array}{l} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\},$$

with every adjunction in \mathbf{Rel} being of the form $\text{Gr}(f) \dashv f^{-1}$ for some function f .

Proof. We proceed step by step:

1. *From Adjunctions in **Rel** to Functions.* An adjunction in **Rel** from A to B consists of a pair of relations

$$R: A \rightarrow B,$$

$$S: B \rightarrow A,$$

together with inclusions

$$\chi_A \subset S \diamond R,$$

$$R \diamond S \subset \chi_B.$$

We claim that these conditions imply that R is total and functional, i.e. that $R(a)$ is a singleton for each $a \in A$:

- (a) *$R(a)$ Has an Element.* Given $a \in A$, since $\chi_A \subset S \diamond R$, we must have $\{a\} \subset S(R(a))$, implying that there exists some $b \in B$ such that $a \sim_R b$ and $b \sim_S a$, and thus $R(a) \neq \emptyset$, as $b \in R(a)$.
- (b) *$R(a)$ Has No More Than One Element.* Suppose that we have $a \sim_R b$ and $a \sim_R b'$ for $b, b' \in B$. We claim that $b = b'$:
 - i. Since $\chi_A \subset S \diamond R$, there exists some $k \in B$ such that $a \sim_R k$ and $k \sim_S a$.
 - ii. Since $R \diamond S \subset \chi_B$, if $b'' \sim_S a'$ and $a' \sim_R b'''$, then $b'' = b'''$.
 - iii. Applying the above to $b'' = k$, $b''' = b$, and $a' = a$, since $k \sim_S a$ and $a \sim_R b'$, we have $k = b$.
 - iv. Similarly $k = b'$.
 - v. Thus $b = b'$.

Together, the above two items show $R(a)$ to be a singleton, being thus given by $\text{Gr}(f)$ for some function $f: A \rightarrow B$, which gives a map

$$\left\{ \begin{array}{c} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\} \rightarrow \left\{ \begin{array}{c} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\}.$$

Moreover, by uniqueness of adjoints (?? of ??), this implies also that $S = f^{-1}$.

2. *From Functions to Adjunctions in **Rel**.* By **Item 2** of **Proposition 6.3.1.1.2**, every function $f: A \rightarrow B$ gives rise to an adjunction $\text{Gr}(f) \dashv f^{-1}$ in **Rel**, giving a map

$$\left\{ \begin{array}{c} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\} \rightarrow \left\{ \begin{array}{c} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\}.$$

3. *Invertibility: From Functions to Adjunctions Back to Functions.* We need to show that starting with a function $f : A \rightarrow B$, passing to $\text{Gr}(f) \dashv f^{-1}$, and then passing again to a function gives f again. This is clear however, since we have $a \sim_{\text{Gr}(f)} b$ iff $f(a) = b$.
4. *Invertibility: From Adjunctions to Functions Back to Adjunctions.* We need to show that, given an adjunction $R \dashv S$ in **Rel** giving rise to a function $f_{R,S} : A \rightarrow B$, we have

$$\begin{aligned}\text{Gr}(f_{R,S}) &= R, \\ f_{R,S}^{-1} &= S.\end{aligned}$$

We check these explicitly:

- $\text{Gr}(f_{R,S}) = R$. We have

$$\begin{aligned}\text{Gr}(f_{R,S}) &\stackrel{\text{def}}{=} \{(a, f_{R,S}(a)) \in A \times B \mid a \in A\} \\ &\stackrel{\text{def}}{=} \{(a, R(a)) \in A \times B \mid a \in A\} \\ &= R.\end{aligned}$$

- $f_{R,S}^{-1} = S$. We first claim that, given $a \in A$ and $b \in B$, the following conditions are equivalent:
 - We have $a \sim_R b$.
 - We have $b \sim_S a$.

Indeed:

- *If $a \sim_R b$, then $b \sim_S a$:* Since $\chi_A \subset S \diamond R$, there exists $k \in B$ such that $a \sim_R k$ and $k \sim_S a$, but since $a \sim_R b$ and R is functional, we have $k = b$ and thus $b \sim_S a$.
- *If $b \sim_S a$, then $a \sim_R b$:* First note that since R is total we have $a \sim_R b'$ for some $b' \in B$. Now, since $R \diamond S \subset \chi_B$, $b \sim_S a$, and $a \sim_R b'$, we have $b = b'$, and thus $a \sim_R b$.

Having show this, we now have

$$\begin{aligned}f_{R,S}^{-1}(b) &\stackrel{\text{def}}{=} \{a \in A \mid f_{R,S}(a) = b\} \\ &\stackrel{\text{def}}{=} \{a \in A \mid a \sim_R b\} \\ &= \{a \in A \mid b \sim_S a\} \\ &\stackrel{\text{def}}{=} S(b).\end{aligned}$$

for each $b \in B$, showing $f_{R,S}^{-1} = S$.

This finishes the proof. □

00L7 5.3.4 Monads in Rel

Let A be a set.

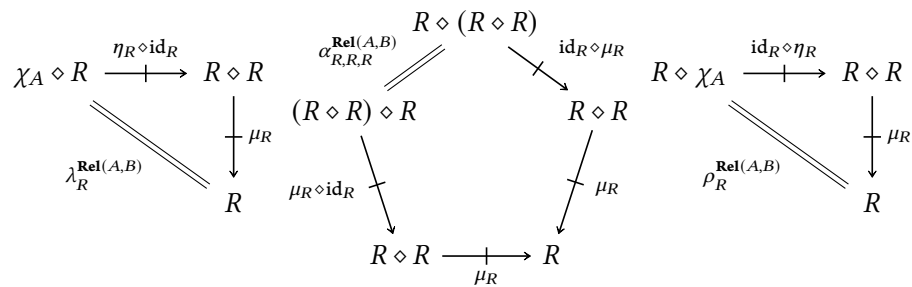
00L8 Proposition 5.3.4.1.1. We have a natural identification¹³

$$\left\{ \begin{array}{l} \text{Monads in} \\ \mathbf{Rel} \text{ on } A \end{array} \right\} \cong \{ \text{Preorders on } A \}.$$

Proof. A monad in \mathbf{Rel} on A consists of a relation $R: A \dashv\vdash A$ together with maps

$$\begin{aligned} \mu_R &: R \diamond R \subset R, \\ \eta_R &: \chi_A \subset R \end{aligned}$$

making the diagrams



commute. However, since all morphisms involved are inclusions, the commutativity of the above diagrams is automatic, and hence all that is left is the data of the two maps μ_R and η_R , which correspond respectively to the following conditions:

1. For each $a, b, c \in A$, if $a \sim_R b$ and $b \sim_R c$, then $a \sim_R c$.
2. For each $a \in A$, we have $a \sim_R a$.

These are exactly the requirements for R to be a preorder (??). Conversely any preorder \preceq gives rise to a pair of maps μ_{\preceq} and η_{\preceq} , forming a monad on A . □

00L9 5.3.5 Comonads in Rel

Let A be a set.

¹³See also ?? for an extension of this correspondence to “relative monads in \mathbf{Rel} ”.

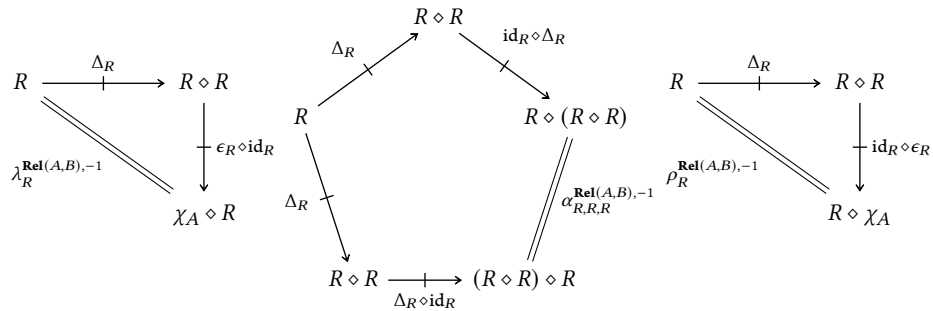
00LA Proposition 5.3.5.1.1. We have a natural identification

$$\left\{ \begin{array}{l} \text{Comonads in} \\ \mathbf{Rel} \text{ on } A \end{array} \right\} \cong \{ \text{Subsets of } A \}.$$

Proof. A comonad in \mathbf{Rel} on A consists of a relation $R: A \rightarrow A$ together with maps

$$\begin{aligned} \Delta_R: R &\subset R \diamond R, \\ \epsilon_R: R &\subset \chi_A \end{aligned}$$

making the diagrams



commute. However, since all morphisms involved are inclusions, the commutativity of the above diagrams is automatic, and hence all that is left is the data of the two maps Δ_R and ϵ_R , which correspond respectively to the following conditions:

1. For each $a, b \in A$, if $a \sim_R b$, then there exists some $k \in A$ such that $a \sim_R k$ and $k \sim_R b$.
2. For each $a, b \in A$, if $a \sim_R b$, then $a = b$.

Taking $k = b$ in the first condition above shows it to be trivially satisfied, while the second condition implies $R \subset \Delta_A$, i.e. R must be a subset of A . Conversely, any subset U of A satisfies $U \subset \Delta_A$, defining a comonad as above. □

00LB 5.3.6 Co/Monoids in Rel

00LC Remark 5.3.6.1.1. The monoids in \mathbf{Rel} with respect to the Cartesian monoidal structure of **Proposition 5.2.2.8.1** are called *hypermonoids*, and their theory is explored in ???. Similarly, the comonoids in \mathbf{Rel} are called *hypercomonoids*, and they are defined and studied in ??.

00LD 5.3.7 Monomorphisms in Rel

In this section we characterise the epimorphisms in the category Rel, following ??.

00LE Proposition 5.3.7.1.1. Let $R: A \rightarrow B$ be a relation. The following conditions are equivalent:

00LF 1. The relation R is a monomorphism in Rel.

00LG 2. The direct image function

$$R_*: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

associated to R is injective.

00LH 3. The direct image with compact support function

$$R_! : \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

associated to R is injective.

Moreover, if R is a monomorphism, then it satisfies the following condition, and the converse holds if R is total:

(★) For each $a, a' \in A$, if there exists some $b \in B$ such that

$$\begin{aligned} a &\sim_R b, \\ a' &\sim_R b, \end{aligned}$$

then $a = a'$.

Proof. Firstly note that **Items 2 and 3** are equivalent by **Item 7 of Proposition 6.4.1.1.3**. We then claim that **Items 1 and 2** are also equivalent:

- **Item 1** \implies **Item 2**: Let $U, V \in \mathcal{P}(A)$ and consider the diagram

$$\text{pt} \begin{array}{ccc} & U & \\ \begin{array}{c} \dashrightarrow \\ \dashrightarrow \\ \dashrightarrow \end{array} & A & \xrightarrow{R} B \\ & V & \end{array}$$

By **Remark 6.4.1.1.2**, we have

$$\begin{aligned} R_*(U) &= R \diamond U, \\ R_*(V) &= R \diamond V. \end{aligned}$$

Now, if $R \diamond U = R \diamond V$, i.e. $R_*(U) = R_*(V)$, then $U = V$ since R is assumed to be a monomorphism, showing R_* to be injective.

- *Item 2* \implies *Item 1*: Conversely, suppose that R_* is injective, consider the diagram

$$X \begin{array}{c} \xrightarrow{S} \\ \dashv \\ \xrightarrow{T} \end{array} A \xrightarrow{R} B,$$

and suppose that $R \diamond S = R \diamond T$. Note that, since R_* is injective, given a diagram of the form

$$\text{pt} \begin{array}{c} \xrightarrow{U} \\ \dashv \\ \xrightarrow{V} \end{array} A \xrightarrow{R} B,$$

if $R_*(U) = R \diamond U = R \diamond V = R_*(V)$, then $U = V$. In particular, for each $x \in X$, we may consider the diagram

$$\text{pt} \xrightarrow{[x]} X \begin{array}{c} \xrightarrow{S} \\ \dashv \\ \xrightarrow{T} \end{array} A \xrightarrow{R} B,$$

for which we have $R \diamond S \diamond [x] = R \diamond T \diamond [x]$, implying that we have

$$S(x) = S \diamond [x] = T \diamond [x] = T(x)$$

for each $x \in X$, implying $S = T$, and thus R is a monomorphism.

We can also prove this in a more abstract way, following [MSE 350788]:

- *Item 1* \implies *Item 2*: Assume that R is a monomorphism.
 - We first notice that the functor $\text{Rel}(\text{pt}, -): \text{Rel} \rightarrow \text{Sets}$ maps R to R_* by Remark 6.4.1.1.2.
 - Since $\text{Rel}(\text{pt}, -)$ preserves all limits by ?? of ??, it follows by ?? of ?? that $\text{Rel}(\text{pt}, -)$ also preserves monomorphisms.
 - Since R is a monomorphism and $\text{Rel}(\text{pt}, -)$ maps R to R_* , it follows that R_* is also a monomorphism.
 - Since the monomorphisms in Sets are precisely the injections (?? of ??), it follows that R_* is injective.
- *Item 2* \implies *Item 1*: Assume that R_* is injective.
 - We first notice that the functor $\text{Rel}(\text{pt}, -): \text{Rel} \rightarrow \text{Sets}$ maps R to R_* by Remark 6.4.1.1.2.
 - Since the monomorphisms in Sets are precisely the injections (?? of ??), it follows that R_* is a monomorphism.
 - Since $\text{Rel}(\text{pt}, -)$ is faithful, it follows by ?? of ?? that $\text{Rel}(\text{pt}, -)$ reflects monomorphisms.

- Since R_* is a monomorphism and $\text{Rel}(\text{pt}, -)$ maps R to R_* , it follows that R is also a monomorphism.

Finally, we prove the second part of the statement. Assume that R is a monomorphism, let $a, a' \in A$ such that $a \sim_R b$ and $a' \sim_R b$ for some $b \in B$, and consider the diagram

$$\begin{array}{ccc} & [a] & \\ \text{pt} & \xrightarrow{\quad} & A \xrightarrow{R} B \\ & [a'] & \end{array}$$

Since $\star \sim_{[a]} a$ and $a \sim_R b$, we have $\star \sim_{R \diamond [a]} b$. Similarly, $\star \sim_{R \diamond [a']} b$. Thus $R \diamond [a] = R \diamond [a']$, and since R is a monomorphism, we have $[a] = [a']$, i.e. $a = a'$.

Conversely, assume the condition

- (\star) For each $a, a' \in A$, if there exists some $b \in B$ such that

$$\begin{array}{l} a \sim_R b, \\ a' \sim_R b, \end{array}$$

then $a = a'$.

consider the diagram

$$\begin{array}{ccc} & S & \\ X & \xrightarrow{\quad} & A \xrightarrow{R} B \\ & T & \end{array}$$

and let $(x, a) \in S$. Since R is total and $a \in A$, there exists some $b \in B$ such that $a \sim_R b$. In this case, we have $x \sim_{R \diamond S} b$, and since $R \diamond S = R \diamond T$, we have also $x \sim_{R \diamond T} b$. Thus there must exist some $a' \in A$ such that $x \sim_T a'$ and $a' \sim_R b$. However, since $a, a' \sim_R b$, we must have $a = a'$, and thus $(x, a) \in T$ as well.

A similar argument shows that if $(x, a) \in T$, then $(x, a) \in S$, and thus $S = T$ and it follows that R is a monomorphism. \square

00LJ 5.3.8 2-Categorical Monomorphisms in Rel

In this section we characterise (for now, some of) the 2-categorical monomorphisms in **Rel**, following [Section 9.1](#).

00LK **Proposition 5.3.8.1.1.** Let $R: A \rightarrow B$ be a relation.

- 00LL 1. *Representably Faithful Morphisms in Rel.* Every morphism of **Rel** is a representably faithful morphism.

00LM 2. *Representably Full Morphisms in \mathbf{Rel} .* The following conditions are equivalent:

00LN (a) The morphism $R: A \rightarrow B$ is a representably full morphism.
00LP (b) For each pair of relations $S, T: X \rightarrow A$, the following condition is satisfied:

(\star) If $R \diamond S \subset R \diamond T$, then $S \subset T$.

00LQ (c) The functor

$$R_*: (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

is full.

00LR (d) For each $U, V \in \mathcal{P}(A)$, if $R_*(U) \subset R_*(V)$, then $U \subset V$.

00LS (e) The functor

$$R_!: (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

is full.

00LT (f) For each $U, V \in \mathcal{P}(A)$, if $R_!(U) \subset R_!(V)$, then $U \subset V$.

00LU 3. *Representably Fully Faithful Morphisms in \mathbf{Rel} .* Every representably full morphism in \mathbf{Rel} is a representably fully faithful morphism.

Proof. **Item 1, Representably Faithful Morphisms in \mathbf{Rel} :** The relation R is a representably faithful morphism in \mathbf{Rel} iff, for each $X \in \text{Obj}(\mathbf{Rel})$, the functor

$$R_*: \mathbf{Rel}(X, A) \rightarrow \mathbf{Rel}(X, B)$$

is faithful, i.e. iff the morphism

$$R_{*|S,T}: \text{Hom}_{\mathbf{Rel}(X,A)}(S, T) \rightarrow \text{Hom}_{\mathbf{Rel}(X,B)}(R \diamond S, R \diamond T)$$

is injective for each $S, T \in \text{Obj}(\mathbf{Rel}(X, A))$. However, $\text{Hom}_{\mathbf{Rel}(X,A)}(S, T)$ is either empty or a singleton, in either case of which the map $R_{*|S,T}$ is necessarily injective.

Item 2, Representably Full Morphisms in \mathbf{Rel} : We claim **Items 2a** to **2f** are indeed equivalent:

- **Item 2a** \iff **Item 2b**: This is simply a matter of unwinding definitions: The relation R is a representably full morphism in \mathbf{Rel} iff, for each $X \in \text{Obj}(\mathbf{Rel})$, the functor

$$R_*: \mathbf{Rel}(X, A) \rightarrow \mathbf{Rel}(X, B)$$

is full, i.e. iff the morphism

$$R_{*|S,T} : \mathbf{Hom}_{\mathbf{Rel}(X,A)}(S, T) \rightarrow \mathbf{Hom}_{\mathbf{Rel}(X,B)}(R \diamond S, R \diamond T)$$

is surjective for each $S, T \in \mathbf{Obj}(\mathbf{Rel}(X, A))$, i.e. iff, whenever $R \diamond S \subset R \diamond T$, we also have $S \subset T$.

- *Item 2c* \iff *Item 2d*: This is also simply a matter of unwinding definitions: The functor

$$R_* : (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

is full iff, for each $U, V \in \mathcal{P}(A)$, the morphism

$$R_{*|U,V} : \mathbf{Hom}_{\mathcal{P}(A)}(U, V) \rightarrow \mathbf{Hom}_{\mathcal{P}(B)}(R_*(U), R_*(V))$$

is surjective, i.e. iff whenever $R_*(U) \subset R_*(V)$, we also necessarily have $U \subset V$.

- *Item 2e* \iff *Item 2f*: This is once again simply a matter of unwinding definitions, and proceeds exactly in the same way as in the proof of the equivalence between *Items 2c* and *2d* given above.
- *Item 2d* \implies *Item 2f*: Suppose that the following condition is true:

$$(\star) \text{ For each } U, V \in \mathcal{P}(A), \text{ if } R_*(U) \subset R_*(V), \text{ then } U \subset V.$$

We need to show that the condition

$$(\star) \text{ For each } U, V \in \mathcal{P}(A), \text{ if } R_!(U) \subset R_!(V), \text{ then } U \subset V.$$

is also true. We proceed step by step:

1. Suppose we have $U, V \in \mathcal{P}(A)$ with $R_!(U) \subset R_!(V)$.
2. By *Item 7* of *Proposition 6.4.4.1.3*, we have

$$\begin{aligned} R_!(U) &= B \setminus R_*(A \setminus U), \\ R_!(V) &= B \setminus R_*(A \setminus V). \end{aligned}$$

3. By *Item 1* of *Proposition 2.3.10.1.2* we have $R_*(A \setminus V) \subset R_*(A \setminus U)$.
4. By assumption, we then have $A \setminus V \subset A \setminus U$.
5. By *Item 1* of *Proposition 2.3.10.1.2* again, we have $U \subset V$.

- *Item 2f* \implies *Item 2d*: Suppose that the following condition is true:

$$(\star) \text{ For each } U, V \in \mathcal{P}(A), \text{ if } R_!(U) \subset R_!(V), \text{ then } U \subset V.$$

We need to show that the condition

(★) For each $U, V \in \mathcal{P}(A)$, if $R_*(U) \subset R_*(V)$, then $U \subset V$.

is also true. We proceed step by step:

1. Suppose we have $U, V \in \mathcal{P}(A)$ with $R_*(U) \subset R_*(V)$.
2. By **Item 7** of **Proposition 6.4.1.1.3**, we have

$$\begin{aligned} R_*(U) &= B \setminus R_!(A \setminus U), \\ R_*(V) &= B \setminus R_!(A \setminus V). \end{aligned}$$

3. By **Item 1** of **Proposition 2.3.10.1.2** we have $R_!(A \setminus V) \subset R_!(A \setminus U)$.
4. By assumption, we then have $A \setminus V \subset A \setminus U$.
5. By **Item 1** of **Proposition 2.3.10.1.2** again, we have $U \subset V$.

- **Item 2b** \implies **Item 2d**: Consider the diagram

$$X \begin{array}{c} \xrightarrow{S} \\ \dashrightarrow \\ \xrightarrow{T} \end{array} A \xrightarrow{R} B,$$

and suppose that $R \diamond S \subset R \diamond T$. Note that, by assumption, given a diagram of the form

$$\text{pt} \begin{array}{c} \xrightarrow{U} \\ \dashrightarrow \\ \xrightarrow{V} \end{array} A \xrightarrow{R} B,$$

if $R_*(U) = R \diamond U \subset R \diamond V = R_*(V)$, then $U \subset V$. In particular, for each $x \in X$, we may consider the diagram

$$\text{pt} \xrightarrow{[x]} X \begin{array}{c} \xrightarrow{S} \\ \dashrightarrow \\ \xrightarrow{T} \end{array} A \xrightarrow{R} B,$$

for which we have $R \diamond S \diamond [x] \subset R \diamond T \diamond [x]$, implying that we have

$$S(x) = S \diamond [x] \subset T \diamond [x] = T(x)$$

for each $x \in X$, implying $S \subset T$.

- **Item 2d** \implies **Item 2b**: Let $U, V \in \mathcal{P}(A)$ and consider the diagram

$$\text{pt} \begin{array}{c} \xrightarrow{U} \\ \dashrightarrow \\ \xrightarrow{V} \end{array} A \xrightarrow{R} B.$$

By [Remark 6.4.1.1.2](#), we have

$$\begin{aligned}R_*(U) &= R \diamond U, \\R_*(V) &= R \diamond V.\end{aligned}$$

Now, if $R_*(U) \subset R_*(V)$, i.e. $R \diamond U \subset R \diamond V$, then $U \subset V$ by assumption.

??, *Fully Faithful Monomorphisms in Rel*: This follows from [Items 1](#) and [2](#). \square

00LV Question 5.3.8.1.2. [Item 2](#) of [Proposition 5.3.8.1.1](#) gives a characterisation of the representably full morphisms in **Rel**.

Are there other nice characterisations of these?

This question also appears as [[MO 467527](#)].

00LW 5.3.9 Epimorphisms in Rel

In this section we characterise the epimorphisms in the category **Rel**, following ??.

00LX Proposition 5.3.9.1.1. Let $R: A \rightarrow B$ be a relation. The following conditions are equivalent:

00LY 1. The relation R is an epimorphism in **Rel**.

00LZ 2. The weak inverse image function

$$R^{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

associated to R is injective.

00M0 3. The strong inverse image function

$$R_{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

associated to R is injective.

00M1 4. The function $R: A \rightarrow \mathcal{P}(B)$ is “surjective on singletons”:

(\star) For each $b \in B$, there exists some $a \in A$ such that $R(a) = \{b\}$.

Moreover, if R is total and an epimorphism, then it satisfies the following equivalent conditions:

1. For each $b \in B$, there exists some $a \in A$ such that $a \sim_R b$.

2. We have $\text{Im}(R) = B$.

Proof. Firstly note that **Items 2** and **3** are equivalent by **Item 7** of **Proposition 6.4.2.1.3**. We then claim that **Items 1** and **2** are also equivalent:

- **Item 1** \implies **Item 2**: Let $U, V \in \mathcal{P}(A)$ and consider the diagram

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{U} \\ \xrightarrow{V} \end{array} \text{pt.}$$

By **Remark 6.4.1.1.2**, we have

$$\begin{aligned} R^{-1}(U) &= U \diamond R, \\ R^{-1}(V) &= V \diamond R. \end{aligned}$$

Now, if $U \diamond R = V \diamond R$, i.e. $R^{-1}(U) = R^{-1}(V)$, then $U = V$ since R is assumed to be an epimorphism, showing R^{-1} to be injective.

- **Item 2** \implies **Item 1**: Conversely, suppose that R^{-1} is injective, consider the diagram

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{S} \\ \xrightarrow{T} \end{array} X,$$

and suppose that $S \diamond R = T \diamond R$. Note that, since R^{-1} is injective, given a diagram of the form

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{U} \\ \xrightarrow{V} \end{array} \text{pt.}$$

if $R^{-1}(U) = U \diamond R = V \diamond R = R^{-1}(V)$, then $U = V$. In particular, for each $x \in X$, we may consider the diagram

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{S} \\ \xrightarrow{T} \end{array} X \xrightarrow{[x]} \text{pt.}$$

for which we have $[x] \diamond S \diamond R = [x] \diamond T \diamond R$, implying that we have

$$S^{-1}(x) = [x] \diamond S = [x] \diamond T = T^{-1}(x)$$

for each $x \in X$, implying $S = T$, and thus R is an epimorphism.

We can also prove this in a more abstract way, following [[MSE 350788](#)]:

- **Item 1** \implies **Item 2**: Assume that R is an epimorphism.
 - We first notice that the functor $\text{Rel}(-, \text{pt}): \text{Rel}^{\text{op}} \rightarrow \text{Sets}$ maps R to R^{-1} by **Remark 6.4.3.1.2**.

- Since $\text{Rel}(-, \text{pt})$ preserves limits by ?? of ??, it follows by ?? of ?? that $\text{Rel}(-, \text{pt})$ also preserves monomorphisms.
 - That is: $\text{Rel}(-, \text{pt})$ sends monomorphisms in Rel^{op} to monomorphisms in Sets.
 - The monomorphisms Rel^{op} are precisely the epimorphisms in Rel by ?? of ??.
 - Since R is an epimorphism and $\text{Rel}(-, \text{pt})$ maps R to R^{-1} , it follows that R^{-1} is a monomorphism.
 - Since the monomorphisms in Sets are precisely the injections (?? of ??), it follows that R^{-1} is injective.
- *Item 2* \implies *Item 1*: Assume that R^{-1} is injective.
 - We first notice that the functor $\text{Rel}(-, \text{pt}) : \text{Rel}^{\text{op}} \rightarrow \text{Sets}$ maps R to R^{-1} by Remark 6.4.3.1.2.
 - Since the monomorphisms in Sets are precisely the injections (?? of ??), it follows that R^{-1} is a monomorphism.
 - Since $\text{Rel}(-, \text{pt})$ is faithful, it follows by ?? of ?? that $\text{Rel}(-, \text{pt})$ reflects monomorphisms.
 - That is: $\text{Rel}(-, \text{pt})$ reflects monomorphisms in Sets to monomorphisms in Rel^{op} .
 - The monomorphisms Rel^{op} are precisely the epimorphisms in Rel by ?? of ??.
 - Since R^{-1} is a monomorphism and $\text{Rel}(-, \text{pt})$ maps R to R^{-1} , it follows that R is an epimorphism.

We also claim that *Items 2* and *4* are equivalent, following [MO 350788]:

- *Item 2* \implies *Item 4*: Since $B \setminus \{b\} \subset B$ and R^{-1} is injective, we have $R^{-1}(B \setminus \{b\}) \subseteq R^{-1}(B)$. So taking some $a \in R^{-1}(B) \setminus R^{-1}(B \setminus \{b\})$ we get an element of A such that $R(a) = \{b\}$.
- *Item 4* \implies *Item 2*: Let $U, V \subset B$ with $U \neq V$. Without loss of generality, we can assume $U \setminus V \neq \emptyset$; otherwise just swap U and V . Let then $b \in U \setminus V$. By assumption, there exists an $a \in A$ with $R(a) = \{b\}$. Then $a \in R^{-1}(U)$ but $a \notin R^{-1}(V)$, and thus $R^{-1}(U) \neq R^{-1}(V)$, showing R^{-1} to be injective.

Finally, we prove the second part of the statement. So assume R is a total epimorphism in Rel and consider the diagram

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{S} \\ \dashrightarrow \\ \xrightarrow{T} \end{array} \{0, 1\},$$

where $b \sim_S 0$ for each $b \in B$ and where we have

$$b \sim_T \begin{cases} 0 & \text{if } b \in \text{Im}(R), \\ 1 & \text{otherwise} \end{cases}$$

for each $b \in B$. Since R is total, we have $a \sim_{S \diamond R} 0$ and $a \sim_{T \diamond R} 0$ for all $a \in A$, and no element of A is related to 1 by $S \diamond R$ or $T \diamond R$. Thus $S \diamond R = T \diamond R$, and since R is an epimorphism, we have $S = T$. But by the definition of T , this implies $\text{Im}(R) = B$. \square

00M2 5.3.10 2-Categorical Epimorphisms in Rel

In this section we characterise (for now, some of) the 2-categorical epimorphisms in **Rel**, following Section 9.2.

00M3 **Proposition 5.3.10.1.1.** Let $R: A \rightarrow B$ be a relation.

00M4 1. *Corepresentably Faithful Morphisms in Rel.* Every morphism of **Rel** is a corepresentably faithful morphism.

00M5 2. *Corepresentably Full Morphisms in Rel.* The following conditions are equivalent:

00M6 (a) The morphism $R: A \rightarrow B$ is a corepresentably full morphism.

00M7 (b) For each pair of relations $S, T: X \rightarrow A$, the following condition is satisfied:

(\star) If $S \diamond R \subset T \diamond R$, then $S \subset T$.

00M8 (c) The functor

$$R^{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

is full.

00M9 (d) For each $U, V \in \mathcal{P}(B)$, if $R^{-1}(U) \subset R^{-1}(V)$, then $U \subset V$.

00MA (e) The functor

$$R_{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

is full.

00MB (f) For each $U, V \in \mathcal{P}(B)$, if $R_{-1}(U) \subset R_{-1}(V)$, then $U \subset V$.

00MC 3. *Corepresentably Fully Faithful Morphisms in Rel.* Every corepresentably full morphism of **Rel** is a corepresentably fully faithful morphism.

Proof. Item 1, Corepresentably Faithful Morphisms in Rel: The relation R is a corepresentably faithful morphism in \mathbf{Rel} iff, for each $X \in \text{Obj}(\mathbf{Rel})$, the functor

$$R^* : \mathbf{Rel}(B, X) \rightarrow \mathbf{Rel}(A, X)$$

is faithful, i.e. iff the morphism

$$R_{S,T}^* : \text{Hom}_{\mathbf{Rel}(B,X)}(S, T) \rightarrow \text{Hom}_{\mathbf{Rel}(A,X)}(S \diamond R, T \diamond R)$$

is injective for each $S, T \in \text{Obj}(\mathbf{Rel}(B, X))$. However, $\text{Hom}_{\mathbf{Rel}(B,X)}(S, T)$ is either empty or a singleton, in either case of which the map $R_{S,T}^*$ is necessarily injective.

Item 2, Corepresentably Full Morphisms in Rel: We claim *Items 2a* to *2f* are indeed equivalent:

- *Item 2a* \iff *Item 2b*: This is simply a matter of unwinding definitions: The relation R is a corepresentably full morphism in \mathbf{Rel} iff, for each $X \in \text{Obj}(\mathbf{Rel})$, the functor

$$R^* : \mathbf{Rel}(B, X) \rightarrow \mathbf{Rel}(A, X)$$

is full, i.e. iff the morphism

$$R_{S,T}^* : \text{Hom}_{\mathbf{Rel}(B,X)}(S, T) \rightarrow \text{Hom}_{\mathbf{Rel}(A,X)}(S \diamond R, T \diamond R)$$

is surjective for each $S, T \in \text{Obj}(\mathbf{Rel}(B, X))$, i.e. iff, whenever $S \diamond R \subset T \diamond R$, we also have $S \subset T$.

- *Item 2c* \iff *Item 2d*: This is also simply a matter of unwinding definitions: The functor

$$R^{-1} : (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

is full iff, for each $U, V \in \mathcal{P}(A)$, the morphism

$$R_{U,V}^{-1} : \text{Hom}_{\mathcal{P}(B)}(U, V) \rightarrow \text{Hom}_{\mathcal{P}(A)}(R^{-1}(U), R^{-1}(V))$$

is surjective, i.e. iff whenever $R^{-1}(U) \subset R^{-1}(V)$, we also necessarily have $U \subset V$.

- *Item 2e* \iff *Item 2f*: This is once again simply a matter of unwinding definitions, and proceeds exactly in the same way as in the proof of the equivalence between *Items 2c* and *2d* given above.
- *Item 2d* \implies *Item 2f*: Suppose that the following condition is true:

(★) For each $U, V \in \mathcal{P}(B)$, if $R^{-1}(U) \subset R^{-1}(V)$, then $U \subset V$.

We need to show that the condition

(★) For each $U, V \in \mathcal{P}(B)$, if $R_{-1}(U) \subset R_{-1}(V)$, then $U \subset V$.

is also true. We proceed step by step:

1. Suppose we have $U, V \in \mathcal{P}(B)$ with $R_{-1}(U) \subset R_{-1}(V)$.
2. By **Item 7** of **Proposition 6.4.2.1.3**, we have

$$\begin{aligned} R_{-1}(U) &= B \setminus R^{-1}(A \setminus U), \\ R_{-1}(V) &= B \setminus R^{-1}(A \setminus V). \end{aligned}$$

3. By **Item 1** of **Proposition 2.3.10.1.2** we have $R^{-1}(A \setminus V) \subset R^{-1}(A \setminus U)$.
4. By assumption, we then have $A \setminus V \subset A \setminus U$.
5. By **Item 1** of **Proposition 2.3.10.1.2** again, we have $U \subset V$.

- **Item 2f** \implies **Item 2d**: Suppose that the following condition is true:

(★) For each $U, V \in \mathcal{P}(B)$, if $R_{-1}(U) \subset R_{-1}(V)$, then $U \subset V$.

We need to show that the condition

(★) For each $U, V \in \mathcal{P}(B)$, if $R^{-1}(U) \subset R^{-1}(V)$, then $U \subset V$.

is also true. We proceed step by step:

1. Suppose we have $U, V \in \mathcal{P}(B)$ with $R^{-1}(U) \subset R^{-1}(V)$.
2. By **Item 7** of **Proposition 6.4.3.1.3**, we have

$$\begin{aligned} R^{-1}(U) &= B \setminus R_{-1}(A \setminus U), \\ R^{-1}(V) &= B \setminus R_{-1}(A \setminus V). \end{aligned}$$

3. By **Item 1** of **Proposition 2.3.10.1.2** we have $R_{-1}(A \setminus V) \subset R_{-1}(A \setminus U)$.
4. By assumption, we then have $A \setminus V \subset A \setminus U$.
5. By **Item 1** of **Proposition 2.3.10.1.2** again, we have $U \subset V$.

- **Item 2b** \implies **Item 2d**: Consider the diagram

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{S} \\ \xrightarrow{T} \end{array} X,$$

and suppose that $S \diamond R \subset T \diamond R$. Note that, by assumption, given a diagram of the form

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{U} \\ \xrightarrow{V} \end{array} \text{pt},$$

if $R^{-1}(U) = R \diamond U \subset R \diamond V = R^{-1}(V)$, then $U \subset V$. In particular, for each $x \in X$, we may consider the diagram

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{S} \\ \xrightarrow{T} \end{array} X \xrightarrow{[x]} \text{pt},$$

for which we have $[x] \diamond S \diamond R \subset [x] \diamond T \diamond R$, implying that we have

$$S^{-1}(x) = [x] \diamond S \subset [x] \diamond T = T^{-1}(x)$$

for each $x \in X$, implying $S \subset T$.

- *Item 2d* \implies *Item 2b*: Let $U, V \in \mathcal{P}(B)$ and consider the diagram

$$A \xrightarrow{R} B \begin{array}{c} \xrightarrow{U} \\ \xrightarrow{V} \end{array} \text{pt}.$$

By **Remark 6.4.1.1.2**, we have

$$\begin{aligned} R^{-1}(U) &= U \diamond R, \\ R^{-1}(V) &= V \diamond R. \end{aligned}$$

Now, if $R^{-1}(U) \subset R^{-1}(V)$, i.e. $U \diamond R \subset V \diamond R$, then $U \subset V$ by assumption.

Item 3, Corepresentably Fully Faithful Morphisms in Rel: This follows from **Items 1 and 2**. □

00MD Question 5.3.10.1.2. **Item 2** of **Proposition 5.3.10.1.1** gives a characterisation of the corepresentably full morphisms in **Rel**. Are there other nice characterisations of these? This question also appears as [**MO 467527**].

00ME 5.3.11 Co/Limits in Rel

00MF Proposition 5.3.11.1.1. This will be properly written later on.

Proof. Omitted. □

00MG 5.3.12 Kan Extensions and Kan Lifts in \mathbf{Rel}

00MH Remark 5.3.12.1.1. The 2-category \mathbf{Rel} admits all right Kan extensions and right Kan lifts, though not all left Kan extensions and neither does it admit all left Kan lifts. See [Section 6.2](#) for a detailed discussion of this.

00MJ 5.3.13 Closedness of \mathbf{Rel}

00MK Proposition 5.3.13.1.1. The 2-category \mathbf{Rel} is a closed bicategory, there being, for each $R: A \dashrightarrow B$ and set X , a pair of adjunctions

$$(R^* \dashv \mathbf{Ran}_R): \mathbf{Rel}(B, X) \begin{array}{c} \xrightarrow{R^*} \\ \perp \\ \xleftarrow{\mathbf{Ran}_R} \end{array} \mathbf{Rel}(A, X),$$

$$(R_* \dashv \mathbf{Rift}_R): \mathbf{Rel}(X, A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{\mathbf{Rift}_R} \end{array} \mathbf{Rel}(X, B),$$

witnessed by bijections

$$\mathbf{Rel}(S \diamond R, T) \cong \mathbf{Rel}(S, \mathbf{Ran}_R(T)),$$

$$\mathbf{Rel}(R \diamond U, V) \cong \mathbf{Rel}(U, \mathbf{Rift}_R(V)),$$

natural in $S \in \mathbf{Rel}(B, X), T \in \mathbf{Rel}(A, X), U \in \mathbf{Rel}(X, A),$ and $V \in \mathbf{Rel}(X, B).$

Proof. This follows from [Propositions 6.2.3.1.1](#) and [6.2.4.1.1](#). □

00ML 5.3.14 \mathbf{Rel} as a Category of Free Algebras

00MM Proposition 5.3.14.1.1. We have an isomorphism of categories

$$\mathbf{Rel} \cong \mathbf{FreeAlg}_{\mathcal{P}_*}(\mathbf{Sets}),$$

where \mathcal{P}_* is the powerset monad of ??.

Proof. Omitted. □

00MN 5.4 The Left Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

00MP 5.4.1 The Left Skew Monoidal Product

Let A and B be sets and let $J: A \dashrightarrow B$ be a relation.

00MQ Definition 5.4.1.1.1. The left J -skew monoidal product of $\mathbf{Rel}(A, B)$ is the functor

$$\triangleleft_J: \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(A, B)$$

where

- *Action on Objects.* For each $R, S \in \text{Obj}(\mathbf{Rel}(A, B))$, we have

$$S \triangleleft_J R \stackrel{\text{def}}{=} S \diamond \text{Rift}_J(R),$$

- *Action on Morphisms.* For each $R, S, R', S' \in \text{Obj}(\mathbf{Rel}(A, B))$, the action on Hom-sets

$$(\triangleleft_J)_{(G,F),(G',F')} : \text{Hom}_{\mathbf{Rel}(A,B)}(S, S') \times \text{Hom}_{\mathbf{Rel}(A,B)}(R, R') \rightarrow \text{Hom}_{\mathbf{Rel}(A,B)}(S \triangleleft_J R, S' \triangleleft_J R')$$

of \triangleleft_J at $((R, S), (R', S'))$ is defined by¹⁴

$$\beta \triangleleft_J \alpha \stackrel{\text{def}}{=} \beta \diamond \text{Rift}_J(\alpha),$$

for each $\beta \in \text{Hom}_{\mathbf{Rel}(A,B)}(S, S')$ and each $\alpha \in \text{Hom}_{\mathbf{Rel}(A,B)}(R, R')$.

00MR 5.4.2 The Left Skew Monoidal Unit

Let A and B be sets and let $J : A \dashv B$ be a relation.

00MS **Definition 5.4.2.1.1.** The left J -skew monoidal unit of $\mathbf{Rel}(A, B)$ is the functor

$$\mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A,B)} : \text{pt} \rightarrow \mathbf{Rel}(A, B)$$

picking the object

$$\mathbb{1}_{\mathbf{Rel}(A,B)}^{\triangleleft_J} \stackrel{\text{def}}{=} J$$

of $\mathbf{Rel}(A, B)$.

¹⁴Since $\mathbf{Rel}(A, B)$ is posetal, this is to say that if $S \subset S'$ and $R \subset R'$, then $S \triangleleft_J R \subset S' \triangleleft_J R'$.

00MT 5.4.3 The Left Skew Associators

Let A and B be sets and let $J: A \dashv\vdash B$ be a relation.

00MU Definition 5.4.3.1.1. The **left J -skew associator of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\alpha^{\mathbf{Rel}(A,B), \triangleleft_J} : \triangleleft_J \circ (\triangleleft_J \times \text{id}) \implies \triangleleft_J \circ (\text{id} \times \triangleleft_J) \circ \alpha_{\mathbf{Rel}(A,B), \mathbf{Rel}(A,B), \mathbf{Rel}(A,B)}^{\mathbf{Cats}},$$

as in the diagram

$$\begin{array}{ccc}
 & \mathbf{Rel}(A, B) \times (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) & \\
 \alpha_{\mathbf{Rel}(A,B), \mathbf{Rel}(A,B), \mathbf{Rel}(A,B)}^{\mathbf{Cats}} \swarrow & \searrow \text{id} \times \triangleleft_J & \\
 (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) \times \mathbf{Rel}(A, B) & & \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \\
 \triangleleft_J \times \text{id} \searrow & \nearrow \alpha^{\mathbf{Rel}(A,B), \triangleleft_J} & \searrow \triangleleft_J \\
 \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) & \xrightarrow{\triangleleft_J} & \mathbf{Rel}(A, B)
 \end{array}$$

whose component

$$\alpha_{T,S,R}^{\mathbf{Rel}(A,B), \triangleleft_J} : \underbrace{(T \triangleleft_J S) \triangleleft_J R}_{\stackrel{\text{def.}}{=} T \diamond \text{Rift}_J(S) \diamond \text{Rift}_J(R)} \hookrightarrow \underbrace{T \triangleleft_J (S \triangleleft_J R)}_{\stackrel{\text{def.}}{=} T \diamond \text{Rift}_J(S \diamond \text{Rift}_J(R))}$$

at (T, S, R) is given by

$$\alpha_{T,S,R}^{\mathbf{Rel}(A,B), \triangleleft_J} \stackrel{\text{def.}}{=} \text{id}_T \diamond \gamma,$$

where

$$\gamma: \text{Rift}_J(S) \diamond \text{Rift}_J(R) \hookrightarrow \text{Rift}_J(S \diamond \text{Rift}_J(R))$$

is the inclusion adjunct to the inclusion

$$\epsilon_S \star \text{id}_{\text{Rift}_J(R)} : \underbrace{J \diamond \text{Rift}_J(S) \diamond \text{Rift}_J(R)}_{\stackrel{\text{def.}}{=} J_* (\text{Rift}_J(S) \diamond \text{Rift}_J(R))} \hookrightarrow S \diamond \text{Rift}_J(R)$$

under the adjunction $J_* \dashv \text{Rift}_J$, where $\epsilon: J \diamond \text{Rift}_J \implies \text{id}_{\mathbf{Rel}(A,B)}$ is the counit of the adjunction $J_* \dashv \text{Rift}_J$.

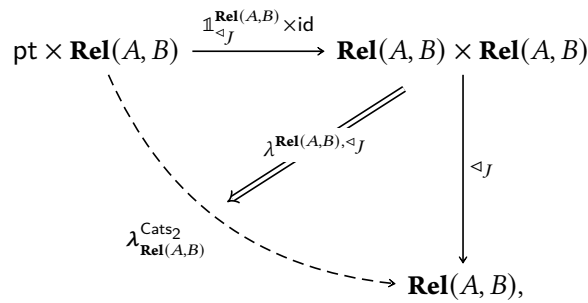
00MV 5.4.4 The Left Skew Left Unitors

Let A and B be sets and let $J: A \dashv\vdash B$ be a relation.

00MW Definition 5.4.4.1.1. The **left J -skew left unitor of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\lambda^{\mathbf{Rel}(A,B), \triangleleft_J} : \triangleleft_J \circ \left(\mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A,B)} \times \text{id} \right) \Longrightarrow \lambda_{\mathbf{Rel}(A,B)}^{\text{Cats}_2}$$

as in the diagram



whose component

$$\lambda_R^{\mathbf{Rel}(A,B), \triangleleft_J} : \underbrace{J \triangleleft_J R}_{\stackrel{\text{def}}{=} J \diamond \text{Rift}_J(R)} \hookrightarrow R$$

at R is given by

$$\lambda_R^{\mathbf{Rel}(A,B), \triangleleft_J} \stackrel{\text{def}}{=} \epsilon_R,$$

where $\epsilon : J_* \diamond \text{Rift}_J \Longrightarrow \text{id}_{\mathbf{Rel}(A,B)}$ is the counit of the adjunction $J_* \dashv \text{Rift}_J$.

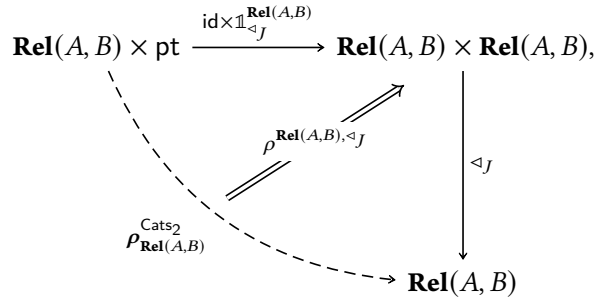
00MX 5.4.5 The Left Skew Right Unitors

Let A and B be sets and let $J: A \dashv\vdash B$ be a relation.

00MY Definition 5.4.5.1.1. The **left J -skew right unitor of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\rho^{\mathbf{Rel}(A,B), \triangleleft_J} : \rho_{\mathbf{Rel}(A,B)}^{\text{Cats}_2} \Longrightarrow \triangleleft_J \circ \left(\text{id} \times \mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A,B)} \right)$$

as in the diagram



whose component

$$\rho_R^{\mathbf{Rel}(A, B), \triangleleft_J} : R \hookrightarrow \underbrace{R \triangleleft_J J}_{\stackrel{\text{def}}{=} R \diamond \mathbf{Rift}_J(J)}$$

at R is given by the composition

$$\begin{aligned} R &\xrightarrow{\sim} R \diamond \chi_A \\ &\xrightarrow{\text{id}_R \diamond \eta_{\chi_A}} R \diamond \mathbf{Rift}_J(J_*(\chi_A)) \\ &\stackrel{\text{def}}{=} R \diamond \mathbf{Rift}_J(J \diamond \chi_A) \\ &\xrightarrow{\sim} R \diamond \mathbf{Rift}_J(J) \\ &\stackrel{\text{def}}{=} R \triangleleft_J J, \end{aligned}$$

where $\eta : \text{id}_{\mathbf{Rel}(A, A)} \Rightarrow \mathbf{Rift}_J \circ J_*$ is the unit of the adjunction $J_* \dashv \mathbf{Rift}_J$.

00MZ 5.4.6 The Left Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

00N0 Proposition 5.4.6.1.1. The category $\mathbf{Rel}(A, B)$ admits a left skew monoidal category structure consisting of

- *The Underlying Category.* The posetal category associated to the poset $\mathbf{Rel}(A, B)$ of relations from A to B of **Item 2** of **Definition 5.1.1.1.3**.
- *The Left Skew Monoidal Product.* The left J -skew monoidal product

$$\triangleleft_J : \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(A, B)$$

of **Definition 5.4.1.1.1**.

- *The Left Skew Monoidal Unit.* The functor

$$\mathbb{1}^{\mathbf{Rel}(A, B), \triangleleft_J} : \text{pt} \rightarrow \mathbf{Rel}(A, B)$$

of **Definition 5.4.2.1.1**.

- *The Left Skew Associators.* The natural transformation

$$\alpha^{\mathbf{Rel}(A,B), \triangleleft_J} : \triangleleft_J \circ (\triangleleft_J \times \text{id}) \implies \triangleleft_J \circ (\text{id} \times \triangleleft_J) \circ \alpha_{\mathbf{Rel}(A,B), \mathbf{Rel}(A,B), \mathbf{Rel}(A,B)}^{\mathbf{Cats}}$$

of **Definition 5.4.3.1.1.**

- *The Left Skew Left Unitors.* The natural transformation

$$\lambda^{\mathbf{Rel}(A,B), \triangleleft_J} : \triangleleft_J \circ \left(\mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A,B)} \times \text{id} \right) \implies \lambda_{\mathbf{Rel}(A,B)}^{\mathbf{Cats}_2}$$

of **Definition 5.4.4.1.1.**

- *The Left Skew Right Unitors.* The natural transformation

$$\rho^{\mathbf{Rel}(A,B), \triangleleft_J} : \rho_{\mathbf{Rel}(A,B)}^{\mathbf{Cats}_2} \implies \triangleleft_J \circ \left(\text{id} \times \mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A,B)} \right)$$

of **Definition 5.4.5.1.1.**

Proof. Since $\mathbf{Rel}(A, B)$ is posetal, the commutativity of the pentagon identity, the left skew left triangle identity, the left skew right triangle identity, the left skew middle triangle identity, and the zigzag identity is automatic, and thus $\mathbf{Rel}(A, B)$ together with the data in the statement forms a left skew monoidal category. \square

00N1 5.5 The Right Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

Let A and B be sets and let $J : A \dashv\vdash B$ be a relation.

00N2 5.5.1 The Right Skew Monoidal Product

00N3 **Definition 5.5.1.1.1.** The right J -skew monoidal product of $\mathbf{Rel}(A, B)$ is the functor

$$\triangleright_J : \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(A, B)$$

where

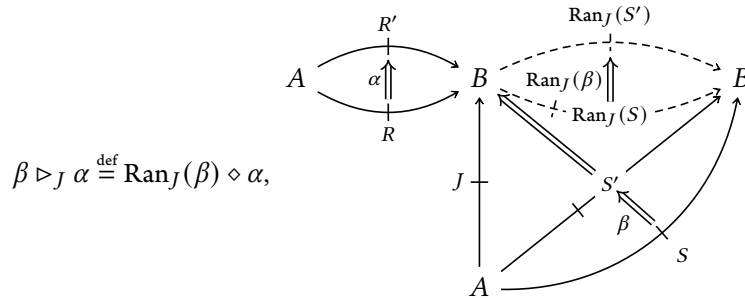
- *Action on Objects.* For each $R, S \in \text{Obj}(\mathbf{Rel}(A, B))$, we have

$$S \triangleright_J R \stackrel{\text{def}}{=} \text{Ran}_J(S) \diamond R,$$

- *Action on Morphisms.* For each $R, S, R', S' \in \mathbf{Obj}(\mathbf{Rel}(A, B))$, the action on Hom-sets

$$(\triangleright_J)_{(S,R),(S',R')} : \mathbf{Hom}_{\mathbf{Rel}(A,B)}(S, S') \times \mathbf{Hom}_{\mathbf{Rel}(A,B)}(R, R') \rightarrow \mathbf{Hom}_{\mathbf{Rel}(A,B)}(S \triangleright_J R, S' \triangleright_J R')$$

of \triangleright_J at $((S, R), (S', R'))$ is defined by¹⁵



for each $\beta \in \mathbf{Hom}_{\mathbf{Rel}(A,B)}(S, S')$ and each $\alpha \in \mathbf{Hom}_{\mathbf{Rel}(A,B)}(R, R')$.

00N4 **5.5.2 The Right Skew Monoidal Unit**

00N5 **Definition 5.5.2.1.1.** The right J -skew monoidal unit of $\mathbf{Rel}(A, B)$ is the functor

$$\mathbb{1}_{\triangleright_J}^{\mathbf{Rel}(A,B)} : \mathbf{pt} \rightarrow \mathbf{Rel}(A, B)$$

picking the object

$$\mathbb{1}_{\mathbf{Rel}(A,B)}^{\triangleright_J} \stackrel{\text{def}}{=} J$$

of $\mathbf{Rel}(A, B)$.

00N6 **5.5.3 The Right Skew Associators**

00N7 **Definition 5.5.3.1.1.** The right J -skew associator of $\mathbf{Rel}(A, B)$ is the natural transformation

$$\alpha^{\mathbf{Rel}(A,B), \triangleright_J} : \triangleright_J \circ (\text{id} \times \triangleright_J) \Longrightarrow \triangleright_J \circ (\triangleright_J \times \text{id}) \circ \alpha_{\mathbf{Rel}(A,B), \mathbf{Rel}(A,B), \mathbf{Rel}(A,B)}^{\mathbf{Cats}, -1}$$

¹⁵Since $\mathbf{Rel}(A, B)$ is posetal, this is to say that if $S \subset S'$ and $R \subset R'$, then $S \triangleright_J R \subset S' \triangleright_J R'$.

as in the diagram

$$\begin{array}{ccc}
 & (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) \times \mathbf{Rel}(A, B) & \\
 \alpha_{\mathbf{Rel}(A, B), \mathbf{Rel}(A, B), \mathbf{Rel}(A, B)}^{\mathbf{Cats}, -1} \nearrow & & \searrow \triangleright_J \times \text{id} \\
 \mathbf{Rel}(A, B) \times (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) & & \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \\
 \text{id} \times \triangleright_J \searrow & \alpha_{\mathbf{Rel}(A, B), \triangleright_J} \nearrow & \searrow \triangleright_J \\
 \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) & \xrightarrow{\triangleright_J} & \mathbf{Rel}(A, B)
 \end{array}$$

whose component

$$\alpha_{T, S, R}^{\mathbf{Rel}(A, B), \triangleright_J} : \underbrace{T \triangleright_J (S \triangleright_J R)}_{\stackrel{\text{def}}{=} \text{Ran}_J(T) \diamond \text{Ran}_J(S) \diamond R} \hookrightarrow \underbrace{(T \triangleright_J S) \triangleright_J R}_{\stackrel{\text{def}}{=} \text{Ran}_J(\text{Ran}_J(T) \diamond S) \diamond R}$$

at (T, S, R) is given by

$$\alpha_{T, S, R}^{\mathbf{Rel}(A, B), \triangleright} \stackrel{\text{def}}{=} \gamma \diamond \text{id}_R,$$

where

$$\gamma : \text{Ran}_J(T) \diamond \text{Ran}_J(S) \hookrightarrow \text{Ran}_J(\text{Ran}_J(T) \diamond S)$$

is the inclusion adjunct to the inclusion

$$\text{id}_{\text{Ran}_J(T)} \diamond \epsilon_S : \underbrace{\text{Ran}_J(T) \diamond \text{Ran}_J(S) \diamond J}_{\stackrel{\text{def}}{=} J^*(\text{Ran}_J(T) \diamond \text{Ran}_J(S))} \hookrightarrow \text{Ran}_J(T) \diamond S$$

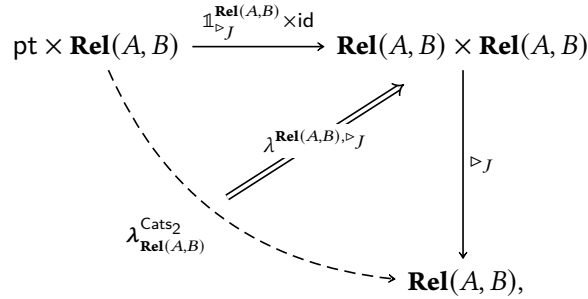
under the adjunction $J^* \dashv \text{Ran}_J$, where $\epsilon : \text{Ran}_J \diamond J \Longrightarrow \text{id}_{\mathbf{Rel}(A, B)}$ is the counit of the adjunction $J^* \dashv \text{Ran}_J$.

00N8 5.5.4 The Right Skew Left Unitors

00N9 **Definition 5.5.4.1.1.** The right J -skew left unitor of $\mathbf{Rel}(A, B)$ is the natural transformation

$$\lambda^{\mathbf{Rel}(A, B), \triangleright_J} : \lambda_{\mathbf{Rel}(A, B)}^{\mathbf{Cats}_2} \Longrightarrow \triangleright_J \circ \left(\mathbb{1}_{\triangleright}^{\mathbf{Rel}(A, B)} \times \text{id} \right),$$

as in the diagram



whose component

$$\lambda_R^{\mathbf{Rel}(A,B), \triangleright J} : R \hookrightarrow \underbrace{J \triangleright_J R}_{\stackrel{\text{def}}{=} \text{Ran}_J(J) \diamond R}$$

at R is given by the composition

$$\begin{aligned}
 R &\xrightarrow{\sim} \chi_B \diamond R \\
 &\xrightarrow{\eta_{\chi_B}} \diamond \text{id}_{\text{Ran}_J(J^*(\chi_A))} \diamond R \\
 &\stackrel{\text{def}}{=} \text{Ran}_J(J^* \diamond \chi_A) \diamond R \\
 &\xrightarrow{\sim} \text{Ran}_J(J) \diamond R \\
 &\stackrel{\text{def}}{=} R \triangleright_J J,
 \end{aligned}$$

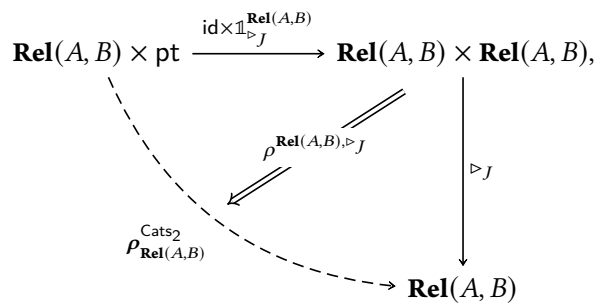
where $\eta : \text{id}_{\mathbf{Rel}(B,B)} \implies \text{Ran}_J \circ J^*$ is the unit of the adjunction $J^* \dashv \text{Ran}_J$.

00NA 5.5.5 The Right Skew Right Unitors

00NB Definition 5.5.5.1.1. The **right J -skew right unitor** of $\mathbf{Rel}(A, B)$ is the natural transformation

$$\rho^{\mathbf{Rel}(A,B), \triangleright J} : \triangleright_J \circ \left(\text{id} \times \mathbb{1}_{\triangleright J}^{\mathbf{Rel}(A,B)} \right) \implies \rho_{\mathbf{Rel}(A,B)}^{\text{Cats}_2},$$

as in the diagram



whose component

$$\rho_S^{\mathbf{Rel}(A,B), \triangleright J} : S \triangleright_J J \hookrightarrow S$$

$\underbrace{\qquad\qquad\qquad}_{\stackrel{\text{def}}{=} \mathbf{Ran}_J(S) \diamond J}$

at S is given by

$$\rho_S^{\mathbf{Rel}(A,B), \triangleright J} \stackrel{\text{def}}{=} \epsilon_R,$$

where $\epsilon : J^* \circ \mathbf{Ran}_J \implies \text{id}_{\mathbf{Rel}(A,B)}$ is the counit of the adjunction $J^* \dashv \mathbf{Ran}_J$.

00NC 5.5.6 The Right Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

00ND **Proposition 5.5.6.1.1.** The category $\mathbf{Rel}(A, B)$ admits a right skew monoidal category structure consisting of

- *The Underlying Category.* The posetal category associated to the poset $\mathbf{Rel}(A, B)$ of relations from A to B of **Item 2** of **Definition 5.1.1.1.3**.
- *The Right Skew Monoidal Product.* The right J -skew monoidal product

$$\triangleleft_J : \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(A, B)$$

of **Definition 5.5.1.1.1**.

- *The Right Skew Monoidal Unit.* The functor

$$\mathbb{1}^{\mathbf{Rel}(A,B), \triangleleft_J} : \text{pt} \rightarrow \mathbf{Rel}(A, B)$$

of **Definition 5.5.2.1.1**.

- *The Right Skew Associators.* The natural transformation

$$\alpha^{\mathbf{Rel}(A,B), \triangleright J} : \triangleright_J \circ (\text{id} \times \triangleright_J) \implies \triangleright_J \circ (\triangleright_J \times \text{id}) \circ \alpha_{\mathbf{Rel}(A,B), \mathbf{Rel}(A,B), \mathbf{Rel}(A,B)}^{\text{Cats}, -1}$$

of **Definition 5.5.3.1.1**.

- *The Right Skew Left Unitors.* The natural transformation

$$\lambda^{\mathbf{Rel}(A,B), \triangleright J} : \lambda_{\mathbf{Rel}(A,B)}^{\text{Cats}_2} \implies \triangleright_J \circ \left(\mathbb{1}_{\triangleright}^{\mathbf{Rel}(A,B)} \times \text{id} \right)$$

of **Definition 5.5.4.1.1**.

- *The Right Skew Right Unitors.* The natural transformation

$$\rho^{\mathbf{Rel}(A,B), \triangleright J} : \triangleright_J \circ \left(\text{id} \times \mathbb{1}_{\triangleright}^{\mathbf{Rel}(A,B)} \right) \implies \rho_{\mathbf{Rel}(A,B)}^{\text{Cats}_2}$$

of **Definition 5.5.5.1.1**.

Proof. Since $\mathbf{Rel}(A, B)$ is posetal, the commutativity of the pentagon identity, the right skew left triangle identity, the right skew right triangle identity, the right skew middle triangle identity, and the zigzag identity is automatic, and thus $\mathbf{Rel}(A, B)$ together with the data in the statement forms a right skew monoidal category. \square

Appendices

5.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets

Relations

5. Relations

6. Constructions With Relations

7. Equivalence Relations and Apartness Relations

Category Theory

8. Categories

Bicategories

9. Types of Morphisms in Bicategories

Chapter 6

Constructions With Relations

00NE This chapter contains some material about constructions with relations. Notably, we discuss and explore:

1. The existence or non-existence of Kan extensions and Kan lifts in the 2-category **Rel** (Section 6.2).
2. The various kinds of constructions involving relations, such as graphs, domains, ranges, unions, intersections, products, inverse relations, composition of relations, and collages (Section 6.3).
3. The adjoint pairs

$$\begin{aligned}R_* \dashv R_{-1} &: \mathcal{P}(A) \rightleftarrows \mathcal{P}(B), \\ R^{-1} \dashv R_! &: \mathcal{P}(B) \rightleftarrows \mathcal{P}(A)\end{aligned}$$

of functors (morphisms of posets) between $\mathcal{P}(A)$ and $\mathcal{P}(B)$ induced by a relation $R: A \dashv\vdash B$, as well as the properties of R_* , R_{-1} , R^{-1} , and $R_!$ (Section 6.4).

Of particular note are the following points:

- (a) These two pairs of adjoint functors are the counterpart for relations of the adjoint triple $f_* \dashv f^{-1} \dashv f_!$ induced by a function $f: A \rightarrow B$ studied in Section 2.4.
- (b) We have $R_{-1} = R^{-1}$ iff R is total and functional (Item 8 of Proposition 6.4.2.1.3).
- (c) As a consequence of the previous item, when R comes from a function f , the pair of adjunctions

$$R_* \dashv R_{-1} = R^{-1} \dashv R_!$$

reduces to the triple adjunction

$$f_* \dashv f^{-1} \dashv f!$$

from [Section 2.4](#).

- (d) The pairs $R_* \dashv R_{-1}$ and $R^{-1} \dashv R!$ turn out to be rather important later on, as they appear in the definition and study of continuous, open, and closed relations between topological spaces (??).

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00NF 6.1 Co/Limits in the Category of Relations

This section is currently just a stub, and will be properly developed later on.

00NG 6.2 Kan Extensions and Kan Lifts in the 2-Category of Relations

00NH 6.2.1 Left Kan Extensions in Rel

00NJ **Proposition 6.2.1.1.1.** Let $R: A \dashrightarrow B$ be a relation.

00NK 1. *Non-Existence of All Left Kan Extensions in Rel.* Not all relations in **Rel** admit left Kan extensions.

2. *Characterisation of Relations Admitting Left Kan Extensions Along Them.*

00NL The following conditions are equivalent:

(a) The left Kan extension

$$\text{Lan}_R: \mathbf{Rel}(A, X) \rightarrow \mathbf{Rel}(B, X)$$

along R exists.

(b) The relation R admits a left adjoint in **Rel**.

(c) The relation R is of the form f^{-1} (as in [Definition 6.3.2.1.1](#)) for some function f .

Proof. [Item 1, Non-Existence of All Left Kan Extensions in Rel](#): Omitted, but will eventually follow [Fosco Loregian's comment](#) on [[MO 460656](#)].

[Item 2, Characterisation of Relations Admitting Left Kan Extensions Along Them](#): Omitted, but will eventually follow [Tim Champion's answer](#) to [[MO 460656](#)]. \square

00NM **Question 6.2.1.1.2.** Given relations $S: A \dashrightarrow X$ and $R: A \dashrightarrow B$, is there a characterisation of when the left Kan extension

$$\text{Lan}_S(R): B \dashrightarrow X$$

exists in terms of properties of R and S ?

This question also appears as [[MO 461592](#)].

00NN **Question 6.2.1.1.3.** As shown in [Item 2](#) of [Proposition 6.2.1.1.1](#), the left Kan extension

$$\text{Lan}_R: \mathbf{Rel}(A, X) \rightarrow \mathbf{Rel}(B, X)$$

along a relation of the form $R = f^{-1}$ exists. Is there an explicit description of it, similarly to the explicit description of right Kan extensions given in [Proposition 6.2.3.1.1](#)?

This question also appears as [\[MO 461592\]](#).

00NP 6.2.2 Left Kan Lifts in Rel

00NQ **Proposition 6.2.2.1.1.** Let $R: A \rightarrow B$ be a relation.

00NR 1. *Non-Existence of All Left Kan Lifts in Rel.* Not all relations in **Rel** admit left Kan lifts.

00NS 2. *Characterisation of Relations Admitting Left Kan Lifts Along Them.* The following conditions are equivalent:

(a) The left Kan lift

$$\text{Lift}_R: \mathbf{Rel}(X, B) \rightarrow \mathbf{Rel}(X, A)$$

along R exists.

(b) The relation R admits a right adjoint in **Rel**.

(c) The relation R is of the form $\text{Gr}(f)$ (as in [Definition 6.3.1.1.1](#)) for some function f .

Proof. **Item 1, Non-Existence of All Left Kan Lifts in Rel:** Omitted, but will eventually follow (the dual of) [Fosco Loregian's comment](#) on [\[MO 460656\]](#).

Item 2, Characterisation of Relations Admitting Left Kan Lifts Along Them: Omitted, but will eventually follow [Tim Champion's answer to](#) [\[MO 460656\]](#).

□

00NT **Question 6.2.2.1.2.** Given relations $S: A \rightarrow X$ and $R: A \rightarrow B$, is there a characterisation of when the left Kan lift

$$\text{Lift}_S(R): X \rightarrow A$$

exists in terms of properties of R and S ?

This question also appears as [\[MO 461592\]](#).

00NU **Question 6.2.2.1.3.** As shown in **Item 2** of [Proposition 6.2.2.1.1](#), the left Kan lift

$$\text{Lift}_R: \mathbf{Rel}(X, B) \rightarrow \mathbf{Rel}(X, A)$$

along a relation of the form $R = \text{Gr}(f)$ exists. Is there an explicit description of it, similarly to the explicit description of right Kan lifts given in [Proposition 6.2.4.1.1](#)?

This question also appears as [\[MO 461592\]](#).

6.2.3 Right Kan Extensions in Rel

Let $R: A \dashv\vdash B$ be a relation.

Proposition 6.2.3.1.1. The right Kan extension

$$\text{Ran}_R: \mathbf{Rel}(A, X) \rightarrow \mathbf{Rel}(B, X)$$

along R in \mathbf{Rel} exists and is given by

$$\text{Ran}_R(S) \stackrel{\text{def}}{=} \int_{a \in A} \mathbf{Hom}_{\{t, f\}}(R_a^{-2}, S_a^{-1})$$

for each $S \in \mathbf{Rel}(A, X)$, so that the following conditions are equivalent:

1. We have $b \sim_{\text{Ran}_R(S)} x$.
2. For each $a \in A$, if $a \sim_R b$, then $a \sim_S x$.

Proof. We have

$$\begin{aligned} \mathbf{Hom}_{\mathbf{Rel}(A, X)}(S \diamond R, T) &\cong \int_{a \in A} \int_{x \in X} \mathbf{Hom}_{\{t, f\}}((S \diamond R)_a^x, T_a^x) \\ &\cong \int_{a \in A} \int_{x \in X} \mathbf{Hom}_{\{t, f\}}\left(\left(\int^{b \in B} S_b^x \times R_a^b\right), T_a^x\right) \\ &\cong \int_{a \in A} \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{t, f\}}(S_b^x \times R_a^b, T_a^x) \\ &\cong \int_{a \in A} \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{t, f\}}(S_b^x, \mathbf{Hom}_{\{t, f\}}(R_a^b, T_a^x)) \\ &\cong \int_{b \in B} \int_{x \in X} \int_{a \in A} \mathbf{Hom}_{\{t, f\}}(S_b^x, \mathbf{Hom}_{\{t, f\}}(R_a^b, T_a^x)) \\ &\cong \int_{b \in B} \int_{x \in X} \mathbf{Hom}_{\{t, f\}}\left(S_b^x, \int_{a \in A} \mathbf{Hom}_{\{t, f\}}(R_a^b, T_a^x)\right) \\ &\cong \mathbf{Hom}_{\mathbf{Rel}(B, X)}\left(S, \int_{a \in A} \mathbf{Hom}_{\{t, f\}}(R_a^{-2}, T_a^{-1})\right) \end{aligned}$$

naturally in each $S \in \mathbf{Rel}(B, X)$ and each $T \in \mathbf{Rel}(A, X)$, showing that

$$\int_{a \in A} \mathbf{Hom}_{\{t, f\}}(R_a^{-2}, T_a^{-1})$$

is right adjoint to the precomposition functor $- \diamond R$, being thus the right Kan extension along R . Here we have used the following results, respectively (i.e. for each \cong sign):

1. **Item 1** of [Proposition 5.1.1.1.5](#).

2. **Definition 6.3.12.1.1.**
3. ?? of ??.
4. **Proposition 1.2.2.1.5.**
5. ?? of ??.
6. ?? of ??.
7. **Item 1 of Proposition 5.1.1.1.5.**

This finishes the proof. □

00NX 6.2.4 Right Kan Lifts in Rel

Let $R: A \dashrightarrow B$ be a relation.

00NY **Proposition 6.2.4.1.1.** The right Kan lift

$$\text{Rift}_R: \text{Rel}(X, B) \rightarrow \text{Rel}(X, A)$$

along R in **Rel** exists and is given by

$$\text{Rift}_R(S) \stackrel{\text{def}}{=} \int_{b \in B} \mathbf{Hom}_{\{t, f\}}(R_{-1}^b, S_{-2}^b)$$

for each $S \in \text{Rel}(X, B)$, so that the following conditions are equivalent:

1. We have $x \sim_{\text{Rift}_R(S)} a$.
2. For each $b \in B$, if $a \sim_R b$, then $x \sim_S b$.

Proof. We have

$$\begin{aligned} \text{Hom}_{\mathbf{Rel}(X, B)}(R \diamond S, T) &\cong \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{t, f\}}\left((R \diamond S)_x^b, T_x^b\right) \\ &\cong \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{t, f\}}\left(\left(\int^{a \in A} R_a^b \times S_x^a\right), T_x^b\right) \\ &\cong \int_{x \in X} \int_{b \in B} \int_{a \in A} \mathbf{Hom}_{\{t, f\}}\left(R_a^b \times S_x^a, T_x^b\right) \\ &\cong \int_{x \in X} \int_{b \in B} \int_{a \in A} \mathbf{Hom}_{\{t, f\}}\left(S_x^a, \mathbf{Hom}_{\{t, f\}}\left(R_a^b, T_x^b\right)\right) \\ &\cong \int_{x \in X} \int_{a \in A} \int_{b \in B} \mathbf{Hom}_{\{t, f\}}\left(S_x^a, \mathbf{Hom}_{\{t, f\}}\left(R_a^b, T_x^b\right)\right) \\ &\cong \int_{x \in X} \int_{a \in A} \mathbf{Hom}_{\{t, f\}}\left(S_x^a, \int_{b \in B} \mathbf{Hom}_{\{t, f\}}\left(R_a^b, T_x^b\right)\right) \\ &\cong \text{Hom}_{\mathbf{Rel}(X, A)}\left(S, \int_{b \in B} \mathbf{Hom}_{\{t, f\}}\left(R_{-1}^b, T_{-2}^b\right)\right) \end{aligned}$$

naturally in each $S \in \mathbf{Rel}(X, A)$ and each $T \in \mathbf{Rel}(X, B)$, showing that

$$\int_{b \in B} \mathbf{Hom}_{\{t, f\}}(R_{-1}^b, S_{-2}^b)$$

is right adjoint to the postcomposition functor $R \diamond -$, being thus the right Kan lift along R . Here we have used the following results, respectively (i.e. for each \cong sign):

1. Item 1 of Proposition 5.1.1.1.5.
2. Definition 6.3.12.1.1.
3. ?? of ??.
4. Proposition 1.2.2.1.5.
5. ?? of ??.
6. ?? of ??.
7. Item 1 of Proposition 5.1.1.1.5.

This finishes the proof. □

00NZ 6.3 More Constructions With Relations

00P0 6.3.1 The Graph of a Function

Let $f: A \rightarrow B$ be a function.

00P1 **Definition 6.3.1.1.1.** The **graph of f** is the relation $\text{Gr}(f): A \rightarrow B$ defined as follows:¹

- Viewing relations from A to B as subsets of $A \times B$, we define

$$\text{Gr}(f) \stackrel{\text{def}}{=} \{(a, f(a)) \in A \times B \mid a \in A\}.$$

- Viewing relations from A to B as functions $A \times B \rightarrow \{\text{true}, \text{false}\}$, we define

$$[\text{Gr}(f)](a, b) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } b = f(a), \\ \text{false} & \text{otherwise} \end{cases}$$

for each $(a, b) \in A \times B$.

¹Further Notation: We write $\text{Gr}(A)$ for $\text{Gr}(\text{id}_A)$, and call it the **graph** of A .

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$[\text{Gr}(f)](a) \stackrel{\text{def}}{=} \{f(a)\}$$

for each $a \in A$, i.e. we define $\text{Gr}(f)$ as the composition

$$A \xrightarrow{f} B \xrightarrow{\chi_B} \mathcal{P}(B).$$

00P2 Proposition 6.3.1.1.2. Let $f: A \rightarrow B$ be a function.

00P3 1. *Functoriality.* The assignment $A \mapsto \text{Gr}(A)$ defines a functor

$$\text{Gr}: \text{Sets} \rightarrow \text{Rel}$$

where

- *Action on Objects.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$\text{Gr}(A) \stackrel{\text{def}}{=} A.$$

- *Action on Morphisms.* For each $A, B \in \text{Obj}(\text{Sets})$, the action on Hom-sets

$$\text{Gr}_{A,B}: \text{Sets}(A, B) \rightarrow \underbrace{\text{Rel}(\text{Gr}(A), \text{Gr}(B))}_{\stackrel{\text{def}}{=} \text{Rel}(A, B)}$$

of Gr at (A, B) is defined by

$$\text{Gr}_{A,B}(f) \stackrel{\text{def}}{=} \text{Gr}(f),$$

where $\text{Gr}(f)$ is the graph of f as in **Definition 6.3.1.1.1.**

In particular:

- *Preservation of Identities.* We have

$$\text{Gr}(\text{id}_A) = \chi_A$$

for each $A \in \text{Obj}(\text{Sets})$.

- *Preservation of Composition.* We have

$$\text{Gr}(g \circ f) = \text{Gr}(g) \diamond \text{Gr}(f)$$

for each pair of functions $f: A \rightarrow B$ and $g: B \rightarrow C$.

00P4 2. *Adjointness Inside Rel.* We have an adjunction

$$(\text{Gr}(f) \dashv f^{-1}): A \begin{array}{c} \xrightarrow{\text{Gr}(f)} \\ \perp \\ \xleftarrow{f^{-1}} \end{array} B$$

in **Rel**, where f^{-1} is the inverse of f of **Definition 6.3.2.1.1**.

00P5 3. *Adjointness.* We have an adjunction

$$(\text{Gr} \dashv \mathcal{P}_*): \text{Sets} \begin{array}{c} \xrightarrow{\text{Gr}} \\ \perp \\ \xleftarrow{\mathcal{P}_*} \end{array} \text{Rel},$$

witnessed by a bijection of sets

$$\text{Rel}(\text{Gr}(A), B) \cong \text{Sets}(A, \mathcal{P}(B))$$

natural in $A \in \text{Obj}(\text{Sets})$ and $B \in \text{Obj}(\text{Rel})$.

00P6 4. *Interaction With Inverses.* We have

$$\begin{aligned} \text{Gr}(f)^\dagger &= f^{-1}, \\ (f^{-1})^\dagger &= \text{Gr}(f). \end{aligned}$$

00P7 5. *Cocontinuity.* The functor $\text{Gr}: \text{Sets} \rightarrow \text{Rel}$ of **Item 1** preserves colimits.

00P8 6. *Characterisations.* Let $R: A \rightarrow B$ be a relation. The following conditions are equivalent:

- 00P9 (a) There exists a function $f: A \rightarrow B$ such that $R = \text{Gr}(f)$.
- 00PA (b) The relation R is total and functional.
- 00PB (c) The weak and strong inverse images of R agree, i.e. we have $R^{-1} = R_{-1}$.
- 00PC (d) The relation R has a right adjoint R^\dagger in **Rel**.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness Inside Rel: We need to check that there are inclusions

$$\begin{aligned} \chi_A &\subset f^{-1} \diamond \text{Gr}(f), \\ \text{Gr}(f) \diamond f^{-1} &\subset \chi_B. \end{aligned}$$

These correspond respectively to the following conditions:

1. For each $a \in A$, there exists some $b \in B$ such that $a \sim_{\text{Gr}(f)} b$ and $b \sim_{f^{-1}} a$.
2. For each $a, b \in A$, if $a \sim_{\text{Gr}(f)} b$ and $b \sim_{f^{-1}} a$, then $a = b$.

In other words, the first condition states that the image of any $a \in A$ by f is nonempty, whereas the second condition states that f is not multivalued. As f is a function, both of these statements are true, and we are done.

Item 3, Adjointness: The stated bijection follows from [Remark 5.1.1.1.4](#), with naturality being clear.

Item 4, Interaction With Inverses: Clear.

Item 5, Cocontinuity: Omitted.

Item 6, Characterisations: We claim that [Items 6a](#) to [6d](#) are indeed equivalent:

- [Item 6a](#) \iff [Item 6b](#). This is shown in the proof of ?? of ??.
- [Item 6b](#) \implies [Item 6c](#). If R is total and functional, then, for each $a \in A$, the set $R(a)$ is a singleton, implying that

$$\begin{aligned} R^{-1}(V) &\stackrel{\text{def}}{=} \{a \in A \mid R(a) \cap V \neq \emptyset\}, \\ R_{-1}(V) &\stackrel{\text{def}}{=} \{a \in A \mid R(a) \subset V\} \end{aligned}$$

are equal for all $V \in \mathcal{P}(B)$, as the conditions $R(a) \cap V \neq \emptyset$ and $R(a) \subset V$ are equivalent when $R(a)$ is a singleton.

- [Item 6c](#) \implies [Item 6b](#). We claim that R is indeed total and functional:
 - *Totality.* If we had $R(a) = \emptyset$ for some $a \in A$, then we would have $a \in R_{-1}(\emptyset)$, so that $R_{-1}(\emptyset) \neq \emptyset$. But since $R^{-1}(\emptyset) = \emptyset$, this would imply $R_{-1}(\emptyset) \neq R^{-1}(\emptyset)$, a contradiction. Thus $R(a) \neq \emptyset$ for all $a \in A$ and R is total.
 - *Functionality.* If $R^{-1} = R_{-1}$, then we have

$$\begin{aligned} \{a\} &= R^{-1}(\{b\}) \\ &= R_{-1}(\{b\}) \end{aligned}$$

for each $b \in R(a)$ and each $a \in A$, and thus $R(a) \subset \{b\}$. But since R is total, we must have $R(a) = \{b\}$, and thus we see that R is functional.

- [Item 6a](#) \iff [Item 6d](#). This follows from [Proposition 5.3.3.1.1](#).

This finishes the proof. \square

00PD 6.3.2 The Inverse of a Function

Let $f: A \rightarrow B$ be a function.

00PE Definition 6.3.2.1.1. The **inverse of f** is the relation $f^{-1}: B \rightarrow A$ defined as follows:

- Viewing relations from B to A as subsets of $B \times A$, we define

$$f^{-1} \stackrel{\text{def}}{=} \{(b, f^{-1}(b)) \in B \times A \mid a \in A\},$$

where

$$f^{-1}(b) \stackrel{\text{def}}{=} \{a \in A \mid f(a) = b\}$$

for each $b \in B$.

- Viewing relations from B to A as functions $B \times A \rightarrow \{\text{true}, \text{false}\}$, we define

$$f^{-1}(b, a) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if there exists } a \in A \text{ with } f(a) = b, \\ \text{false} & \text{otherwise} \end{cases}$$

for each $(b, a) \in B \times A$.

- Viewing relations from B to A as functions $B \rightarrow \mathcal{P}(A)$, we define

$$f^{-1}(b) \stackrel{\text{def}}{=} \{a \in A \mid f(a) = b\}$$

for each $b \in B$.

00PF Proposition 6.3.2.1.2. Let $f: A \rightarrow B$ be a function.

00PG 1. *Functoriality.* The assignment $A \mapsto A, f \mapsto f^{-1}$ defines a functor

$$(-)^{-1}: \text{Sets} \rightarrow \text{Rel}$$

where

- *Action on Objects.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$[(-)^{-1}](A) \stackrel{\text{def}}{=} A.$$

- *Action on Morphisms.* For each $A, B \in \text{Obj}(\text{Sets})$, the action on Hom-sets

$$(-)_{A,B}^{-1}: \text{Sets}(A, B) \rightarrow \text{Rel}(A, B)$$

of $(-)^{-1}$ at (A, B) is defined by

$$(-)_{A,B}^{-1}(f) \stackrel{\text{def}}{=} [(-)^{-1}](f),$$

where f^{-1} is the inverse of f as in **Definition 6.3.2.1.1**.

In particular:

- *Preservation of Identities.* We have

$$\text{id}_A^{-1} = \chi_A$$

for each $A \in \text{Obj}(\text{Sets})$.

- *Preservation of Composition.* We have

$$(g \circ f)^{-1} = g^{-1} \diamond f^{-1}$$

for pair of functions $f: A \rightarrow B$ and $g: B \rightarrow C$.

00PH 2. *Adjointness Inside Rel.* We have an adjunction

$$(\text{Gr}(f) \dashv f^{-1}): A \begin{array}{c} \xrightarrow{\text{Gr}(f)} \\ \perp \\ \xleftarrow{f^{-1}} \end{array} B$$

in **Rel**.

00PJ 3. *Interaction With Inverses of Relations.* We have

$$\begin{aligned} (f^{-1})^\dagger &= \text{Gr}(f), \\ \text{Gr}(f)^\dagger &= f^{-1}. \end{aligned}$$

Proof. **Item 1, Functoriality:** Clear.

Item 2, Adjointness Inside Rel: This is proved in **Item 2** of **Proposition 6.3.1.1.2**.

Item 3, Interaction With Inverses of Relations: Clear. \square

00PK 6.3.3 Representable Relations

Let A and B be sets.

00PL **Definition 6.3.3.1.1.** Let $f: A \rightarrow B$ and $g: B \rightarrow A$ be functions.²

²More generally, given functions

$$\begin{aligned} f: A &\rightarrow C, \\ g: B &\rightarrow D \end{aligned}$$

and a relation $B \dashv\vdash D$, we may consider the composite relation

$$A \times B \xrightarrow{f \times g} C \times D \xrightarrow{R} \{\text{true}, \text{false}\},$$

for which we have $a \sim_{R \circ (f \times g)} b$ iff $f(a) \sim_R g(b)$.

1. The **representable relation associated to** f is the relation $\chi_f: A \rightarrow B$ defined as the composition

$$A \times B \xrightarrow{f \times \text{id}_B} B \times B \xrightarrow{\chi_B} \{\text{true}, \text{false}\},$$

i.e. given by declaring $a \sim_{\chi_f} b$ iff $f(a) = b$.

2. The **corepresentable relation associated to** g is the relation $\chi^g: B \rightarrow A$ defined as the composition

$$B \times A \xrightarrow{g \times \text{id}_A} A \times A \xrightarrow{\chi_A} \{\text{true}, \text{false}\},$$

i.e. given by declaring $b \sim_{\chi^g} a$ iff $g(b) = a$.

00PM 6.3.4 The Domain and Range of a Relation

Let A and B be sets.

00PN **Definition 6.3.4.1.1.** Let $R \subset A \times B$ be a relation.^{3,4}

1. The **domain of** R is the subset $\text{dom}(R)$ of A defined by

$$\text{dom}(R) \stackrel{\text{def}}{=} \left\{ a \in A \mid \begin{array}{l} \text{there exists some } b \in B \\ \text{such that } a \sim_R b \end{array} \right\}.$$

³Following ??, we may compute the (characteristic functions associated to the) domain and range of a relation using the following colimit formulas:

$$\begin{aligned} \chi_{\text{dom}(R)}(a) &\cong \text{colim}_{b \in B} (R_a^b) & (a \in A) \\ &\cong \bigvee_{b \in B} R_a^b, \\ \chi_{\text{range}(R)}(b) &\cong \text{colim}_{a \in A} (R_a^b) & (b \in B) \\ &\cong \bigvee_{a \in A} R_a^b, \end{aligned}$$

where the join \bigvee is taken in the poset $(\{\text{true}, \text{false}\}, \preceq)$ of **Definition 1.2.2.1.3.**

⁴Viewing R as a function $R: A \rightarrow \mathcal{P}(B)$, we have

$$\begin{aligned} \text{dom}(R) &\cong \text{colim}_{y \in Y} (R(y)) \\ &\cong \bigcup_{y \in Y} R(y), \\ \text{range}(R) &\cong \text{colim}_{x \in X} (R(x)) \\ &\cong \bigcup_{x \in X} R(x), \end{aligned}$$

2. The **range of R** is the subset $\text{range}(R)$ of B defined by

$$\text{range}(R) \stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{there exists some } a \in A \\ \text{such that } a \sim_R b \end{array} \right\}.$$

00PP 6.3.5 Binary Unions of Relations

Let A and B be sets and let R and S be relations from A to B .

00PQ **Definition 6.3.5.1.1.** The **union of R and S** ⁵ is the relation $R \cup S$ from A to B defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define⁶

$$R \cup S \stackrel{\text{def}}{=} \{(a, b) \in B \times A \mid \text{we have } a \sim_R b \text{ or } a \sim_S b\}.$$

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$[R \cup S](a) \stackrel{\text{def}}{=} R(a) \cup S(a)$$

for each $a \in A$.

00PR **Proposition 6.3.5.1.2.** Let R, S, R_1 , and R_2 be relations from A to B , and let S_1 and S_2 be relations from B to C .

00PS 1. *Interaction With Inverses.* We have

$$(R \cup S)^\dagger = R^\dagger \cup S^\dagger.$$

00PT 2. *Interaction With Composition.* We have

$$(S_1 \diamond R_1) \cup (S_2 \diamond R_2) \stackrel{\text{poss.}}{\neq} (S_1 \cup S_2) \diamond (R_1 \cup R_2).$$

Proof. **Item 1, Interaction With Inverses:** Clear.

Item 2, Interaction With Composition: Unwinding the definitions, we see that:

1. The condition for $(S_1 \diamond R_1) \cup (S_2 \diamond R_2)$ is:

(a) There exists some $b \in B$ such that:

i. $a \sim_{R_1} b$ and $b \sim_{S_1} c$;

or

⁵*Further Terminology:* Also called the **binary union of R and S** , for emphasis.

⁶This is the same as the union of R and S as subsets of $A \times B$.

$$\text{i. } a \sim_{R_2} b \text{ and } b \sim_{S_2} c;$$

3. The condition for $(S_1 \cup S_2) \diamond (R_1 \cup R_2)$ is:

(a) There exists some $b \in B$ such that:

$$\text{i. } a \sim_{R_1} b \text{ or } a \sim_{R_2} b;$$

and

$$\text{i. } b \sim_{S_1} c \text{ or } b \sim_{S_2} c.$$

These two conditions may fail to agree (counterexample omitted), and thus the two resulting relations on $A \times C$ may differ. \square

00PU 6.3.6 Unions of Families of Relations

Let A and B be sets and let $\{R_i\}_{i \in I}$ be a family of relations from A to B .

00PV **Definition 6.3.6.1.1.** The **union of the family** $\{R_i\}_{i \in I}$ is the relation $\bigcup_{i \in I} R_i$ from A to B defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define⁷

$$\bigcup_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a, b) \in (A \times B)^{\times I} \mid \begin{array}{l} \text{there exists some } i \in I \\ \text{such that } a \sim_{R_i} b \end{array} \right\}.$$

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$\left[\bigcup_{i \in I} R_i \right] (a) \stackrel{\text{def}}{=} \bigcup_{i \in I} R_i(a)$$

for each $a \in A$.

00PW **Proposition 6.3.6.1.2.** Let A and B be sets and let $\{R_i\}_{i \in I}$ be a family of relations from A to B .

00PX 1. *Interaction With Inverses.* We have

$$\left(\bigcup_{i \in I} R_i \right)^\dagger = \bigcup_{i \in I} R_i^\dagger.$$

Proof. **Item 1, Interaction With Inverses:** Clear. \square

⁷This is the same as the union of $\{R_i\}_{i \in I}$ as a collection of subsets of $A \times B$.

00PY 6.3.7 Binary Intersections of Relations

Let A and B be sets and let R and S be relations from A to B .

00PZ Definition 6.3.7.1.1. The **intersection of R and S** ⁸ is the relation $R \cap S$ from A to B defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define⁹

$$R \cap S \stackrel{\text{def}}{=} \{(a, b) \in A \times B \mid \text{we have } a \sim_R b \text{ and } a \sim_S b\}.$$

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$[R \cap S](a) \stackrel{\text{def}}{=} R(a) \cap S(a)$$

for each $a \in A$.

00Q0 Proposition 6.3.7.1.2. Let R, S, R_1 , and R_2 be relations from A to B , and let S_1 and S_2 be relations from B to C .

00Q1 1. *Interaction With Inverses.* We have

$$(R \cap S)^\dagger = R^\dagger \cap S^\dagger.$$

00Q2 2. *Interaction With Composition.* We have

$$(S_1 \diamond R_1) \cap (S_2 \diamond R_2) = (S_1 \cap S_2) \diamond (R_1 \cap R_2).$$

Proof. **Item 1, Interaction With Inverses:** Clear.

Item 2, Interaction With Composition: Unwinding the definitions, we see that:

1. The condition for $(S_1 \diamond R_1) \cap (S_2 \diamond R_2)$ is:

(a) There exists some $b \in B$ such that:

i. $a \sim_{R_1} b$ and $b \sim_{S_1} c$;

and

i. $a \sim_{R_2} b$ and $b \sim_{S_2} c$;

3. The condition for $(S_1 \cap S_2) \diamond (R_1 \cap R_2)$ is:

(a) There exists some $b \in B$ such that:

i. $a \sim_{R_1} b$ and $a \sim_{R_2} b$;

and

i. $b \sim_{S_1} c$ and $b \sim_{S_2} c$.

These two conditions agree, and thus so do the two resulting relations on $A \times C$. \square

⁸*Further Terminology:* Also called the **binary intersection of R and S** , for emphasis.

⁹This is the same as the intersection of R and S as subsets of $A \times B$.

00Q3 6.3.8 Intersections of Families of Relations

Let A and B be sets and let $\{R_i\}_{i \in I}$ be a family of relations from A to B .

Definition 6.3.8.1.1. The **intersection of the family** $\{R_i\}_{i \in I}$ is the relation $\bigcup_{i \in I} R_i$ defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define¹⁰

$$\bigcup_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a, b) \in (A \times B)^{\times I} \mid \begin{array}{l} \text{for each } i \in I, \\ \text{we have } a \sim_{R_i} b \end{array} \right\}.$$

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$\left[\bigcap_{i \in I} R_i \right] (a) \stackrel{\text{def}}{=} \bigcap_{i \in I} R_i(a)$$

for each $a \in A$.

00Q5 Proposition 6.3.8.1.2. Let A and B be sets and let $\{R_i\}_{i \in I}$ be a family of relations from A to B .

00Q6 1. *Interaction With Inverses.* We have

$$\left(\bigcap_{i \in I} R_i \right)^\dagger = \bigcap_{i \in I} R_i^\dagger.$$

Proof. **Item 1, Interaction With Inverses:** Clear. □

00Q7 6.3.9 Binary Products of Relations

Let $A, B, X,$ and Y be sets, let $R: A \rightarrow B$ be a relation from A to B , and let $S: X \rightarrow Y$ be a relation from X to Y .

00Q8 Definition 6.3.9.1.1. The **product of R and S** ¹¹ is the relation $R \times S$ from $A \times X$ to $B \times Y$ defined as follows:

- Viewing relations from $A \times X$ to $B \times Y$ as subsets of $(A \times X) \times (B \times Y)$, we define $R \times S$ as the Cartesian product of R and S as subsets of $A \times X$ and $B \times Y$.¹²

¹⁰This is the same as the intersection of $\{R_i\}_{i \in I}$ as a collection of subsets of $A \times B$.

¹¹*Further Terminology:* Also called the **binary product of R and S** , for emphasis.

¹²That is, $R \times S$ is the relation given by declaring $(a, x) \sim_{R \times S} (b, y)$ iff $a \sim_R b$ and $x \sim_S y$.

- Viewing relations from $A \times X$ to $B \times Y$ as functions $A \times X \rightarrow \mathcal{P}(B \times Y)$, we define $R \times S$ as the composition

$$A \times X \xrightarrow{R \times S} \mathcal{P}(B) \times \mathcal{P}(Y) \xrightarrow{\mathcal{P}_{B,Y}^\otimes} \mathcal{P}(B \times Y)$$

in Sets, i.e. by

$$[R \times S](a, x) \stackrel{\text{def}}{=} R(a) \times S(x)$$

for each $(a, x) \in A \times X$.

00Q9 Proposition 6.3.9.1.2. Let A, B, X , and Y be sets.

00QA 1. *Interaction With Inverses.* Let

$$\begin{aligned} R &: A \rightarrowtail A, \\ S &: X \rightarrowtail X \end{aligned}$$

We have

$$(R \times S)^\dagger = R^\dagger \times S^\dagger.$$

00QB 2. *Interaction With Composition.* Let

$$\begin{aligned} R_1 &: A \rightarrowtail B, \\ S_1 &: B \rightarrowtail C, \\ R_2 &: X \rightarrowtail Y, \\ S_2 &: Y \rightarrowtail Z \end{aligned}$$

be relations. We have

$$(S_1 \diamond R_1) \times (S_2 \diamond R_2) = (S_1 \times S_2) \diamond (R_1 \times R_2).$$

Proof. **Item 1, Interaction With Inverses:** Unwinding the definitions, we see that:

1. We have $(a, x) \sim_{(R \times S)^\dagger} (b, y)$ iff:

- We have $(b, y) \sim_{R \times S} (a, x)$, i.e. iff:
 - We have $b \sim_R a$;
 - We have $y \sim_S x$;

2. We have $(a, x) \sim_{R^\dagger \times S^\dagger} (b, y)$ iff:

- We have $a \sim_{R^\dagger} b$ and $x \sim_{S^\dagger} y$, i.e. iff:

- We have $b \sim_R a$;
- We have $y \sim_S x$.

These two conditions agree, and thus the two resulting relations on $A \times X$ are equal.

Item 2, Interaction With Composition: Unwinding the definitions, we see that:

1. We have $(a, x) \sim_{(S_1 \circ R_1) \times (S_2 \circ R_2)} (c, z)$ iff:
 - (a) We have $a \sim_{S_1 \circ R_1} c$ and $x \sim_{S_2 \circ R_2} z$, i.e. iff:
 - i. There exists some $b \in B$ such that $a \sim_{R_1} b$ and $b \sim_{S_1} c$;
 - ii. There exists some $y \in Y$ such that $x \sim_{R_2} y$ and $y \sim_{S_2} z$;
2. We have $(a, x) \sim_{(S_1 \times S_2) \circ (R_1 \times R_2)} (c, z)$ iff:
 - (a) There exists some $(b, y) \in B \times Y$ such that $(a, x) \sim_{R_1 \times R_2} (b, y)$ and $(b, y) \sim_{S_1 \times S_2} (c, z)$, i.e. such that:
 - i. We have $a \sim_{R_1} b$ and $x \sim_{R_2} y$;
 - ii. We have $b \sim_{S_1} c$ and $y \sim_{S_2} z$.

These two conditions agree, and thus the two resulting relations from $A \times X$ to $C \times Z$ are equal. \square

00QC 6.3.10 Products of Families of Relations

Let $\{A_i\}_{i \in I}$ and $\{B_i\}_{i \in I}$ be families of sets, and let $\{R_i : A_i \rightarrow B_i\}_{i \in I}$ be a family of relations.

00QD Definition 6.3.10.1.1. The **product of the family** $\{R_i\}_{i \in I}$ is the relation $\prod_{i \in I} R_i$ from $\prod_{i \in I} A_i$ to $\prod_{i \in I} B_i$ defined as follows:

- Viewing relations as subsets, we define $\prod_{i \in I} R_i$ as its product as a family of sets, i.e. we have

$$\prod_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a_i, b_i)_{i \in I} \in \prod_{i \in I} (A_i \times B_i) \left| \begin{array}{l} \text{for each } i \in I, \\ \text{we have } a_i \sim_{R_i} b_i \end{array} \right. \right\}.$$

- Viewing relations as functions to powersets, we define

$$\left[\prod_{i \in I} R_i \right] ((a_i)_{i \in I}) \stackrel{\text{def}}{=} \prod_{i \in I} R_i(a_i)$$

for each $(a_i)_{i \in I} \in \prod_{i \in I} A_i$.

00QE 6.3.11 The Inverse of a Relation

Let A , B , and C be sets and let $R \subset A \times B$ be a relation.

00QF Definition 6.3.11.1.1. The **inverse of R** ¹³ is the relation R^\dagger defined as follows:

- Viewing relations as subsets, we define

$$R^\dagger \stackrel{\text{def}}{=} \{(b, a) \in B \times A \mid \text{we have } b \sim_R a\}.$$

- Viewing relations as functions $A \times B \rightarrow \{\text{true}, \text{false}\}$, we define

$$[R^\dagger]_b^a \stackrel{\text{def}}{=} R_a^b$$

for each $(b, a) \in B \times A$.

- Viewing relations as functions $A \rightarrow \mathcal{P}(B)$, we define

$$\begin{aligned} [R^\dagger](b) &\stackrel{\text{def}}{=} R^\dagger(\{b\}) \\ &\stackrel{\text{def}}{=} \{a \in A \mid b \in R(a)\} \end{aligned}$$

for each $b \in B$, where $R^\dagger(\{b\})$ is the fibre of R over $\{b\}$.

00QG Example 6.3.11.1.2. Here are some examples of inverses of relations.

00QH 1. *Less Than Equal Signs.* We have $(\leq)^\dagger = \geq$.

00QJ 2. *Greater Than Equal Signs.* Dually to **Item 1**, we have $(\geq)^\dagger = \leq$.

00QK 3. *Functions.* Let $f: A \rightarrow B$ be a function. We have

$$\begin{aligned} \text{Gr}(f)^\dagger &= f^{-1}, \\ (f^{-1})^\dagger &= \text{Gr}(f). \end{aligned}$$

00QL Proposition 6.3.11.1.3. Let $R: A \rightarrow B$ and $S: B \rightarrow C$ be relations.

00QM 1. *Functoriality.* The assignment $R \mapsto R^\dagger$ defines a functor (i.e. morphism of posets)

$$(-)^\dagger: \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(B, A).$$

In particular, given relations $R, S: A \rightarrow B$, we have:

¹³*Further Terminology:* Also called the **opposite of R** , the **transpose of R** , or the **converse**

(★) If $R \subset S$, then $R^\dagger \subset S^\dagger$.

00QN 2. *Interaction With Ranges and Domains.* We have

$$\begin{aligned}\text{dom}(R^\dagger) &= \text{range}(R), \\ \text{range}(R^\dagger) &= \text{dom}(R).\end{aligned}$$

00QP 3. *Interaction With Composition I.* We have

$$(S \diamond R)^\dagger = R^\dagger \diamond S^\dagger.$$

00QQ 4. *Interaction With Composition II.* We have

$$\begin{aligned}\chi_B &\subset R \diamond R^\dagger, \\ \chi_A &\subset R^\dagger \diamond R.\end{aligned}$$

00QR 5. *Invertibility.* We have

$$(R^\dagger)^\dagger = R.$$

00QS 6. *Identity.* We have

$$\chi_A^\dagger = \chi_A.$$

Proof. Item 1, Functoriality: Clear.

Item 2, Interaction With Ranges and Domains: Clear.

Item 3, Interaction With Composition I: Clear.

Item 4, Interaction With Composition II: Clear.

Item 5, Invertibility: Clear.

Item 6, Identity: Clear. □

00QT 6.3.12 Composition of Relations

Let A , B , and C be sets and let $R: A \rightarrow B$ and $S: B \rightarrow C$ be relations.

00QU **Definition 6.3.12.1.1.** The **composition of R and S** is the relation $S \diamond R$ defined as follows:

- Viewing relations from A to C as subsets of $A \times C$, we define

$$S \diamond R \stackrel{\text{def}}{=} \left\{ (a, c) \in A \times C \left| \begin{array}{l} \text{there exists some } b \in B \text{ such} \\ \text{that } a \sim_R b \text{ and } b \sim_S c \end{array} \right. \right\}.$$

- Viewing relations as functions $A \times B \rightarrow \{\text{true}, \text{false}\}$, we define

$$\begin{aligned} (S \diamond R)_{-2}^{-1} &\stackrel{\text{def}}{=} \int^{b \in B} S_b^{-1} \times R_{-2}^b \\ &= \bigvee_{b \in B} S_b^{-1} \times R_{-2}^b, \end{aligned}$$

where the join \bigvee is taken in the poset $(\{\text{true}, \text{false}\}, \preceq)$ of **Definition 1.2.2.1.3**.

- Viewing relations as functions $A \rightarrow \mathcal{P}(B)$, we define

$$S \diamond R \stackrel{\text{def}}{=} \text{Lan}_{\chi_B}(S) \circ R,$$

where $\text{Lan}_{\chi_B}(S)$ is computed by the formula

$$\begin{aligned} [\text{Lan}_{\chi_B}(S)](V) &\cong \int^{y \in B} \chi_{\mathcal{P}(B)}(\chi_y, V) \odot S_y \\ &\cong \int^{y \in B} \chi_V(y) \odot S_y \\ &\cong \bigcup_{y \in B} \chi_V(y) \odot S_y \\ &\cong \bigcup_{y \in V} S_y \end{aligned}$$

for each $V \in \mathcal{P}(B)$. In other words, $S \diamond R$ is defined by¹⁴

$$\begin{aligned} [S \diamond R](a) &\stackrel{\text{def}}{=} S(R(a)) \\ &\stackrel{\text{def}}{=} \bigcup_{x \in R(a)} S(x). \end{aligned}$$

for each $a \in A$.

00QV Example 6.3.12.1.2. Here are some examples of composition of relations.

of R .

¹⁴That is: the relation R may send $a \in A$ to a number of elements $\{b_i\}_{i \in I}$ in B , and then the relation S may send the image of each of the b_i 's to a number of elements $\{S(b_i)\}_{i \in I} = \{\{c_{j_i}\}_{j_i \in J_i}\}_{i \in I}$ in C .

1. *Composing Less/Greater Than Equal With Greater/Less Than Equal Signs.* We have

$$\begin{aligned}\leq \diamond \geq &= \sim_{\text{triv}}, \\ \geq \diamond \leq &= \sim_{\text{triv}}.\end{aligned}$$

2. *Composing Less/Greater Than Equal Signs With Less/Greater Than Equal Signs.* We have

$$\begin{aligned}\leq \diamond \leq &= \leq, \\ \geq \diamond \geq &= \geq.\end{aligned}$$

00QW Proposition 6.3.12.1.3. Let $R: A \rightarrow B$, $S: B \rightarrow C$, and $T: C \rightarrow D$ be relations.

- 00QX** 1. *Interaction With Ranges and Domains.* We have

$$\begin{aligned}\text{dom}(S \diamond R) &\subset \text{dom}(R), \\ \text{range}(S \diamond R) &\subset \text{range}(S).\end{aligned}$$

- 00QY** 2. *Associativity.* We have

$$(T \diamond S) \diamond R = T \diamond (S \diamond R).$$

- 00QZ** 3. *Unitality.* We have

$$\begin{aligned}\chi_B \diamond R &= R, \\ R \diamond \chi_A &= R.\end{aligned}$$

- 00R0** 4. *Interaction With Inverses.* We have

$$(S \diamond R)^\dagger = R^\dagger \diamond S^\dagger.$$

- 00R1** 5. *Interaction With Composition.* We have

$$\begin{aligned}\chi_B &\subset R \diamond R^\dagger, \\ \chi_A &\subset R^\dagger \diamond R.\end{aligned}$$

Proof. **Item 1**, *Interaction With Ranges and Domains:* Clear.

Item 2, Associativity: Indeed, we have

$$\begin{aligned}
(T \diamond S) \diamond R &\stackrel{\text{def}}{=} \left(\int^{c \in C} T_c^{-1} \times S_{-2}^c \right) \diamond R \\
&\stackrel{\text{def}}{=} \int^{b \in B} \left(\int^{c \in C} T_c^{-1} \times S_b^c \right) \diamond R_{-2}^b \\
&= \int^{b \in B} \int^{c \in C} (T_c^{-1} \times S_b^c) \diamond R_{-2}^b \\
&= \int^{c \in C} \int^{b \in B} (T_c^{-1} \times S_b^c) \diamond R_{-2}^b \\
&= \int^{c \in C} \int^{b \in B} T_c^{-1} \times (S_b^c \diamond R_{-2}^b) \\
&= \int^{c \in C} T_c^{-1} \times \left(\int^{b \in B} S_b^c \diamond R_{-2}^b \right) \\
&\stackrel{\text{def}}{=} \int^{c \in C} T_c^{-1} \times (S \diamond R)_{-2}^c \\
&\stackrel{\text{def}}{=} T \diamond (S \diamond R).
\end{aligned}$$

In the language of relations, given $a \in A$ and $d \in D$, the stated equality witnesses the equivalence of the following two statements:

1. We have $a \sim_{(T \diamond S) \diamond R} d$, i.e. there exists some $b \in B$ such that:
 - (a) We have $a \sim_R b$;
 - (b) We have $b \sim_{T \diamond S} d$, i.e. there exists some $c \in C$ such that:
 - i. We have $b \sim_S c$;
 - ii. We have $c \sim_T d$;
2. We have $a \sim_{T \diamond (S \diamond R)} d$, i.e. there exists some $c \in C$ such that:
 - (a) We have $a \sim_{S \diamond R} c$, i.e. there exists some $b \in B$ such that:
 - i. We have $a \sim_R b$;
 - ii. We have $b \sim_S c$;
 - (b) We have $c \sim_T d$;

both of which are equivalent to the statement

- There exist $b \in B$ and $c \in C$ such that $a \sim_R b \sim_S c \sim_T d$.

Item 3, Unitality: Indeed, we have

$$\begin{aligned}\chi_B \diamond R &\stackrel{\text{def}}{=} \int^{x \in B} (\chi_B)_x^{-1} \times R_{-2}^x \\ &= \bigvee_{x \in B} (\chi_B)_x^{-1} \times R_{-2}^x \\ &= \bigvee_{\substack{x \in B \\ x = -1}} R_{-2}^x \\ &= R_{-2}^{-1},\end{aligned}$$

and

$$\begin{aligned}R \diamond \chi_A &\stackrel{\text{def}}{=} \int^{x \in A} R_x^{-1} \times (\chi_A)_{-2}^x \\ &= \bigvee_{x \in B} R_x^{-1} \times (\chi_A)_{-2}^x \\ &= \bigvee_{\substack{x \in B \\ x = -2}} R_x^{-1} \\ &= R_{-2}^{-1}.\end{aligned}$$

In the language of relations, given $a \in A$ and $b \in B$:

- The equality

$$\chi_B \diamond R = R$$

witnesses the equivalence of the following two statements:

1. We have $a \sim_b B$.
2. There exists some $b' \in B$ such that:
 - (a) We have $a \sim_R b'$
 - (b) We have $b' \sim_{\chi_B} b$, i.e. $b' = b$.

- The equality

$$R \diamond \chi_A = R$$

witnesses the equivalence of the following two statements:

1. There exists some $a' \in A$ such that:
 - (a) We have $a \sim_{\chi_B} a'$, i.e. $a = a'$.
 - (b) We have $a' \sim_R b$
2. We have $a \sim_b B$.

Item 4, Interaction With Inverses: Clear.

Item 5, Interaction With Composition: Clear. □

00R2 6.3.13 The Collage of a Relation

Let A and B be sets and let $R: A \rightarrow B$ be a relation from A to B .

00R3 Definition 6.3.13.1.1. The **collage of R** ¹⁵ is the poset $\mathbf{Coll}(R) \stackrel{\text{def}}{=} (\mathbf{Coll}(R), \preceq_{\mathbf{Coll}(R)})$ consisting of:

- *The Underlying Set.* The set $\mathbf{Coll}(R)$ defined by

$$\mathbf{Coll}(R) \stackrel{\text{def}}{=} A \amalg B.$$

- *The Partial Order.* The partial order

$$\preceq_{\mathbf{Coll}(R)}: \mathbf{Coll}(R) \times \mathbf{Coll}(R) \rightarrow \{\text{true}, \text{false}\}$$

on $\mathbf{Coll}(R)$ defined by

$$\preceq(a, b) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } a = b \text{ or } a \sim_R b, \\ \text{false} & \text{otherwise.} \end{cases}$$

00R4 Proposition 6.3.13.1.2. Let A and B be sets and let $R: A \rightarrow B$ be a relation from A to B .

00R5 1. *Functoriality I.* The assignment $R \mapsto \mathbf{Coll}(R)$ defines a functor¹⁶

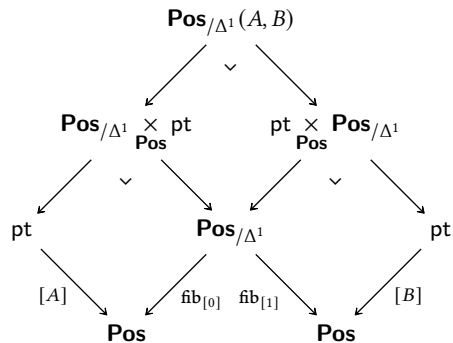
$$\mathbf{Coll}: \mathbf{Rel}(A, B) \rightarrow \mathbf{Pos}_{/\Delta^1}(A, B),$$

¹⁵Further Terminology: Also called the **cograph** of R .

¹⁶Here $\mathbf{Pos}_{/\Delta^1}(A, B)$ is the category defined as the pullback

$$\mathbf{Pos}_{/\Delta^1}(A, B) \stackrel{\text{def}}{=} \text{pt}_{[A], \mathbf{Pos}, \text{fib}_0} \times_{\mathbf{Pos}_{/\Delta^1}} \text{pt}_{\text{fib}_1, \mathbf{Pos}, [B]}$$

as in the diagram



Explicitly, an object of $\mathbf{Pos}_{/\Delta^1}(A, B)$ is a pair (X, ϕ_X) consisting of

where

- *Action on Objects.* For each $R \in \text{Obj}(\mathbf{Rel}(A, B))$, we have

$$[\mathbf{Coll}](R) \stackrel{\text{def}}{=} (\mathbf{Coll}(R), \phi_R)$$

for each $R \in \mathbf{Rel}(A, B)$, where

- The poset $\mathbf{Coll}(R)$ is the collage of R of [Definition 6.3.13.1.1](#).
- The morphism $\phi_R: \mathbf{Coll}(R) \rightarrow \Delta^1$ is given by

$$\phi_R(x) \stackrel{\text{def}}{=} \begin{cases} 0 & \text{if } x \in A, \\ 1 & \text{if } x \in B \end{cases}$$

for each $x \in \mathbf{Coll}(R)$.

- *Action on Morphisms.* For each $R, S \in \text{Obj}(\mathbf{Rel}(A, B))$, the action on Hom-sets

$$\mathbf{Coll}_{R,S}: \text{Hom}_{\mathbf{Rel}(A,B)}(R, S) \rightarrow \text{Pos}(\mathbf{Coll}(R), \mathbf{Coll}(S))$$

of \mathbf{Coll} at (R, S) is given by sending an inclusion

$$\iota: R \subset S$$

to the morphism

$$\mathbf{Coll}(\iota): \mathbf{Coll}(R) \rightarrow \mathbf{Coll}(S)$$

of posets over Δ^1 defined by

$$[\mathbf{Coll}(\iota)](x) \stackrel{\text{def}}{=} x$$

for each $x \in \mathbf{Coll}(R)$.¹⁷

00R6 2. *Equivalence.* The functor of [Item 1](#) is an equivalence of categories.

Proof. Item 1, Functoriality: Clear.

Item 2, Equivalence: Omitted. □

-
- A poset X ;
 - A morphism $\phi_X: X \rightarrow \Delta^1$;

such that $\phi_X^{-1}(0) = A$ and $\phi_X^{-1}(1) = B$, with morphisms between such objects being morphisms of posets over Δ^1 .

¹⁷Note that this is indeed a morphism of posets: if $x \preceq_{\mathbf{Coll}(R)} y$, then $x = y$ or $x \sim_R y$, so we have either $x = y$ or $x \sim_S y$ (as $R \subset S$), and thus $x \preceq_{\mathbf{Coll}(S)} y$.

00R7 6.4 Functoriality of Powersets

00R8 6.4.1 Direct Images

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

00R9 **Definition 6.4.1.1.1.** The **direct image function associated to R** is the function

$$R_*: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by^{18,19}

$$\begin{aligned} R_*(U) &\stackrel{\text{def}}{=} R(U) \\ &\stackrel{\text{def}}{=} \bigcup_{a \in U} R(a) \\ &= \left\{ b \in B \mid \begin{array}{l} \text{there exists some } a \in U \\ \text{such that } b \in R(a) \end{array} \right\} \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

00RA **Remark 6.4.1.1.2.** Identifying subsets of A with relations from pt to A via **Item 3** of **Proposition 2.4.3.1.6**, we see that the direct image function associated to R is equivalently the function

$$R_*: \underbrace{\mathcal{P}(A)}_{\cong \text{Rel}(\text{pt}, A)} \rightarrow \underbrace{\mathcal{P}(B)}_{\cong \text{Rel}(\text{pt}, B)}$$

defined by

$$R_*(U) \stackrel{\text{def}}{=} R \diamond U$$

for each $U \in \mathcal{P}(A)$, where $R \diamond U$ is the composition

$$\text{pt} \xrightarrow{U} A \xrightarrow{R} B.$$

00RB **Proposition 6.4.1.1.3.** Let $R: A \rightarrow B$ be a relation.

00RC 1. *Functoriality.* The assignment $U \mapsto R_*(U)$ defines a functor

$$R_*: (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

where

¹⁸Further Terminology: The set $R(U)$ is called the **direct image of U by R** .

¹⁹We also have

$$R_*(U) = B \setminus R!(A \setminus U);$$

- *Action on Objects.* For each $U \in \mathcal{P}(A)$, we have

$$[R_*](U) \stackrel{\text{def}}{=} R_*(U).$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(A)$:
 - If $U \subset V$, then $R_*(U) \subset R_*(V)$.

00RD 2. *Adjointness.* We have an adjunction

$$(R_* \dashv R_{-1}): \mathcal{P}(A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{R_{-1}} \end{array} \mathcal{P}(B),$$

witnessed by a bijections of sets

$$\text{Hom}_{\mathcal{P}(A)}(R_*(U), V) \cong \text{Hom}_{\mathcal{P}(A)}(U, R_{-1}(V)),$$

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$, i.e. such that:

- (★) The following conditions are equivalent:
- We have $R_*(U) \subset V$.
 - We have $U \subset R_{-1}(V)$.

00RE 3. *Preservation of Colimits.* We have an equality of sets

$$R_*\left(\bigcup_{i \in I} U_i\right) = \bigcup_{i \in I} R_*(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have equalities

$$\begin{aligned} R_*(U) \cup R_*(V) &= R_*(U \cup V), \\ R_*(\emptyset) &= \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

00RF 4. *Oplax Preservation of Limits.* We have an inclusion of sets

$$R_*\left(\bigcap_{i \in I} U_i\right) \subset \bigcap_{i \in I} R_*(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have inclusions

$$\begin{aligned} R_*(U \cap V) &\subset R_*(U) \cap R_*(V), \\ R_*(A) &\subset B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 00RG** 5. *Symmetric Strict Monoidality With Respect to Unions.* The direct image function of **Item 1** has a symmetric strict monoidal structure

$$\left(R_*, R_*^\otimes, R_{*|\perp}^\otimes \right): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} R_{*|U,V}^\otimes: R_*(U) \cup R_*(V) &\xrightarrow{=} R_*(U \cup V), \\ R_{*|\perp}^\otimes: \emptyset &\xrightarrow{=} \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 00RH** 6. *Symmetric Oplax Monoidality With Respect to Intersections.* The direct image function of **Item 1** has a symmetric oplax monoidal structure

$$\left(R_*, R_*^\otimes, R_{*|\perp}^\otimes \right): (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} R_{*|U,V}^\otimes: R_*(U \cap V) &\subset R_*(U) \cap R_*(V), \\ R_{*|\perp}^\otimes: R_*(A) &\subset B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 00RJ** 7. *Relation to Direct Images With Compact Support.* We have

$$R_*(U) = B \setminus R_!(A \setminus U)$$

for each $U \in \mathcal{P}(A)$.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness: This follows from ?? of ??.

Item 3, Preservation of Colimits: This follows from **Item 2** and ?? of ??.

Item 4, Oplax Preservation of Limits: Omitted.

Item 5, Symmetric Strict Monoidality With Respect to Unions: This follows from **Item 3**.

Item 6, Symmetric Oplax Monoidality With Respect to Intersections: This follows from **Item 4**.

Item 7, Relation to Direct Images With Compact Support: The proof proceeds in the same way as in the case of functions (?? of **Proposition 2.4.4.1.4**): applying **Item 7** of **Proposition 6.4.4.1.3** to $A \setminus U$, we have

$$\begin{aligned} R_!(A \setminus U) &= B \setminus R_*(A \setminus (A \setminus U)) \\ &= B \setminus R_*(U). \end{aligned}$$

Taking complements, we then obtain

$$\begin{aligned} R_*(U) &= B \setminus (B \setminus R_*(U)), \\ &= B \setminus R_!(A \setminus U), \end{aligned}$$

which finishes the proof. \square

00RK Proposition 6.4.1.1.4. Let $R: A \rightarrow B$ be a relation.

00RL 1. *Functionality I.* The assignment $R \mapsto R_*$ defines a function

$$(-)_* : \text{Rel}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

00RM 2. *Functionality II.* The assignment $R \mapsto R_*$ defines a function

$$(-)_* : \text{Rel}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

00RN 3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have²⁰

$$(\chi_A)_* = \text{id}_{\mathcal{P}(A)}.$$

00RP 4. *Interaction With Composition.* For each pair of composable relations $R: A \rightarrow B$ and $S: B \rightarrow C$, we have²¹

$$(S \circ R)_* = S_* \circ R_*,$$

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{R_*} & \mathcal{P}(B) \\ & \searrow (S \circ R)_* & \downarrow S_* \\ & & \mathcal{P}(C). \end{array}$$

Proof. Item 1, Functionality I: Clear.

see **Item 7** of **Proposition 6.4.1.1.3**.

²⁰That is, the postcomposition function

$$(\chi_A)_* : \text{Rel}(\text{pt}, A) \rightarrow \text{Rel}(\text{pt}, A)$$

is equal to $\text{id}_{\text{Rel}(\text{pt}, A)}$.

²¹That is, we have

$$(S \circ R)_* = S_* \circ R_*,$$

$$\begin{array}{ccc} \text{Rel}(\text{pt}, A) & \xrightarrow{R_*} & \text{Rel}(\text{pt}, B) \\ & \searrow (S \circ R)_* & \downarrow S_* \\ & & \text{Rel}(\text{pt}, C). \end{array}$$

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: Indeed, we have

$$\begin{aligned} (\chi_A)_*(U) &\stackrel{\text{def}}{=} \bigcup_{a \in U} \chi_A(a) \\ &\stackrel{\text{def}}{=} \bigcup_{a \in U} \{a\} \\ &= U \\ &\stackrel{\text{def}}{=} \text{id}_{\mathcal{P}(A)}(U) \end{aligned}$$

for each $U \in \mathcal{P}(A)$. Thus $(\chi_A)_* = \text{id}_{\mathcal{P}(A)}$.

Item 4, Interaction With Composition: Indeed, we have

$$\begin{aligned} (S \diamond R)_*(U) &\stackrel{\text{def}}{=} \bigcup_{a \in U} [S \diamond R](a) \\ &\stackrel{\text{def}}{=} \bigcup_{a \in U} S(R(a)) \\ &\stackrel{\text{def}}{=} \bigcup_{a \in U} S_*(R(a)) \\ &= S_* \left(\bigcup_{a \in U} R(a) \right) \\ &\stackrel{\text{def}}{=} S_*(R_*(U)) \\ &\stackrel{\text{def}}{=} [S_* \circ R_*](U) \end{aligned}$$

for each $U \in \mathcal{P}(A)$, where we used *Item 3* of **Proposition 6.4.1.1.3**. Thus $(S \diamond R)_* = S_* \circ R_*$. \square

00RQ 6.4.2 Strong Inverse Images

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

00RR Definition 6.4.2.1.1. The strong inverse image function associated to R is the function

$$R_{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

defined by²²

$$R_{-1}(V) \stackrel{\text{def}}{=} \{a \in A \mid R(a) \subset V\}$$

for each $V \in \mathcal{P}(B)$.

²²Further Terminology: The set $R_{-1}(V)$ is called the **strong inverse image of V by R** .

00RS Remark 6.4.2.1.2. Identifying subsets of B with relations from pt to B via **Item 3** of **Proposition 2.4.3.1.6**, we see that the inverse image function associated to R is equivalently the function

$$R_{-1}: \underbrace{\mathcal{P}(B)}_{\cong \text{Rel}(\text{pt}, B)} \rightarrow \underbrace{\mathcal{P}(A)}_{\cong \text{Rel}(\text{pt}, A)}$$

defined by

$$R_{-1}(V) \stackrel{\text{def}}{=} \text{Rift}_R(V),$$

and being explicitly computed by

$$R_{-1}(V) \stackrel{\text{def}}{=} \text{Rift}_R(V) \cong \int_{b \in B} \text{Hom}_{\{t, f\}}(R_{-1}^b, V_{-2}^b),$$

where we have used **Proposition 6.2.4.1.1**.

Proof. We have

$$\begin{aligned}
\text{Rift}_R(V) &\cong \int_{b \in B} \text{Hom}_{\{t,f\}}(R_{-1}^b, V_{-2}^b) \\
&= \left\{ a \in A \mid \int_{b \in B} \text{Hom}_{\{t,f\}}(R_a^b, V_{\star}^b) = \text{true} \right\} \\
&= \left\{ a \in A \mid \begin{array}{l} \text{for each } b \in B, \text{ at least one of the} \\ \text{following conditions hold:} \\ \\ 1. \text{ We have } R_a^b = \text{false} \\ 2. \text{ The following conditions hold:} \\ \\ \quad \text{(a) We have } R_a^b = \text{true} \\ \quad \text{(b) We have } V_{\star}^b = \text{true} \end{array} \right\} \\
&= \left\{ a \in A \mid \begin{array}{l} \text{for each } b \in B, \text{ at least one of the} \\ \text{following conditions hold:} \\ \\ 1. \text{ We have } b \notin R(a) \\ 2. \text{ The following conditions hold:} \\ \\ \quad \text{(a) We have } b \in R(a) \\ \quad \text{(b) We have } b \in V \end{array} \right\} \\
&= \{a \in A \mid \text{for each } b \in R(a), \text{ we have } b \in V\} \\
&= \{a \in A \mid R(a) \subset V\} \\
&\stackrel{\text{def}}{=} R_{-1}(V).
\end{aligned}$$

This finishes the proof. \square

00RT Proposition 6.4.2.1.3. Let $R: A \rightarrow B$ be a relation.

00RU 1. *Functoriality.* The assignment $V \mapsto R_{-1}(V)$ defines a functor

$$R_{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

where

- *Action on Objects.* For each $V \in \mathcal{P}(B)$, we have

$$[R_{-1}](V) \stackrel{\text{def}}{=} R_{-1}(V).$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(B)$:
 - If $U \subset V$, then $R_{-1}(U) \subset R_{-1}(V)$.

00RV 2. *Adjointness.* We have an adjunction

$$(R_* \dashv R_{-1}): \mathcal{P}(A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{R_{-1}} \end{array} \mathcal{P}(B),$$

witnessed by a bijections of sets

$$\mathrm{Hom}_{\mathcal{P}(A)}(R_*(U), V) \cong \mathrm{Hom}_{\mathcal{P}(A)}(U, R_{-1}(V)),$$

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$, i.e. such that:

(★) The following conditions are equivalent:

- We have $R_*(U) \subset V$.
- We have $U \subset R_{-1}(V)$.

00RW 3. *Lax Preservation of Colimits.* We have an inclusion of sets

$$\bigcup_{i \in I} R_{-1}(U_i) \subset R_{-1}\left(\bigcup_{i \in I} U_i\right),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(B)^{\times I}$. In particular, we have inclusions

$$\begin{aligned} R_{-1}(U) \cup R_{-1}(V) &\subset R_{-1}(U \cup V), \\ \emptyset &\subset R_{-1}(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

00RX 4. *Preservation of Limits.* We have an equality of sets

$$R_{-1}\left(\bigcap_{i \in I} U_i\right) = \bigcap_{i \in I} R_{-1}(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(B)^{\times I}$. In particular, we have equalities

$$\begin{aligned} R_{-1}(U \cap V) &= R_{-1}(U) \cap R_{-1}(V), \\ R_{-1}(B) &= B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

00RY 5. *Symmetric Lax Monoidality With Respect to Unions.* The direct image with compact support function of **Item 1** has a symmetric lax monoidal structure

$$\left(R_{-1}, R_{-1}^{\otimes}, R_{-1}^{\otimes}[\mathbb{1}]\right): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with inclusions

$$R_{-1|U,V}^{\otimes} : R_{-1}(U) \cup R_{-1}(V) \subset R_{-1}(U \cup V),$$

$$R_{-1|\mathbb{1}}^{\otimes} : \emptyset \subset R_{-1}(\emptyset),$$

natural in $U, V \in \mathcal{P}(B)$.

- 00RZ 6. *Symmetric Strict Monoidality With Respect to Intersections.* The direct image function of **Item 1** has a symmetric strict monoidal structure

$$\left(R_{-1}, R_{-1}^{\otimes}, R_{-1|\mathbb{1}}^{\otimes} \right) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

$$R_{-1|U,V}^{\otimes} : R_{-1}(U \cap V) \xrightarrow{=} R_{-1}(U) \cap R_{-1}(V),$$

$$R_{-1|\mathbb{1}}^{\otimes} : R_{-1}(A) \xrightarrow{=} B,$$

natural in $U, V \in \mathcal{P}(B)$.

- 00S0 7. *Interaction With Weak Inverse Images I.* We have

$$R_{-1}(V) = A \setminus R^{-1}(B \setminus V)$$

for each $V \in \mathcal{P}(B)$.

- 00S1 8. *Interaction With Weak Inverse Images II.* Let $R: A \dashv B$ be a relation from A to B .

- 00S2 (a) If R is a total relation, then we have an inclusion of sets

$$R_{-1}(V) \subset R^{-1}(V)$$

natural in $V \in \mathcal{P}(B)$.

- 00S3 (b) If R is total and functional, then the above inclusion is in fact an equality.

- 00S4 (c) Conversely, if we have $R_{-1} = R^{-1}$, then R is total and functional.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness: This follows from ?? of ??.

Item 3, Lax Preservation of Colimits: Omitted.

Item 4, Preservation of Limits: This follows from **Item 2** and ?? of ??.

Item 5, Symmetric Lax Monoidality With Respect to Unions: This follows from **Item 3**.

Item 6, Symmetric Strict Monoidality With Respect to Intersections: This follows from *Item 4*.

Item 7, Interaction With Weak Inverse Images I: We claim we have an equality

$$R_{-1}(B \setminus V) = A \setminus R^{-1}(V).$$

Indeed, we have

$$\begin{aligned} R_{-1}(B \setminus V) &= \{a \in A \mid R(a) \subset B \setminus V\}, \\ A \setminus R^{-1}(V) &= \{a \in A \mid R(a) \cap V = \emptyset\}. \end{aligned}$$

Taking $V = B \setminus V$ then implies the original statement.

Item 8, Interaction With Weak Inverse Images II: *Item 8a* is clear, while *Items 8b* and *8c* follow from *Item 6* of *Proposition 6.3.1.1.2*. \square

00S5 Proposition 6.4.2.1.4. Let $R: A \rightarrow B$ be a relation.

00S6 1. *Functionality I.* The assignment $R \mapsto R_{-1}$ defines a function

$$(-)_{-1}: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

00S7 2. *Functionality II.* The assignment $R \mapsto R_{-1}$ defines a function

$$(-)_{-1}: \text{Sets}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

00S8 3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$(\text{id}_A)_{-1} = \text{id}_{\mathcal{P}(A)}.$$

00S9 4. *Interaction With Composition.* For each pair of composable relations $R: A \rightarrow B$ and $S: B \rightarrow C$, we have

$$(S \circ R)_{-1} = R_{-1} \circ S_{-1},$$

$$\begin{array}{ccc} \mathcal{P}(C) & \xrightarrow{S_{-1}} & \mathcal{P}(B) \\ & \searrow (S \circ R)_{-1} & \downarrow R_{-1} \\ & & \mathcal{P}(A). \end{array}$$

Proof. Item 1, Functionality I: Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: Indeed, we have

$$\begin{aligned} (\chi_A)_{-1}(U) &\stackrel{\text{def}}{=} \{a \in A \mid \chi_A(a) \subset U\} \\ &\stackrel{\text{def}}{=} \{a \in A \mid \{a\} \subset U\} \\ &= U \end{aligned}$$

for each $U \in \mathcal{P}(A)$. Thus $(\chi_A)_{-1} = \text{id}_{\mathcal{P}(A)}$.

Item 4, Interaction With Composition: Indeed, we have

$$\begin{aligned} (S \diamond R)_{-1}(U) &\stackrel{\text{def}}{=} \{a \in A \mid [S \diamond R](a) \subset U\} \\ &\stackrel{\text{def}}{=} \{a \in A \mid S(R(a)) \subset U\} \\ &\stackrel{\text{def}}{=} \{a \in A \mid S_*(R(a)) \subset U\} \\ &= \{a \in A \mid R(a) \subset S_{-1}(U)\} \\ &\stackrel{\text{def}}{=} R_{-1}(S_{-1}(U)) \\ &\stackrel{\text{def}}{=} [R_{-1} \circ S_{-1}](U) \end{aligned}$$

for each $U \in \mathcal{P}(C)$, where we used *Item 2* of [Proposition 6.4.2.1.3](#), which implies that the conditions

- We have $S_*(R(a)) \subset U$.
- We have $R(a) \subset S_{-1}(U)$.

are equivalent. Thus $(S \diamond R)_{-1} = R_{-1} \circ S_{-1}$. □

00SA 6.4.3 Weak Inverse Images

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

00SB Definition 6.4.3.1.1. The **weak inverse image function associated to R** ²³ is the function

$$R^{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

defined by²⁴

$$R^{-1}(V) \stackrel{\text{def}}{=} \{a \in A \mid R(a) \cap V \neq \emptyset\}$$

for each $V \in \mathcal{P}(B)$.

00SC Remark 6.4.3.1.2. Identifying subsets of B with relations from B to pt via [Item 3](#) of [Proposition 2.4.3.1.6](#), we see that the weak inverse image function associated to R is equivalently the function

$$R^{-1}: \underbrace{\mathcal{P}(B)}_{\cong \text{Rel}(B, \text{pt})} \rightarrow \underbrace{\mathcal{P}(A)}_{\cong \text{Rel}(A, \text{pt})}$$

defined by

$$R^{-1}(V) \stackrel{\text{def}}{=} V \diamond R$$

²³*Further Terminology:* Also called simply the **inverse image function associated to R** .

²⁴*Further Terminology:* The set $R^{-1}(V)$ is called the **weak inverse image of V by R** or

for each $V \in \mathcal{P}(A)$, where $R \diamond V$ is the composition

$$A \xrightarrow{R} B \xrightarrow{V} \text{pt.}$$

Explicitly, we have

$$\begin{aligned} R^{-1}(V) &\stackrel{\text{def}}{=} V \diamond R \\ &\stackrel{\text{def}}{=} \int^{b \in B} V_b^{-1} \times R_{-2}^b. \end{aligned}$$

Proof. We have

$$\begin{aligned} V \diamond R &\stackrel{\text{def}}{=} \int^{b \in B} V_b^{-1} \times R_{-2}^b \\ &= \left\{ a \in A \mid \int^{b \in B} V_b^* \times R_a^b = \text{true} \right\} \\ &= \left\{ a \in A \mid \begin{array}{l} \text{there exists } b \in B \text{ such that the} \\ \text{following conditions hold:} \\ \quad 1. \text{ We have } V_b^* = \text{true} \\ \quad 2. \text{ We have } R_a^b = \text{true} \end{array} \right\} \\ &= \left\{ a \in A \mid \begin{array}{l} \text{there exists } b \in B \text{ such that the} \\ \text{following conditions hold:} \\ \quad 1. \text{ We have } b \in V \\ \quad 2. \text{ We have } b \in R(a) \end{array} \right\} \\ &= \{ a \in A \mid \text{there exists } b \in V \text{ such that } b \in R(a) \} \\ &= \{ a \in A \mid R(a) \cap V \neq \emptyset \} \\ &\stackrel{\text{def}}{=} R^{-1}(V) \end{aligned}$$

This finishes the proof. \square

00SD Proposition 6.4.3.1.3. Let $R: A \rightarrow B$ be a relation.

00SE 1. *Functoriality.* The assignment $V \mapsto R^{-1}(V)$ defines a functor

$$R^{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

where

- *Action on Objects.* For each $V \in \mathcal{P}(B)$, we have

$$[R^{-1}](V) \stackrel{\text{def}}{=} R^{-1}(V).$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(B)$:
 - If $U \subset V$, then $R^{-1}(U) \subset R^{-1}(V)$.

00SF 2. *Adjointness.* We have an adjunction

$$(R^{-1} \dashv R_!): \mathcal{P}(B) \begin{array}{c} \xrightarrow{R^{-1}} \\ \perp \\ \xleftarrow{R_!} \end{array} \mathcal{P}(A),$$

witnessed by a bijections of sets

$$\text{Hom}_{\mathcal{P}(A)}(R^{-1}(U), V) \cong \text{Hom}_{\mathcal{P}(A)}(U, R_!(V)),$$

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$, i.e. such that:

- (★) The following conditions are equivalent:
- We have $R^{-1}(U) \subset V$.
 - We have $U \subset R_!(V)$.

00SG 3. *Preservation of Colimits.* We have an equality of sets

$$R^{-1}\left(\bigcup_{i \in I} U_i\right) = \bigcup_{i \in I} R^{-1}(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(B)^{\times I}$. In particular, we have equalities

$$\begin{aligned} R^{-1}(U) \cup R^{-1}(V) &= R^{-1}(U \cup V), \\ R^{-1}(\emptyset) &= \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

00SH 4. *Oplax Preservation of Limits.* We have an inclusion of sets

$$R^{-1}\left(\bigcap_{i \in I} U_i\right) \subset \bigcap_{i \in I} R^{-1}(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(B)^{\times I}$. In particular, we have inclusions

$$\begin{aligned} R^{-1}(U \cap V) &\subset R^{-1}(U) \cap R^{-1}(V), \\ R^{-1}(A) &\subset B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

- 00SJ 5. *Symmetric Strict Monoidality With Respect to Unions.* The direct image function of **Item 1** has a symmetric strict monoidal structure

$$\left(R^{-1}, R^{-1, \otimes}, R_{\perp}^{-1, \otimes}\right): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} R_{U,V}^{-1, \otimes}: R^{-1}(U) \cup R^{-1}(V) &\xrightarrow{=} R^{-1}(U \cup V), \\ R_{\perp}^{-1, \otimes}: \emptyset &\xrightarrow{=} \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

- 00SK 6. *Symmetric Oplax Monoidality With Respect to Intersections.* The direct image function of **Item 1** has a symmetric oplax monoidal structure

$$\left(R^{-1}, R^{-1, \otimes}, R_{\perp}^{-1, \otimes}\right): (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} R_{U,V}^{-1, \otimes}: R^{-1}(U \cap V) &\subset R^{-1}(U) \cap R^{-1}(V), \\ R_{\perp}^{-1, \otimes}: R^{-1}(A) &\subset B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

- 00SL 7. *Interaction With Strong Inverse Images I.* We have

$$R^{-1}(V) = A \setminus R_{-1}(B \setminus V)$$

for each $V \in \mathcal{P}(B)$.

- 00SM 8. *Interaction With Strong Inverse Images II.* Let $R: A \rightarrow B$ be a relation from A to B .

- 00SN (a) If R is a total relation, then we have an inclusion of sets

$$R_{-1}(V) \subset R^{-1}(V)$$

natural in $V \in \mathcal{P}(B)$.

- 00SP (b) If R is total and functional, then the above inclusion is in fact an equality.

- 00SQ (c) Conversely, if we have $R_{-1} = R^{-1}$, then R is total and functional.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness: This follows from ?? of ??.

Item 3, Preservation of Colimits: This follows from **Item 2** and ?? of ??.

Item 4, Oplax Preservation of Limits: Omitted.

Item 5, Symmetric Strict Monoidality With Respect to Unions: This follows from **Item 3**.

Item 6, Symmetric Oplax Monoidality With Respect to Intersections: This follows from **Item 4**.

Item 7, Interaction With Strong Inverse Images I: This follows from **Item 7** of **Proposition 6.4.2.1.3**.

Item 8, Interaction With Strong Inverse Images II: This was proved in **Item 8** of **Proposition 6.4.2.1.3**. \square

00SR Proposition 6.4.3.1.4. Let $R: A \dashrightarrow B$ be a relation.

00SS 1. *Functionality I.* The assignment $R \mapsto R^{-1}$ defines a function

$$(-)^{-1}: \text{Rel}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

00ST 2. *Functionality II.* The assignment $R \mapsto R^{-1}$ defines a function

$$(-)^{-1}: \text{Rel}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

00SU 3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have²⁵

$$(\chi_A)^{-1} = \text{id}_{\mathcal{P}(A)}.$$

00SV 4. *Interaction With Composition.* For each pair of composable relations

_____ simply the **inverse image of V by R** .

²⁵That is, the postcomposition

$$(\chi_A)^{-1}: \text{Rel}(\text{pt}, A) \rightarrow \text{Rel}(\text{pt}, A)$$

is equal to $\text{id}_{\text{Rel}(\text{pt}, A)}$.

$R: A \rightarrow B$ and $S: B \rightarrow C$, we have²⁶

$$(S \circ R)^{-1} = R^{-1} \circ S^{-1},$$

$$\begin{array}{ccc} \mathcal{P}(C) & \xrightarrow{S^{-1}} & \mathcal{P}(B) \\ & \searrow^{(S \circ R)^{-1}} & \downarrow R^{-1} \\ & & \mathcal{P}(A). \end{array}$$

Proof. Item 1, Functionality I: Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: This follows from *Item 5* of *Proposition 8.1.6.1.2*.

Item 4, Interaction With Composition: This follows from *Item 2* of *Proposition 8.1.6.1.2*. \square

00SW 6.4.4 Direct Images With Compact Support

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

00SX Definition 6.4.4.1.1. The **direct image with compact support function associated to R** is the function

$$R_! : \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by^{27,28}

$$\begin{aligned} R_!(U) &\stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ if we have} \\ b \in R(a), \text{ then } a \in U \end{array} \right\} \\ &= \{ b \in B \mid R^{-1}(b) \subset U \} \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

²⁶That is, we have

$$(S \circ R)^{-1} = R^{-1} \circ S^{-1},$$

$$\begin{array}{ccc} \text{Rel}(\text{pt}, C) & \xrightarrow{R^{-1}} & \text{Rel}(\text{pt}, B) \\ & \searrow^{(S \circ R)^{-1}} & \downarrow S^{-1} \\ & & \text{Rel}(\text{pt}, A). \end{array}$$

²⁷*Further Terminology:* The set $R_!(U)$ is called the **direct image with compact support of U by R** .

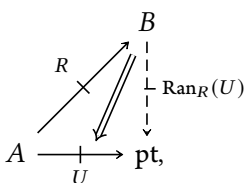
²⁸We also have

$$R_!(U) = B \setminus R_*(A \setminus U);$$

00SY Remark 6.4.4.1.2. Identifying subsets of B with relations from pt to B via **Item 3** of **Proposition 2.4.3.1.6**, we see that the direct image with compact support function associated to R is equivalently the function

$$R_! : \underbrace{\mathcal{P}(A)}_{\cong \text{Rel}(A, \text{pt})} \rightarrow \underbrace{\mathcal{P}(B)}_{\cong \text{Rel}(B, \text{pt})}$$

defined by

$$R_!(U) \stackrel{\text{def}}{=} \text{Ran}_R(U),$$


being explicitly computed by

$$\begin{aligned} R^*(U) &\stackrel{\text{def}}{=} \text{Ran}_R(U) \\ &\cong \int_{a \in A} \text{Hom}_{\{\text{t}, \text{f}\}}(R_a^{-2}, U_a^{-1}), \end{aligned}$$

where we have used **Proposition 6.2.3.1.1**.

see **Item 7** of **Proposition 6.4.4.1.3**.

Proof. We have

$$\begin{aligned}
\text{Ran}_R(V) &\cong \int_{a \in A} \text{Hom}_{\{t,f\}}(R_a^{-2}, U_a^{-1}) \\
&= \left\{ b \in B \mid \int_{a \in A} \text{Hom}_{\{t,f\}}(R_a^b, U_a^*) = \text{true} \right\} \\
&= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ at least one of the} \\ \text{following conditions hold:} \\ \\ 1. \text{ We have } R_a^b = \text{false} \\ 2. \text{ The following conditions hold:} \\ \\ \quad (a) \text{ We have } R_a^b = \text{true} \\ \quad (b) \text{ We have } U_a^* = \text{true} \end{array} \right\} \\
&= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ at least one of the} \\ \text{following conditions hold:} \\ \\ 1. \text{ We have } b \notin R(a) \\ 2. \text{ The following conditions hold:} \\ \\ \quad (a) \text{ We have } b \in R(a) \\ \quad (b) \text{ We have } a \in U \end{array} \right\} \\
&= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ if we have} \\ b \in R(a), \text{ then } a \in U \end{array} \right\} \\
&= \{ b \in B \mid R^{-1}(b) \subset U \} \\
&\stackrel{\text{def}}{=} R^{-1}(U).
\end{aligned}$$

This finishes the proof. \square

00SZ Proposition 6.4.4.1.3. Let $R: A \dashrightarrow B$ be a relation.

00T0 1. *Functoriality.* The assignment $U \mapsto R_!(U)$ defines a functor

$$R_!: (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

where

- *Action on Objects.* For each $U \in \mathcal{P}(A)$, we have

$$[R_!](U) \stackrel{\text{def}}{=} R_!(U).$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(A)$:

– If $U \subset V$, then $R_!(U) \subset R_!(V)$.

00T1 2. *Adjointness.* We have an adjunction

$$(R^{-1} \dashv R_!): \mathcal{P}(B) \begin{array}{c} \xrightarrow{R^{-1}} \\ \perp \\ \xleftarrow{R_!} \end{array} \mathcal{P}(A),$$

witnessed by a bijections of sets

$$\mathrm{Hom}_{\mathcal{P}(A)}(R^{-1}(U), V) \cong \mathrm{Hom}_{\mathcal{P}(A)}(U, R_!(V)),$$

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$, i.e. such that:

(★) The following conditions are equivalent:

- We have $R^{-1}(U) \subset V$.
- We have $U \subset R_!(V)$.

00T2 3. *Lax Preservation of Colimits.* We have an inclusion of sets

$$\bigcup_{i \in I} R_!(U_i) \subset R_!\left(\bigcup_{i \in I} U_i\right),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have inclusions

$$\begin{aligned} R_!(U) \cup R_!(V) &\subset R_!(U \cup V), \\ \emptyset &\subset R_!(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

00T3 4. *Preservation of Limits.* We have an equality of sets

$$R_!\left(\bigcap_{i \in I} U_i\right) = \bigcap_{i \in I} R_!(U_i),$$

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(A)^{\times I}$. In particular, we have equalities

$$\begin{aligned} R_!(U \cap V) &= R_!(U) \cap R_!(V), \\ R_!(A) &= B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

00T4 5. *Symmetric Lax Monoidality With Respect to Unions.* The direct image

with compact support function of **Item 1** has a symmetric lax monoidal structure

$$\left(R_!, R_!^\otimes, R_{! \perp}^\otimes \right): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with inclusions

$$\begin{aligned} R_{!|U,V}^\otimes &: R_!(U) \cup R_!(V) \subset R_!(U \cup V), \\ R_{! \perp}^\otimes &: \emptyset \subset R_!(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 00T5** 6. *Symmetric Strict Monoidality With Respect to Intersections.* The direct image function of **Item 1** has a symmetric strict monoidal structure

$$\left(R_!, R_!^\otimes, R_{! \perp}^\otimes \right): (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

$$\begin{aligned} R_{!|U,V}^\otimes &: R_!(U \cap V) \xrightarrow{=} R_!(U) \cap R_!(V), \\ R_{! \perp}^\otimes &: R_!(A) \xrightarrow{=} B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

- 00T6** 7. *Relation to Direct Images.* We have

$$R_!(U) = B \setminus R_*(A \setminus U)$$

for each $U \in \mathcal{P}(A)$.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness: This follows from ?? of ??.

Item 3, Lax Preservation of Colimits: Omitted.

Item 4, Preservation of Limits: This follows from **Item 2** and ?? of ??.

Item 5, Symmetric Lax Monoidality With Respect to Unions: This follows from **Item 3**.

Item 6, Symmetric Strict Monoidality With Respect to Intersections: This follows from **Item 4**.

Item 7, Relation to Direct Images: This follows from **Item 7** of **Proposition 6.4.1.1.3**.

Alternatively, we may prove it directly as follows, with the proof proceeding in the same way as in the case of functions (**Item 9** of **Proposition 2.4.6.1.6**).

We claim that $R_!(U) = B \setminus R_*(A \setminus U)$:

- *The First Implication.* We claim that

$$R_!(U) \subset B \setminus R_*(A \setminus U).$$

Let $b \in R_!(U)$. We need to show that $b \notin R_*(A \setminus U)$, i.e. that there is no $a \in A \setminus U$ such that $b \in R(a)$.

This is indeed the case, as otherwise we would have $a \in R^{-1}(b)$ and $a \notin U$, contradicting $R^{-1}(b) \subset U$ (which holds since $b \in R_!(U)$).

Thus $b \in B \setminus R_*(A \setminus U)$.

- *The Second Implication.* We claim that

$$B \setminus R_*(A \setminus U) \subset R_!(U).$$

Let $b \in B \setminus R_*(A \setminus U)$. We need to show that $b \in R_!(U)$, i.e. that $R^{-1}(b) \subset U$.

Since $b \notin R_*(A \setminus U)$, there exists no $a \in A \setminus U$ such that $b \in R(a)$, and hence $R^{-1}(b) \subset U$.

Thus $b \in R_!(U)$.

This finishes the proof. \square

00T7 Proposition 6.4.4.1.4. Let $R: A \rightarrow B$ be a relation.

00T8 1. *Functionality I.* The assignment $R \mapsto R_!$ defines a function

$$(-)_!: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

00T9 2. *Functionality II.* The assignment $R \mapsto R_!$ defines a function

$$(-)_!: \text{Sets}(A, B) \rightarrow \text{Hom}_{\text{Pos}}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

00TA 3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$(\text{id}_A)_! = \text{id}_{\mathcal{P}(A)}.$$

00TB 4. *Interaction With Composition.* For each pair of composable relations $R: A \rightarrow B$ and $S: B \rightarrow C$, we have

$$(S \circ R)_! = S_! \circ R_!,$$

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{R_!} & \mathcal{P}(B) \\ & \searrow (S \circ R)_! & \downarrow S_! \\ & & \mathcal{P}(C). \end{array}$$

Proof. Item 1, Functionality I: Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: Indeed, we have

$$\begin{aligned} (\chi_A)_!(U) &\stackrel{\text{def}}{=} \{a \in A \mid \chi_A^{-1}(a) \subset U\} \\ &\stackrel{\text{def}}{=} \{a \in A \mid \{a\} \subset U\} \\ &= U \end{aligned}$$

for each $U \in \mathcal{P}(A)$. Thus $(\chi_A)_! = \text{id}_{\mathcal{P}(A)}$.

Item 4, Interaction With Composition: Indeed, we have

$$\begin{aligned} (S \diamond R)_!(U) &\stackrel{\text{def}}{=} \{c \in C \mid [S \diamond R]^{-1}(c) \subset U\} \\ &\stackrel{\text{def}}{=} \{c \in C \mid S^{-1}(R^{-1}(c)) \subset U\} \\ &= \{c \in C \mid R^{-1}(c) \subset S_!(U)\} \\ &\stackrel{\text{def}}{=} R_!(S_!(U)) \\ &\stackrel{\text{def}}{=} [R_! \circ S_!](U) \end{aligned}$$

for each $U \in \mathcal{P}(C)$, where we used *Item 2* of [Proposition 6.4.4.1.3](#), which implies that the conditions

- We have $S^{-1}(R^{-1}(c)) \subset U$.
- We have $R^{-1}(c) \subset S_!(U)$.

are equivalent. Thus $(S \diamond R)_! = S_! \circ R_!$. □

00TC 6.4.5 Functoriality of Powersets

00TD **Proposition 6.4.5.1.1.** The assignment $X \mapsto \mathcal{P}(X)$ defines functors²⁹

$$\begin{aligned} \mathcal{P}_* &: \text{Rel} \rightarrow \text{Sets}, \\ \mathcal{P}_{-1} &: \text{Rel}^{\text{op}} \rightarrow \text{Sets}, \\ \mathcal{P}^{-1} &: \text{Rel}^{\text{op}} \rightarrow \text{Sets}, \\ \mathcal{P}_! &: \text{Rel} \rightarrow \text{Sets} \end{aligned}$$

where

- *Action on Objects.* For each $A \in \text{Obj}(\text{Rel})$, we have

$$\begin{aligned} \mathcal{P}_*(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}_{-1}(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}^{-1}(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}_!(A) &\stackrel{\text{def}}{=} \mathcal{P}(A). \end{aligned}$$

²⁹The functor $\mathcal{P}_* : \text{Rel} \rightarrow \text{Sets}$ admits a left adjoint; see *Item 3* of [Proposition 6.3.1.1.2](#).

- *Action on Morphisms.* For each morphism $R: A \rightarrow B$ of \mathbf{Rel} , the images

$$\begin{aligned}\mathcal{P}_*(R) &: \mathcal{P}(A) \rightarrow \mathcal{P}(B), \\ \mathcal{P}_{-1}(R) &: \mathcal{P}(B) \rightarrow \mathcal{P}(A), \\ \mathcal{P}^{-1}(R) &: \mathcal{P}(B) \rightarrow \mathcal{P}(A), \\ \mathcal{P}_! (R) &: \mathcal{P}(A) \rightarrow \mathcal{P}(B)\end{aligned}$$

of R by \mathcal{P}_* , \mathcal{P}_{-1} , \mathcal{P}^{-1} , and $\mathcal{P}_!$ are defined by

$$\begin{aligned}\mathcal{P}_*(R) &\stackrel{\text{def}}{=} R_*, \\ \mathcal{P}_{-1}(R) &\stackrel{\text{def}}{=} R_{-1}, \\ \mathcal{P}^{-1}(R) &\stackrel{\text{def}}{=} R^{-1}, \\ \mathcal{P}_!(R) &\stackrel{\text{def}}{=} R_!\end{aligned}$$

as in [Definitions 6.4.1.1.1](#), [6.4.2.1.1](#), [6.4.3.1.1](#) and [6.4.4.1.1](#).

Proof. This follows from [Items 3 and 4 of Proposition 6.4.1.1.4](#), [Items 3 and 4 of Proposition 6.4.2.1.4](#), [Items 3 and 4 of Proposition 6.4.3.1.4](#), and [Items 3 and 4 of Proposition 6.4.4.1.4](#). \square

6.4.6 Functoriality of Powersets: Relations on Powersets

00TE Let A and B be sets and let $R: A \rightarrow B$ be a relation.

00TF **Definition 6.4.6.1.1.** The **relation on powersets associated to R** is the relation

$$\mathcal{P}(R): \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by³⁰

$$\mathcal{P}(R)_U^V \stackrel{\text{def}}{=} \mathbf{Rel}(\chi_{\text{pt}}, V \diamond R \diamond U)$$

for each $U \in \mathcal{P}(A)$ and each $V \in \mathcal{P}(B)$.

00TG **Remark 6.4.6.1.2.** In detail, we have $U \sim_{\mathcal{P}(R)} V$ iff the following equivalent conditions hold:

- We have $\chi_{\text{pt}} \subset V \diamond R \diamond U$.
- We have $(V \diamond R \diamond U)_*^* = \text{true}$, i.e. we have

$$\int^{a \in A} \int^{b \in B} V_b^* \times R_a^b \times U_a^* = \text{true}.$$

³⁰Illustration:

$$\begin{array}{ccccccc} & & & \chi_{\text{pt}} & & & \\ & & & \downarrow & & & \\ \text{pt} & \xrightarrow{U} & A & \xrightarrow{R} & B & \xrightarrow{V} & \text{pt} \end{array}$$

- There exists some $a \in A$ and some $b \in B$ such that:
 - We have $U_{\star}^a = \text{true}$.
 - We have $R_a^b = \text{true}$.
 - We have $V_b^{\star} = \text{true}$.
- There exists some $a \in A$ and some $b \in B$ such that:
 - We have $a \in U$.
 - We have $a \sim_R b$.
 - We have $b \in V$.

00TH Proposition 6.4.6.1.3. The assignment $R \mapsto \mathcal{P}(R)$ defines a functor

$$\mathcal{P}: \text{Rel} \rightarrow \text{Rel}.$$

Proof. Omitted. □

Appendices

6.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets

Relations

5. Relations

6. Constructions With Relations

7. Equivalence Relations and Apartness Relations

Category Theory

8. Categories

Bicategories

9. Types of Morphisms in Bicategories
-

Chapter 7

Equivalence Relations and Apartness Relations

00TJ This chapter contains some material about reflexive, symmetric, transitive, equivalence, and apartness relations.

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00TK 7.1 Reflexive Relations**00TL 7.1.1 Foundations**

Let A be a set.

00TM Definition 7.1.1.1.1. A **reflexive relation** is equivalently:¹

- An \mathbb{E}_0 -monoid in $(\mathbf{N}_\bullet(\mathbf{Rel}(A, A)), \chi_A)$.
- A pointed object in $(\mathbf{Rel}(A, A), \chi_A)$.

00TN Remark 7.1.1.1.2. In detail, a relation R on A is **reflexive** if we have an inclusion

$$\eta_R: \chi_A \subset R$$

of relations in $\mathbf{Rel}(A, A)$, i.e. if, for each $a \in A$, we have $a \sim_R a$.

00TP Definition 7.1.1.1.3. Let A be a set.

1. The **set of reflexive relations on A** is the subset $\mathbf{Rel}^{\text{refl}}(A, A)$ of $\mathbf{Rel}(A, A)$ spanned by the reflexive relations.

00TQ

2. The **poset of relations on A** is the subposet $\mathbf{Rel}^{\text{refl}}(A, A)$ of $\mathbf{Rel}(A, A)$ spanned by the reflexive relations.

00TR

00TS Proposition 7.1.1.1.4. Let R and S be relations on A .

00TT 1. *Interaction With Inverses.* If R is reflexive, then so is R^\dagger .

00TU 2. *Interaction With Composition.* If R and S are reflexive, then so is $S \diamond R$.

Proof. Item 1, Interaction With Inverses: Clear.

Item 2, Interaction With Composition: Clear. □

00TV 7.1.2 The Reflexive Closure of a Relation

Let R be a relation on A .

00TW Definition 7.1.2.1.1. The **reflexive closure** of \sim_R is the relation \sim_R^{refl} satisfying the following universal property:³

- (★) Given another reflexive relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{refl}} \subset \sim_S$.

¹Note that since $\mathbf{Rel}(A, A)$ is posetal, reflexivity is a property of a relation, rather than extra structure.

²*Further Notation:* Also written R^{refl} .

³*Slogan:* The reflexive closure of R is the smallest reflexive relation containing R .

00TX Construction 7.1.2.1.2. Concretely, \sim_R^{refl} is the free pointed object on R in $(\mathbf{Rel}(A, A), \chi_A)$ ⁴, being given by

$$\begin{aligned} R^{\text{refl}} &\stackrel{\text{def}}{=} R \amalg \mathbf{Rel}(A, A) \Delta_A \\ &= R \cup \Delta_A \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } a = b\}. \end{aligned}$$

Proof. Clear. □

00TY Proposition 7.1.2.1.3. Let R be a relation on A .

00TZ 1. *Adjointness.* We have an adjunction

$$\left((-)^{\text{refl}} \dashv \overline{\text{忘}} \right): \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{refl}}} \\ \perp \\ \xleftarrow{\overline{\text{忘}}} \end{array} \mathbf{Rel}^{\text{refl}}(A, A),$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\text{refl}}(R^{\text{refl}}, S) \cong \mathbf{Rel}(R, S),$$

natural in $R \in \text{Obj}(\mathbf{Rel}^{\text{refl}}(A, A))$ and $S \in \text{Obj}(\mathbf{Rel}(A, A))$.

00U0 2. *The Reflexive Closure of a Reflexive Relation.* If R is reflexive, then $R^{\text{refl}} = R$.

00U1 3. *Idempotency.* We have

$$(R^{\text{refl}})^{\text{refl}} = R^{\text{refl}}.$$

00U2 4. *Interaction With Inverses.* We have

$$\left(R^\dagger \right)^{\text{refl}} = \left(R^{\text{refl}} \right)^\dagger, \quad \begin{array}{ccc} \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{refl}}} & \mathbf{Rel}(A, A) \\ (-)^\dagger \downarrow & & \downarrow (-)^\dagger \\ \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{refl}}} & \mathbf{Rel}(A, A). \end{array}$$

⁴Or, equivalently, the free \mathbb{E}_0 -monoid on R in $(\mathbf{N}_\bullet(\mathbf{Rel}(A, A)), \chi_A)$.

00U3 5. *Interaction With Composition.* We have

$$\begin{array}{ccc}
 \text{Rel}(A, A) \times \text{Rel}(A, A) & \xrightarrow{\diamond} & \text{Rel}(A, A) \\
 (S \diamond R)^{\text{refl}} = S^{\text{refl}} \diamond R^{\text{refl}}, & \begin{array}{c} \downarrow (-)^{\text{refl}} \times (-)^{\text{refl}} \\ \text{Rel}(A, A) \times \text{Rel}(A, A) \end{array} & \begin{array}{c} \downarrow (-)^{\text{refl}} \\ \text{Rel}(A, A) \end{array} \\
 & \xrightarrow{\diamond} & \text{Rel}(A, A)
 \end{array}$$

Proof. Item 1, Adjointness: This is a rephrasing of the universal property of the reflexive closure of a relation, stated in **Definition 7.1.2.1.1**.

Item 2, The Reflexive Closure of a Reflexive Relation: Clear.

Item 3, Idempotency: This follows from **Item 2**.

Item 4, Interaction With Inverses: Clear.

Item 5, Interaction With Composition: This follows from **Item 2** of **Proposition 7.1.1.1.4**. \square

00U4 7.2 Symmetric Relations

00U5 7.2.1 Foundations

Let A be a set.

00U6 **Definition 7.2.1.1.1.** A relation R on A is **symmetric** if we have $R^\dagger = R$.

00U7 **Remark 7.2.1.1.2.** In detail, a relation R is symmetric if it satisfies the following condition:

(\star) For each $a, b \in A$, if $a \sim_R b$, then $b \sim_R a$.

00U8 **Definition 7.2.1.1.3.** Let A be a set.

00U9 1. The **set of symmetric relations on A** is the subset $\text{Rel}^{\text{symm}}(A, A)$ of $\text{Rel}(A, A)$ spanned by the symmetric relations.

00UA 2. The **poset of relations on A** is the subposet $\mathbf{Rel}^{\text{symm}}(A, A)$ of $\mathbf{Rel}(A, A)$ spanned by the symmetric relations.

00UB **Proposition 7.2.1.1.4.** Let R and S be relations on A .

00UC 1. *Interaction With Inverses.* If R is symmetric, then so is R^\dagger .

00UD 2. *Interaction With Composition.* If R and S are symmetric, then so is $S \diamond R$.

Proof. Item 1, Interaction With Inverses: Clear.

Item 2, Interaction With Composition: Clear. \square

00UE 7.2.2 The Symmetric Closure of a Relation

Let R be a relation on A .

00UF Definition 7.2.2.1.1. The **symmetric closure** of \sim_R is the relation \sim_R^{symm} ⁵ satisfying the following universal property:⁶

(★) Given another symmetric relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{symm}} \subset \sim_S$.

00UG Construction 7.2.2.1.2. Concretely, \sim_R^{symm} is the symmetric relation on A defined by

$$\begin{aligned} R^{\text{symm}} &\stackrel{\text{def}}{=} R \cup R^\dagger \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } b \sim_R a\}. \end{aligned}$$

Proof. Clear. □

00UH Proposition 7.2.2.1.3. Let R be a relation on A .

00UJ 1. *Adjointness.* We have an adjunction

$$\left((-)^{\text{symm}} \dashv \overline{} \right): \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{symm}}} \\ \perp \\ \xleftarrow{\overline{}} \end{array} \mathbf{Rel}^{\text{symm}}(A, A),$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\text{symm}}(R^{\text{symm}}, S) \cong \mathbf{Rel}(R, S),$$

natural in $R \in \text{Obj}(\mathbf{Rel}^{\text{symm}}(A, A))$ and $S \in \text{Obj}(\mathbf{Rel}(A, A))$.

00UK 2. *The Symmetric Closure of a Symmetric Relation.* If R is symmetric, then $R^{\text{symm}} = R$.

00UL 3. *Idempotency.* We have

$$(R^{\text{symm}})^{\text{symm}} = R^{\text{symm}}.$$

00UM 4. *Interaction With Inverses.* We have

$$\left(R^\dagger \right)^{\text{symm}} = \left(R^{\text{symm}} \right)^\dagger, \quad \begin{array}{ccc} \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{symm}}} & \mathbf{Rel}(A, A) \\ (-)^\dagger \downarrow & & \downarrow (-)^\dagger \\ \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{symm}}} & \mathbf{Rel}(A, A). \end{array}$$

⁵Further Notation: Also written R^{symm} .

⁶Slogan: The symmetric closure of R is the smallest symmetric relation containing R .

00UN 5. *Interaction With Composition.* We have

$$\begin{array}{ccc}
 \text{Rel}(A, A) \times \text{Rel}(A, A) & \xrightarrow{\diamond} & \text{Rel}(A, A) \\
 (S \diamond R)^{\text{symm}} = S^{\text{symm}} \diamond R^{\text{symm}}, & \begin{array}{c} \downarrow (-)^{\text{symm}} \times (-)^{\text{symm}} \\ \text{Rel}(A, A) \times \text{Rel}(A, A) \end{array} & \begin{array}{c} \downarrow (-)^{\text{symm}} \\ \text{Rel}(A, A) \end{array} \\
 & & \xrightarrow{\diamond} \text{Rel}(A, A).
 \end{array}$$

Proof. **Item 1, Adjointness:** This is a rephrasing of the universal property of the symmetric closure of a relation, stated in **Definition 7.2.2.1.1**.

Item 2, The Symmetric Closure of a Symmetric Relation: Clear.

Item 3, Idempotency: This follows from **Item 2**.

Item 4, Interaction With Inverses: Clear.

Item 5, Interaction With Composition: This follows from **Item 2** of **Proposition 7.2.1.1.4**. \square

00UP 7.3 Transitive Relations

00UQ 7.3.1 Foundations

Let A be a set.

00UR **Definition 7.3.1.1.1.** A **transitive relation** is equivalently:⁷

- A non-unital \mathbb{E}_1 -monoid in $(\mathbf{N}_\bullet(\mathbf{Rel}(A, A)), \diamond)$.
- A non-unital monoid in $(\mathbf{Rel}(A, A), \diamond)$.

00US **Remark 7.3.1.1.2.** In detail, a relation R on A is **transitive** if we have an inclusion

$$\mu_R: R \diamond R \subset R$$

of relations in $\mathbf{Rel}(A, A)$, i.e. if, for each $a, c \in A$, the following condition is satisfied:

- (\star) If there exists some $b \in A$ such that $a \sim_R b$ and $b \sim_R c$, then $a \sim_R c$.

00UT **Definition 7.3.1.1.3.** Let A be a set.

1. The **set of transitive relations from A to B** is the subset $\mathbf{Rel}^{\text{trans}}(A)$ of $\mathbf{Rel}(A, A)$ spanned by the transitive relations.

⁷Note that since $\mathbf{Rel}(A, A)$ is posetal, transitivity is a property of a relation, rather than extra structure.

00UV 2. The **poset of relations from A to B** is the subposet $\mathbf{Rel}^{\text{trans}}(A)$ of $\mathbf{Rel}(A, A)$ spanned by the transitive relations.

00UW **Proposition 7.3.1.1.4.** Let R and S be relations on A .

00UX 1. *Interaction With Inverses.* If R is transitive, then so is R^\dagger .

00UY 2. *Interaction With Composition.* If R and S are transitive, then $S \diamond R$ **may fail to be transitive.**

Proof. **Item 1, Interaction With Inverses:** Clear.

Item 2, Interaction With Composition: See [MSE 2096272].⁸ \square

00UZ 7.3.2 The Transitive Closure of a Relation

Let R be a relation on A .

00V0 **Definition 7.3.2.1.1.** The **transitive closure** of \sim_R is the relation \sim_R^{trans} ⁹ satisfying the following universal property:¹⁰

(\star) Given another transitive relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{trans}} \subset \sim_S$.

00V1 **Construction 7.3.2.1.2.** Concretely, \sim_R^{trans} is the free non-unital monoid on R in $(\mathbf{Rel}(A, A), \diamond)$ ¹¹, being given by

$$\begin{aligned} R^{\text{trans}} &\stackrel{\text{def}}{=} \prod_{n=1}^{\infty} R^{\diamond n} \\ &\stackrel{\text{def}}{=} \bigcup_{n=1}^{\infty} R^{\diamond n} \\ &\stackrel{\text{def}}{=} \left\{ (a, b) \in A \times B \mid \begin{array}{l} \text{there exists some } (x_1, \dots, x_n) \in R^{\times n} \\ \text{such that } a \sim_R x_1 \sim_R \dots \sim_R x_n \sim_R b \end{array} \right\}. \end{aligned}$$

⁸*Intuition:* Transitivity for R and S fails to imply that of $S \diamond R$ because the composition operation for relations intertwines R and S in an incompatible way:

1. If $a \sim_{S \diamond R} c$ and $c \sim_{S \diamond R} e$, then:

(a) There is some $b \in A$ such that:

- i. $a \sim_R b$;
- ii. $b \sim_S c$;

(b) There is some $d \in A$ such that:

- i. $c \sim_R d$;
- ii. $d \sim_S e$.

⁹*Further Notation:* Also written R^{trans} .

¹⁰*Slogan:* The transitive closure of R is the smallest transitive relation containing R .

¹¹Or, equivalently, the free non-unital \mathbb{E}_1 -monoid on R in $(\mathbf{N}_\bullet(\mathbf{Rel}(A, A)), \diamond)$.

Proof. Clear. □

00V2 Proposition 7.3.2.1.3. Let R be a relation on A .

00V3 1. *Adjointness.* We have an adjunction

$$((-)^{\text{trans}} \dashv \overline{}) : \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{trans}}} \\ \perp \\ \xleftarrow{\overline{}} \end{array} \mathbf{Rel}^{\text{trans}}(A, A),$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\text{trans}}(R^{\text{trans}}, S) \cong \mathbf{Rel}(R, S),$$

natural in $R \in \text{Obj}(\mathbf{Rel}^{\text{trans}}(A, A))$ and $S \in \text{Obj}(\mathbf{Rel}(A, B))$.

00V4 2. *The Transitive Closure of a Transitive Relation.* If R is transitive, then $R^{\text{trans}} = R$.

00V5 3. *Idempotency.* We have

$$(R^{\text{trans}})^{\text{trans}} = R^{\text{trans}}.$$

00V6 4. *Interaction With Inverses.* We have

$$(R^\dagger)^{\text{trans}} = (R^{\text{trans}})^\dagger, \quad \begin{array}{ccc} \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{trans}}} & \mathbf{Rel}(A, A) \\ (-)^\dagger \downarrow & & \downarrow (-)^\dagger \\ \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{trans}}} & \mathbf{Rel}(A, A). \end{array}$$

00V7 5. *Interaction With Composition.* We have

$$(S \diamond R)^{\text{trans}} \stackrel{\text{poss.}}{\neq} S^{\text{trans}} \diamond R^{\text{trans}}, \quad \begin{array}{ccc} \mathbf{Rel}(A, A) \times \mathbf{Rel}(A, A) & \xrightarrow{\diamond} & \mathbf{Rel}(A, A) \\ (-)^{\text{trans}} \times (-)^{\text{trans}} \downarrow & \color{red}{\times} & \downarrow (-)^{\text{trans}} \\ \mathbf{Rel}(A, A) \times \mathbf{Rel}(A, A) & \xrightarrow{\diamond} & \mathbf{Rel}(A, A). \end{array}$$

Proof. Item 1, Adjointness: This is a rephrasing of the universal property of the transitive closure of a relation, stated in **Definition 7.3.2.1.1**.

Item 2, The Transitive Closure of a Transitive Relation: Clear.

Item 3, Idempotency: This follows from **Item 2**.

Item 4, Interaction With Inverses: We have

$$\begin{aligned} (R^\dagger)^{\text{trans}} &= \bigcup_{n=1}^{\infty} (R^\dagger)^{\diamond n} \\ &= \bigcup_{n=1}^{\infty} (R^{\diamond n})^\dagger \\ &= \left(\bigcup_{n=1}^{\infty} R^{\diamond n} \right)^\dagger \\ &= (R^{\text{trans}})^\dagger, \end{aligned}$$

where we have used, respectively:

1. **Construction 7.3.2.1.2.**
2. **Item 4 of Proposition 6.3.12.1.3.**
3. **Item 1 of Proposition 6.3.6.1.2.**
4. **Construction 7.3.2.1.2.**

Item 5, Interaction With Composition: This follows from **Item 2 of Proposition 7.3.1.1.4.** \square

00V8 7.4 Equivalence Relations

00V9 7.4.1 Foundations

Let A be a set.

00VA Definition 7.4.1.1.1. A relation R is an **equivalence relation** if it is reflexive, symmetric, and transitive.¹²

00VB Example 7.4.1.1.2. The **kernel of a function** $f: A \rightarrow B$ is the equivalence relation $\sim_{\text{Ker}(f)}$ on A obtained by declaring $a \sim_{\text{Ker}(f)} b$ iff $f(a) = f(b)$.¹³

00VC Definition 7.4.1.1.3. Let A and B be sets.

1. The **set of equivalence relations from A to B** is the subset $\text{Rel}^{\text{eq}}(A, B)$ of $\text{Rel}(A, B)$ spanned by the equivalence relations.
2. The **poset of relations from A to B** is the subposet $\mathbf{Rel}^{\text{eq}}(A, B)$ of $\mathbf{Rel}(A, B)$ spanned by the equivalence relations.

00VE

¹²*Further Terminology:* If instead R is just symmetric and transitive, then it is called a **partial equivalence relation**.

¹³The kernel $\text{Ker}(f): A \rightarrow A$ of f is the underlying functor of the monad induced by the

00VF 7.4.2 The Equivalence Closure of a Relation

Let R be a relation on A .

00VG Definition 7.4.2.1.1. The **equivalence closure**¹⁴ of \sim_R is the relation \sim_R^{eq} ¹⁵ satisfying the following universal property:¹⁶

(★) Given another equivalence relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{eq}} \subset \sim_S$.

00VH Construction 7.4.2.1.2. Concretely, \sim_R^{eq} is the equivalence relation on A defined by

$$\begin{aligned}
 R^{\text{eq}} &\stackrel{\text{def}}{=} \left(\left(R^{\text{refl}} \right)^{\text{symm}} \right)^{\text{trans}} \\
 &= \left(\left(R^{\text{symm}} \right)^{\text{trans}} \right)^{\text{refl}} \\
 &= \left\{ (a, b) \in A \times B \mid \left. \begin{array}{l} \text{there exists } (x_1, \dots, x_n) \in R^{\times n} \text{ satisfying at} \\ \text{least one of the following conditions:} \\ \\ \text{1. The following conditions are satisfied:} \\ \\ \text{(a) We have } a \sim_R x_1 \text{ or } x_1 \sim_R a; \\ \text{(b) We have } x_i \sim_R x_{i+1} \text{ or } x_{i+1} \sim_R x_i \\ \text{for each } 1 \leq i \leq n-1; \\ \text{(c) We have } b \sim_R x_n \text{ or } x_n \sim_R b; \\ \\ \text{2. We have } a = b. \end{array} \right\} \right.
 \end{aligned}$$

Proof. From the universal properties of the reflexive, symmetric, and transitive closures of a relation (Definitions 7.1.2.1.1, 7.2.2.1.1 and 7.3.2.1.1), we see that it suffices to prove that:

00VJ 1. The symmetric closure of a reflexive relation is still reflexive.

00VK 2. The transitive closure of a symmetric relation is still symmetric.

which are both clear. □

00VL Proposition 7.4.2.1.3. Let R be a relation on A .

adjunction $\text{Gr}(f) \dashv f^{-1} : A \rightleftarrows B$ in **Rel** of **Item 2** of **Proposition 6.3.1.1.2**.

¹⁴*Further Terminology:* Also called the **equivalence relation associated to** \sim_R .

¹⁵*Further Notation:* Also written R^{eq} .

¹⁶*Slogan:* The equivalence closure of R is the smallest equivalence relation containing R .

00VM 1. *Adjointness.* We have an adjunction

$$((-)^{\text{eq}} \dashv \overline{\text{eq}}): \mathbf{Rel}(A, B) \begin{array}{c} \xrightarrow{(-)^{\text{eq}}} \\ \perp \\ \xleftarrow{\overline{\text{eq}}} \end{array} \mathbf{Rel}^{\text{eq}}(A, B),$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\text{eq}}(R^{\text{eq}}, S) \cong \mathbf{Rel}(R, S),$$

natural in $R \in \text{Obj}(\mathbf{Rel}^{\text{eq}}(A, B))$ and $S \in \text{Obj}(\mathbf{Rel}(A, B))$.

00VN 2. *The Equivalence Closure of an Equivalence Relation.* If R is an equivalence relation, then $R^{\text{eq}} = R$.

00VP 3. *Idempotency.* We have

$$(R^{\text{eq}})^{\text{eq}} = R^{\text{eq}}.$$

Proof. **Item 1, Adjointness:** This is a rephrasing of the universal property of the equivalence closure of a relation, stated in **Definition 7.4.2.1.1**.

Item 2, The Equivalence Closure of an Equivalence Relation: Clear.

Item 3, Idempotency: This follows from **Item 2**. \square

00VQ 7.5 Quotients by Equivalence Relations

00VR 7.5.1 Equivalence Classes

Let A be a set, let R be a relation on A , and let $a \in A$.

00VS **Definition 7.5.1.1.1.** The **equivalence class associated to a** is the set $[a]$ defined by

$$\begin{aligned} [a] &\stackrel{\text{def}}{=} \{x \in X \mid x \sim_R a\} \\ &= \{x \in X \mid a \sim_R x\}. \end{aligned} \quad (\text{since } R \text{ is symmetric})$$

00VT 7.5.2 Quotients of Sets by Equivalence Relations

Let A be a set and let R be a relation on A .

00VU **Definition 7.5.2.1.1.** The **quotient of X by R** is the set X/\sim_R defined by

$$X/\sim_R \stackrel{\text{def}}{=} \{[a] \in \mathcal{P}(X) \mid a \in X\}.$$

00VV Remark 7.5.2.1.2. The reason we define quotient sets for equivalence relations only is that each of the properties of being an equivalence relation—reflexivity, symmetry, and transitivity—ensures that the equivalence classes $[a]$ of X under R are well-behaved:

- *Reflexivity.* If R is reflexive, then, for each $a \in X$, we have $a \in [a]$.
- *Symmetry.* The equivalence class $[a]$ of an element a of X is defined by

$$[a] \stackrel{\text{def}}{=} \{x \in X \mid x \sim_R a\},$$

but we could equally well define

$$[a]' \stackrel{\text{def}}{=} \{x \in X \mid a \sim_R x\}$$

instead. This is not a problem when R is symmetric, as we then have $[a] = [a]'$.¹⁷

- *Transitivity.* If R is transitive, then $[a]$ and $[b]$ are disjoint iff $a \not\sim_R b$, and equal otherwise.

00VV Proposition 7.5.2.1.3. Let $f : X \rightarrow Y$ be a function and let R be a relation on X .

00VX 1. *As a Coequaliser.* We have an isomorphism of sets

$$X/\sim_R^{\text{eq}} \cong \text{CoEq}\left(R \hookrightarrow X \times X \begin{array}{c} \xrightarrow{\text{pr}_1} \\ \xrightarrow{\text{pr}_2} \end{array} X\right),$$

where \sim_R^{eq} is the equivalence relation generated by \sim_R .

00VY 2. *As a Pushout.* We have an isomorphism of sets¹⁸

$$X/\sim_R^{\text{eq}} \cong X \amalg_{\text{Eq}(\text{pr}_1, \text{pr}_2)} X, \quad \begin{array}{ccc} X/\sim_R^{\text{eq}} & \longleftarrow & X \\ \uparrow & \lrcorner & \uparrow \\ X & \longleftarrow & \text{Eq}(\text{pr}_1, \text{pr}_2) \end{array}$$

¹⁷When categorifying equivalence relations, one finds that $[a]$ and $[a]'$ correspond to presheaves and copresheaves; see ??.

¹⁸Dually, we also have an isomorphism of sets

$$\text{Eq}(\text{pr}_1, \text{pr}_2) \cong X \times_{X/\sim_R^{\text{eq}}} X, \quad \begin{array}{ccc} \text{Eq}(\text{pr}_1, \text{pr}_2) & \longrightarrow & X \\ \downarrow & \lrcorner & \downarrow \\ X & \longrightarrow & X/\sim_R^{\text{eq}} \end{array}$$

where \sim_R^{eq} is the equivalence relation generated by \sim_R .

- 00VZ 3. *The First Isomorphism Theorem for Sets.* We have an isomorphism of sets^{19,20}

$$X/\sim_{\text{Ker}(f)} \cong \text{Im}(f).$$

- 00W0 4. *Descending Functions to Quotient Sets, I.* Let R be an equivalence relation on X . The following conditions are equivalent:

(a) There exists a map

$$\bar{f}: X/\sim_R \rightarrow Y$$

making the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \downarrow q & \searrow \bar{f} & \uparrow \\ X/\sim_R & & \end{array}$$

commute.

(b) We have $R \subset \text{Ker}(f)$.

(c) For each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$.

- 00W1 5. *Descending Functions to Quotient Sets, II.* Let R be an equivalence relation on X . If the conditions of **Item 4** hold, then \bar{f} is the *unique* map making the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \downarrow q & \searrow \bar{f} & \uparrow \\ X/\sim_R & & \end{array}$$

¹⁹*Further Terminology:* The set $X/\sim_{\text{Ker}(f)}$ is often called the **coimage** of f , and denoted by $\text{Coim}(f)$.

²⁰In a sense this is a result relating the monad in **Rel** induced by f with the comonad in **Rel** induced by f , as the kernel and image

$$\begin{aligned} \text{Ker}(f) &: X \rightarrow X, \\ \text{Im}(f) &\subset Y \end{aligned}$$

of f are the underlying functors of (respectively) the induced monad and comonad of the

commute.

- 00W2 6. *Descending Functions to Quotient Sets, III.* Let R be an equivalence relation on X . We have a bijection

$$\text{Hom}_{\text{Sets}}(X/\sim_R, Y) \cong \text{Hom}_{\text{Sets}}^R(X, Y),$$

natural in $X, Y \in \text{Obj}(\text{Sets})$, given by the assignment $f \mapsto \bar{f}$ of **Items 4 and 5**, where $\text{Hom}_{\text{Sets}}^R(X, Y)$ is the set defined by

$$\text{Hom}_{\text{Sets}}^R(X, Y) \stackrel{\text{def}}{=} \left\{ f \in \text{Hom}_{\text{Sets}}(X, Y) \left| \begin{array}{l} \text{for each } x, y \in X, \\ \text{if } x \sim_R y, \text{ then} \\ f(x) = f(y) \end{array} \right. \right\}.$$

- 00W3 7. *Descending Functions to Quotient Sets, IV.* Let R be an equivalence relation on X . If the conditions of **Item 4** hold, then the following conditions are equivalent:

- (a) The map \bar{f} is an injection.
- (b) We have $R = \text{Ker}(f)$.
- (c) For each $x, y \in X$, we have $x \sim_R y$ iff $f(x) = f(y)$.

- 00W4 8. *Descending Functions to Quotient Sets, V.* Let R be an equivalence relation on X . If the conditions of **Item 4** hold, then the following conditions are equivalent:

- (a) The map $f: X \rightarrow Y$ is surjective.
- (b) The map $\bar{f}: X/\sim_R \rightarrow Y$ is surjective.

- 00W5 9. *Descending Functions to Quotient Sets, VI.* Let R be a relation on X and let \sim_R^{eq} be the equivalence relation associated to R . The following conditions are equivalent:

- 00W6 (a) The map f satisfies the equivalent conditions of **Item 4**:
- There exists a map

$$\bar{f}: X/\sim_R^{\text{eq}} \rightarrow Y$$

adjunction

$$(\text{Gr}(f) \dashv f^{-1}): \begin{array}{ccc} & \text{Gr}(f) & \\ & \uparrow & \\ (\text{Gr}(f) \dashv f^{-1}): & A & \xrightarrow{\quad} B \\ & \downarrow & \\ & f^{-1} & \end{array}$$

making the diagram

$$\begin{array}{ccc}
 X & \xrightarrow{f} & Y \\
 q \downarrow & \exists \nearrow \bar{f} & \\
 X/\sim_R^{\text{eq}} & &
 \end{array}$$

commute.

- For each $x, y \in X$, if $x \sim_R^{\text{eq}} y$, then $f(x) = f(y)$.

00W7 (b) For each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$.

Proof. **Item 1**, As a Coequaliser: Omitted.

Item 2, As a Pushout: Omitted.

Item 3, The First Isomorphism Theorem for Sets: Clear.

Item 4, Descending Functions to Quotient Sets, I: See [Pro24o].

Item 5, Descending Functions to Quotient Sets, II: See [Pro24aa].

Item 6, Descending Functions to Quotient Sets, III: This follows from **Items 5** and **6**.

Item 7, Descending Functions to Quotient Sets, IV: See [Pro24n].

Item 8, Descending Functions to Quotient Sets, V: See [Pro24m].

Item 9, Descending Functions to Quotient Sets, VI: The implication **Item 9a** \implies **Item 9b** is clear.

Conversely, suppose that, for each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$. Spelling out the definition of the equivalence closure of R , we see that the condition $x \sim_R^{\text{eq}} y$ unwinds to the following:

(★) There exist $(x_1, \dots, x_n) \in R^{\times n}$ satisfying at least one of the following conditions:

1. The following conditions are satisfied:
 - (a) We have $x \sim_R x_1$ or $x_1 \sim_R x$;
 - (b) We have $x_i \sim_R x_{i+1}$ or $x_{i+1} \sim_R x_i$ for each $1 \leq i \leq n-1$;
 - (c) We have $y \sim_R x_n$ or $x_n \sim_R y$;
2. We have $x = y$.

of **Item 2** of **Proposition 6.3.1.1.2**.

Now, if $x = y$, then $f(x) = f(y)$ trivially; otherwise, we have

$$\begin{aligned} f(x) &= f(x_1), \\ f(x_1) &= f(x_2), \\ &\vdots \\ f(x_{n-1}) &= f(x_n), \\ f(x_n) &= f(y), \end{aligned}$$

and $f(x) = f(y)$, as we wanted to show. \square

Appendices

7.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets

Relations

5. Relations

6. Constructions With Relations

7. Equivalence Relations and Apartness Relations

Category Theory

8. Categories

Bicategories

9. Types of Morphisms in Bicategories

Part III

Category Theory

Chapter 8

Categories

00W8 This chapter contains some elementary material about categories, functors, and natural transformations. Notably, we discuss and explore:

1. Categories ([Section 8.1](#)).
2. The quadruple adjunction $\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}$ between the category of categories and the category of sets ([Section 8.2](#)).
3. Groupoids, categories in which all morphisms admit inverses ([Section 8.3](#)).
4. Functors ([Section 8.4](#)).
5. The conditions one may impose on functors in decreasing order of importance:
 - (a) [Section 8.5](#) introduces the foundationally important conditions one may impose on functors, such as faithfulness, conservativity, essential surjectivity, etc.
 - (b) [Section 8.6](#) introduces more conditions one may impose on functors that are still important but less omni-present than those of [Section 8.5](#), such as being dominant, being a monomorphism, being pseudomononic, etc.
 - (c) [Section 8.7](#) introduces some rather rare or uncommon conditions one may impose on functors that are nevertheless still useful to explicit record in this chapter.
6. Natural transformations ([Section 8.8](#)).
7. The various categorical and 2-categorical structures formed by categories, functors, and natural transformations ([Section 8.9](#)).

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00W9 8.1 Categories

00WA 8.1.1 Foundations

00WB **Definition 8.1.1.1.1.** A category $(C, \circ^C, 1^C)$ consists of:

- *Objects.* A class $\text{Obj}(C)$ of **objects**.
- *Morphisms.* For each $A, B \in \text{Obj}(C)$, a class $\text{Hom}_C(A, B)$, called the **class of morphisms of C from A to B** .
- *Identities.* For each $A \in \text{Obj}(C)$, a map of sets

$$\mathbb{1}_A^C : \text{pt} \rightarrow \text{Hom}_C(A, A),$$

called the **unit map of C at A** , determining a morphism

$$\text{id}_A : A \rightarrow A$$

of C , called the **identity morphism of A** .

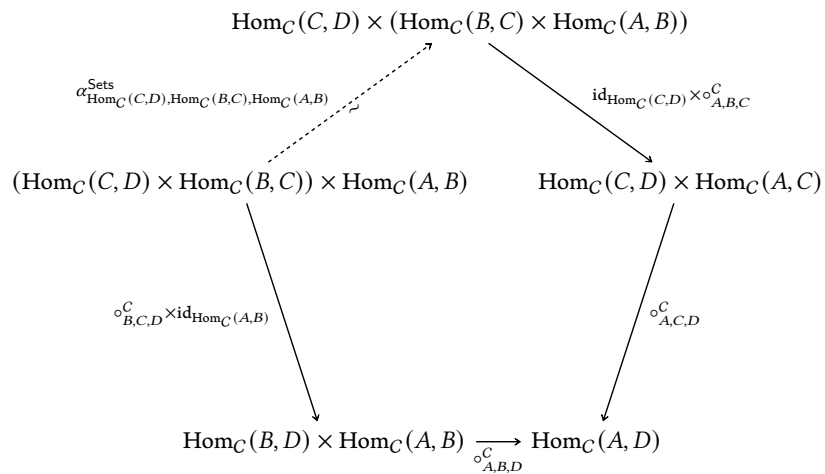
- *Composition.* For each $A, B, C \in \text{Obj}(C)$, a map of sets

$$\circ_{A,B,C}^C : \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) \rightarrow \text{Hom}_C(A, C),$$

called the **composition map of C at (A, B, C)** .

such that the following conditions are satisfied:

1. *Associativity.* The diagram



commutes, i.e. for each composable triple (f, g, h) of morphisms of C , we have

$$(f \circ g) \circ h = f \circ (g \circ h).$$

2. *Left Unitality.* The diagram

$$\begin{array}{ccc}
 \text{pt} \times \text{Hom}_C(A, B) & & \\
 \downarrow \mathbb{1}_B^C \times \text{id}_{\text{Hom}_C(A, B)} & \searrow \lambda_{\text{Hom}_C(A, B)}^{\text{Sets}} & \\
 \text{Hom}_C(B, B) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A, B, B}^C} & \text{Hom}_C(A, B)
 \end{array}$$

commutes, i.e. for each morphism $f : A \rightarrow B$ of C , we have

$$\text{id}_B \circ f = f.$$

3. *Right Unitality.* The diagram

$$\begin{array}{ccc}
 \text{Hom}_C(A, B) \times \text{pt} & & \\
 \downarrow \text{id}_{\text{Hom}_C(A, B)} \times \mathbb{1}_A^C & \searrow \rho_{\text{Hom}_C(A, B)}^{\text{Sets}} & \\
 \text{Hom}_C(A, B) \times \text{Hom}_C(A, A) & \xrightarrow{\circ_{A, A, B}^C} & \text{Hom}_C(A, B)
 \end{array}$$

commutes, i.e. for each morphism $f : A \rightarrow B$ of C , we have

$$f \circ \text{id}_A = f.$$

00WC **Notation 8.1.1.1.2.** Let C be a category.

00WD 1. We also write $C(A, B)$ for $\text{Hom}_C(A, B)$.

00WE 2. We write $\text{Mor}(C)$ for the class of all morphisms of C .

00WF **Definition 8.1.1.1.3.** Let κ be a regular cardinal. A category C is

00WG 1. **Locally small** if, for each $A, B \in \text{Obj}(C)$, the class $\text{Hom}_C(A, B)$ is a set.

00WH 2. **Locally essentially small** if, for each $A, B \in \text{Obj}(C)$, the class

$$\text{Hom}_C(A, B) / \{\text{isomorphisms}\}$$

is a set.

00WJ 3. **Small** if C is locally small and $\text{Obj}(C)$ is a set.

00WK 4. **κ -Small** if C is locally small, $\text{Obj}(C)$ is a set, and we have $\#\text{Obj}(C) < \kappa$.

00WL 8.1.2 Examples of Categories

00WM Example 8.1.2.1.1. The **punctual category**¹ is the category pt where

- *Objects.* We have

$$\text{Obj}(\text{pt}) \stackrel{\text{def}}{=} \{\star\}.$$

- *Morphisms.* The unique Hom-set of pt is defined by

$$\text{Hom}_{\text{pt}}(\star, \star) \stackrel{\text{def}}{=} \{\text{id}_{\star}\}.$$

- *Identities.* The unit map

$$\mathbb{1}_{\star}^{\text{pt}} : \text{pt} \rightarrow \text{Hom}_{\text{pt}}(\star, \star)$$

of pt at \star is defined by

$$\text{id}_{\star}^{\text{pt}} \stackrel{\text{def}}{=} \text{id}_{\star}.$$

- *Composition.* The composition map

$$\circ_{\star, \star, \star}^{\text{pt}} : \text{Hom}_{\text{pt}}(\star, \star) \times \text{Hom}_{\text{pt}}(\star, \star) \rightarrow \text{Hom}_{\text{pt}}(\star, \star)$$

of pt at (\star, \star, \star) is given by the bijection $\text{pt} \times \text{pt} \cong \text{pt}$.

00WN Example 8.1.2.1.2. We have an isomorphism of categories²

$$\text{Mon} \cong \text{pt} \times_{\text{Sets}} \text{Cats}, \quad \begin{array}{ccc} \text{Mon} & \longrightarrow & \text{Cats} \\ \downarrow \lrcorner & & \downarrow \text{Obj} \\ \text{pt} & \xrightarrow{[\text{pt}]} & \text{Sets} \end{array}$$

via the delooping functor $B : \text{Mon} \rightarrow \text{Cats}$ of ?? of ??, exhibiting monoids as exactly those categories having a single object.

¹Further Terminology: Also called the **singleton category**.

²This can be enhanced to an isomorphism of 2-categories

$$\text{Mon}_{2\text{disc}} \cong \text{pt}_{\text{bi}} \times_{\text{Sets}_{2\text{disc}}} \text{Cats}_{2,*}, \quad \begin{array}{ccc} \text{Mon}_{2\text{disc}} & \longrightarrow & \text{Cats}_{2,*} \\ \downarrow \lrcorner & & \downarrow \text{Obj} \\ \text{pt}_{\text{bi}} & \xrightarrow{[\text{pt}]} & \text{Sets}_{2\text{disc}} \end{array}$$

Proof. Omitted. □

00WP Example 8.1.2.1.3. The **empty category** is the category \emptyset_{cat} where

- *Objects.* We have

$$\text{Obj}(\emptyset_{\text{cat}}) \stackrel{\text{def}}{=} \emptyset.$$

- *Morphisms.* We have

$$\text{Mor}(\emptyset_{\text{cat}}) \stackrel{\text{def}}{=} \emptyset.$$

- *Identities and Composition.* Having no objects, \emptyset_{cat} has no unit nor composition maps.

00WQ Example 8.1.2.1.4. The **n th ordinal category** is the category \mathfrak{n} where³

- *Objects.* We have

$$\text{Obj}(\mathfrak{n}) \stackrel{\text{def}}{=} \{[0], \dots, [n]\}.$$

- *Morphisms.* For each $[i], [j] \in \text{Obj}(\mathfrak{n})$, we have

$$\text{Hom}_{\mathfrak{n}}([i], [j]) \stackrel{\text{def}}{=} \begin{cases} \{\text{id}_{[i]}\} & \text{if } [i] = [j], \\ \{[i] \rightarrow [j]\} & \text{if } [j] < [i], \\ \emptyset & \text{if } [j] > [i]. \end{cases}$$

between the discrete 2-category $\text{Mon}_{2\text{disc}}$ on Mon and the 2-category of pointed categories with one object.

³In other words, \mathfrak{n} is the category associated to the poset

$$[0] \rightarrow [1] \rightarrow \dots \rightarrow [n-1] \rightarrow [n].$$

The category \mathfrak{n} for $n \geq 2$ may also be defined in terms of \emptyset and joins (\star): we have isomorphisms of categories

$$\begin{aligned} 1 &\cong \emptyset \star \emptyset, \\ 2 &\cong 1 \star \emptyset \\ &\cong (\emptyset \star \emptyset) \star \emptyset, \\ 3 &\cong 2 \star \emptyset \\ &\cong (1 \star \emptyset) \star \emptyset \\ &\cong ((\emptyset \star \emptyset) \star \emptyset) \star \emptyset, \\ 4 &\cong 3 \star \emptyset \\ &\cong (2 \star \emptyset) \star \emptyset \\ &\cong ((1 \star \emptyset) \star \emptyset) \star \emptyset \\ &\cong (((\emptyset \star \emptyset) \star \emptyset) \star \emptyset) \star \emptyset, \end{aligned}$$

and so on.

- *Identities.* For each $[i] \in \text{Obj}(\mathfrak{n})$, the unit map

$$\mathbb{1}_{[i]}^{\mathfrak{n}} : \text{pt} \rightarrow \text{Hom}_{\mathfrak{n}}([i], [i])$$

of \mathfrak{n} at $[i]$ is defined by

$$\text{id}_{[i]}^{\mathfrak{n}} \stackrel{\text{def}}{=} \mathbb{1}_{[i]}^{\mathfrak{n}}.$$

- *Composition.* For each $[i], [j], [k] \in \text{Obj}(\mathfrak{n})$, the composition map

$$\circ_{[i],[j],[k]}^{\mathfrak{n}} : \text{Hom}_{\mathfrak{n}}([j], [k]) \times \text{Hom}_{\mathfrak{n}}([i], [j]) \rightarrow \text{Hom}_{\mathfrak{n}}([i], [k])$$

of \mathfrak{n} at $([i], [j], [k])$ is defined by

$$\begin{aligned} \text{id}_{[i]} \circ \text{id}_{[i]} &= \text{id}_{[i]}, \\ ([j] \rightarrow [k]) \circ ([i] \rightarrow [j]) &= ([i] \rightarrow [k]). \end{aligned}$$

00WR Example 8.1.2.1.5. Here we list some of the other categories appearing throughout this work.

- 00WS 1. The category Sets_* of pointed sets of **Definition 3.1.3.1.1.**
- 00WT 2. The category Rel of sets and relations of **Definition 5.2.1.1.1.**
- 00WU 3. The category $\text{Span}(A, B)$ of spans from a set A to a set B of ??.
- 00WV 4. The category $\text{ISets}(K)$ of K -indexed sets of ??.
- 00WW 5. The category ISets of indexed sets of ??.
- 00WX 6. The category $\text{FibSets}(K)$ of K -fibred sets of ??.
- 00WY 7. The category FibSets of fibred sets of ??.
- 00WZ 8. Categories of functors $\text{Fun}(\mathcal{C}, \mathcal{D})$ as in **Definition 8.9.1.1.1.**
- 00X0 9. The category of categories Cats of **Definition 8.9.2.1.1.**
- 00X1 10. The category of groupoids Grpd of **Definition 8.9.4.1.1.**

00X2 8.1.3 Posetal Categories

00X3 Definition 8.1.3.1.1. Let (X, \preceq_X) be a poset.

- 00X4 1. The **posetal category associated to** (X, \preceq_X) is the category X_{pos} where

- *Objects.* We have

$$\text{Obj}(X_{\text{pos}}) \stackrel{\text{def}}{=} X.$$

- *Morphisms.* For each $a, b \in \text{Obj}(X_{\text{pos}})$, we have

$$\text{Hom}_{X_{\text{pos}}}(a, b) \stackrel{\text{def}}{=} \begin{cases} \text{pt} & \text{if } a \preceq_X b, \\ \emptyset & \text{otherwise.} \end{cases}$$

- *Identities.* For each $a \in \text{Obj}(X_{\text{pos}})$, the unit map

$$\mathbb{1}_a^{X_{\text{pos}}} : \text{pt} \rightarrow \text{Hom}_{X_{\text{pos}}}(a, a)$$

of X_{pos} at a is given by the identity map.

- *Composition.* For each $a, b, c \in \text{Obj}(X_{\text{pos}})$, the composition map

$$\circ_{a,b,c}^{X_{\text{pos}}} : \text{Hom}_{X_{\text{pos}}}(b, c) \times \text{Hom}_{X_{\text{pos}}}(a, b) \rightarrow \text{Hom}_{X_{\text{pos}}}(a, c)$$

of X_{pos} at (a, b, c) is defined as either the inclusion $\emptyset \hookrightarrow \text{pt}$ or the identity map of pt , depending on whether we have $a \preceq_X b$, $b \preceq_X c$, and $a \preceq_X c$.

00X5 2. A category C is **posetal**⁴ if C is equivalent to X_{pos} for some poset (X, \preceq_X) .

00X6 **Proposition 8.1.3.1.2.** Let (X, \preceq_X) be a poset and let C be a category.

00X7 1. *Functoriality.* The assignment $(X, \preceq_X) \mapsto X_{\text{pos}}$ defines a functor

$$(-)_{\text{pos}} : \text{Pos} \rightarrow \text{Cats}.$$

00X8 2. *Fully Faithfulness.* The functor $(-)_{\text{pos}}$ of **Item 1** is fully faithful.

00X9 3. *Characterisations.* The following conditions are equivalent:

00XA (a) The category C is posetal.

(b) For each $A, B \in \text{Obj}(C)$ and each $f, g \in \text{Hom}_C(A, B)$, we have

00XB $f = g$.

Proof. **Item 1, Functoriality:** Omitted.

Item 2, Fully Faithfulness: Omitted.

Item 3, Characterisations: Clear. □

⁴*Further Terminology:* Also called a **thin** category or a **(0, 1)-category**.

00XC 8.1.4 Subcategories

Let C be a category.

00XD Definition 8.1.4.1.1. A **subcategory** of C is a category \mathcal{A} satisfying the following conditions:

1. *Objects.* We have $\text{Obj}(\mathcal{A}) \subset \text{Obj}(C)$.
2. *Morphisms.* For each $A, B \in \text{Obj}(\mathcal{A})$, we have

$$\text{Hom}_{\mathcal{A}}(A, B) \subset \text{Hom}_C(A, B).$$

3. *Identities.* For each $A \in \text{Obj}(\mathcal{A})$, we have

$$\mathbb{1}_A^{\mathcal{A}} = \mathbb{1}_A^C.$$

4. *Composition.* For each $A, B, C \in \text{Obj}(\mathcal{A})$, we have

$$\circ_{A,B,C}^{\mathcal{A}} = \circ_{A,B,C}^C.$$

00XE Definition 8.1.4.1.2. A subcategory \mathcal{A} of C is **full** if the canonical inclusion functor $\mathcal{A} \rightarrow C$ is full, i.e. if, for each $A, B \in \text{Obj}(\mathcal{A})$, the inclusion

$$\iota_{A,B}: \text{Hom}_{\mathcal{A}}(A, B) \hookrightarrow \text{Hom}_C(A, B)$$

is surjective (and thus bijective).

00XF Definition 8.1.4.1.3. A subcategory \mathcal{A} of a category C is **strictly full** if it satisfies the following conditions:

1. *Fullness.* The subcategory \mathcal{A} is full.
2. *Closedness Under Isomorphisms.* The class $\text{Obj}(\mathcal{A})$ is closed under isomorphisms.⁵

00XG Definition 8.1.4.1.4. A subcategory \mathcal{A} of C is **wide**⁶ if $\text{Obj}(\mathcal{A}) = \text{Obj}(C)$.

00XH 8.1.5 Skeletons of Categories

00XJ Definition 8.1.5.1.1. A⁷ **skeleton** of a category C is a full subcategory $\text{Sk}(C)$ with one object from each isomorphism class of objects of C .

⁵That is, given $A \in \text{Obj}(\mathcal{A})$ and $C \in \text{Obj}(C)$, if $C \cong A$, then $C \in \text{Obj}(\mathcal{A})$.

⁶*Further Terminology:* Also called **lluf**.

⁷Due to **Item 3** of **Proposition 8.1.5.1.3**, we often refer to any such full subcategory $\text{Sk}(C)$

00XK Definition 8.1.5.1.2. A category C is **skeletal** if $C \cong \text{Sk}(C)$.⁸

00XL Proposition 8.1.5.1.3. Let C be a category.

00XM 1. *Existence.* Assuming the axiom of choice, $\text{Sk}(C)$ always exists.

00XN 2. *Pseudofunctoriality.* The assignment $C \mapsto \text{Sk}(C)$ defines a pseudo-functor

$$\text{Sk}: \text{Cats}_2 \rightarrow \text{Cats}_2.$$

00XP 3. *Uniqueness Up to Equivalence.* Any two skeletons of C are equivalent.

00XQ 4. *Inclusions of Skeletons Are Equivalences.* The inclusion

$$\iota_C: \text{Sk}(C) \hookrightarrow C$$

of a skeleton of C into C is an equivalence of categories.

Proof. Item 1, Existence: See [nLab23, Section “Existence of Skeletons of Categories”].

Item 2, Pseudofunctoriality: See [nLab23, Section “Skeletons as an Endo-Pseudofunctor on \mathfrak{Cat} ”].

Item 3, Uniqueness Up to Equivalence: Clear.

Item 4, Inclusions of Skeletons Are Equivalences: Clear. \square

00XR 8.1.6 Precomposition and Postcomposition

Let C be a category and let $A, B, C \in \text{Obj}(C)$.

00XS Definition 8.1.6.1.1. Let $f: A \rightarrow B$ and $g: B \rightarrow C$ be morphisms of C .

00XT 1. The **precomposition function associated to f** is the function

$$f^*: \text{Hom}_C(B, C) \rightarrow \text{Hom}_C(A, C)$$

defined by

$$f^*(\phi) \stackrel{\text{def}}{=} \phi \circ f$$

for each $\phi \in \text{Hom}_C(B, C)$.

00XU 2. The **postcomposition function associated to g** is the function

$$g_*: \text{Hom}_C(A, B) \rightarrow \text{Hom}_C(A, C)$$

defined by

$$g_*(\phi) \stackrel{\text{def}}{=} g \circ \phi$$

for each $\phi \in \text{Hom}_C(A, B)$.

of C as *the* skeleton of C .

⁸That is, C is **skeletal** if isomorphic objects of C are equal.

00XV Proposition 8.1.6.1.2. Let $A, B, C, D \in \text{Obj}(C)$ and let $f: A \rightarrow B$ and $g: B \rightarrow C$ be morphisms of C .

00XW 1. *Interaction Between Precomposition and Postcomposition.* We have

$$\begin{array}{ccc}
 \text{Hom}_C(B, C) & \xrightarrow{g_*} & \text{Hom}_C(B, D) \\
 f^* \downarrow & & \downarrow f^* \\
 \text{Hom}_C(A, C) & \xrightarrow{g_*} & \text{Hom}_C(A, D).
 \end{array}$$

$g_* \circ f^* = f^* \circ g_*$

00XX 2. *Interaction With Composition I.* We have

$$\begin{array}{ccc}
 \text{Hom}_C(X, A) & \xrightarrow{f_*} & \text{Hom}_C(X, B) \\
 & \searrow (g \circ f)_* & \downarrow g_* \\
 & & \text{Hom}_C(X, C),
 \end{array}$$

$(g \circ f)^* = f^* \circ g^*$

$$\begin{array}{ccc}
 \text{Hom}_C(C, X) & \xrightarrow{g^*} & \text{Hom}_C(B, X) \\
 & \searrow (g \circ f)^* & \downarrow f^* \\
 & & \text{Hom}_C(A, X).
 \end{array}$$

$(g \circ f)_* = g_* \circ f_*$

00XY 3. *Interaction With Composition II.* We have

$$\begin{array}{ccc}
 \text{pt} \xrightarrow{[f]} \text{Hom}_C(A, B) & & \text{pt} \xrightarrow{[g]} \text{Hom}_C(B, C) \\
 \searrow [g \circ f] \quad \downarrow g_* & [g \circ f] = g_* \circ [f], & \searrow [g \circ f] \quad \downarrow f^* \\
 \text{Hom}_C(A, C) & [g \circ f] = f^* \circ [g], & \text{Hom}_C(A, C).
 \end{array}$$

00XZ 4. Interaction With Composition III. We have

$$\begin{array}{ccc}
 \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_C(A, C) \\
 \downarrow \text{id} \times f^* & & \downarrow f^* \\
 \text{Hom}_C(B, C) \times \text{Hom}_C(X, B) & \xrightarrow{\circ_{X,B,C}^C} & \text{Hom}_C(X, C), \\
 \\
 \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_C(A, C) \\
 \downarrow g_* \times \text{id} & & \downarrow g^* \\
 \text{Hom}_C(B, D) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,D}^C} & \text{Hom}_C(A, D).
 \end{array}$$

$f^* \circ \circ_{A,B,C}^C = \circ_{X,B,C}^C \circ (f^* \times \text{id}),$
 $g_* \circ \circ_{A,B,C}^C = \circ_{A,B,D}^C \circ (\text{id} \times g_*),$

00Y0 5. Interaction With Identities. We have

$$\begin{aligned}
 (\text{id}_A)^* &= \text{id}_{\text{Hom}_C(A,B)}, \\
 (\text{id}_B)_* &= \text{id}_{\text{Hom}_C(A,B)}.
 \end{aligned}$$

Proof. Item 1, Interaction Between Precomposition and Postcomposition: Clear.

Item 2, Interaction With Composition I: Clear.

Item 3, Interaction With Composition II: Clear.

Item 4, Interaction With Composition III: Clear.

Item 5, Interaction With Identities: Clear. □

00Y1 8.2 The Quadruple Adjunction With Sets

00Y2 8.2.1 Statement

Let C be a category.

00Y3 **Proposition 8.2.1.1.1.** We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}): \text{Sets} \begin{array}{c} \xrightarrow{\pi_0} \\ \dashv \\ \xrightarrow{(-)_{\text{disc}}} \\ \dashv \\ \xrightarrow{\text{Obj}} \\ \dashv \\ \xrightarrow{(-)_{\text{indisc}}} \end{array} \text{Cats},$$

witnessed by bijections of sets

$$\begin{aligned}
 \text{Hom}_{\text{Sets}}(\pi_0(C), X) &\cong \text{Hom}_{\text{Cats}}(C, X_{\text{disc}}), \\
 \text{Hom}_{\text{Cats}}(X_{\text{disc}}, C) &\cong \text{Hom}_{\text{Sets}}(X, \text{Obj}(C)), \\
 \text{Hom}_{\text{Sets}}(\text{Obj}(C), X) &\cong \text{Hom}_{\text{Cats}}(C, X_{\text{indisc}}),
 \end{aligned}$$

natural in $C \in \text{Obj}(\text{Cats})$ and $X \in \text{Obj}(\text{Sets})$, where

- The functor

$$\pi_0 : \text{Cats} \rightarrow \text{Sets},$$

the **connected components functor**, is the functor sending a category to its set of connected components of [Definition 8.2.2.1](#).

- The functor

$$(-)_{\text{disc}} : \text{Sets} \rightarrow \text{Cats},$$

the **discrete category functor**, is the functor sending a set to its associated discrete category of [Item 1](#).

- The functor

$$\text{Obj} : \text{Cats} \rightarrow \text{Sets},$$

the **object functor**, is the functor sending a category to its set of objects.

- The functor

$$(-)_{\text{indisc}} : \text{Sets} \rightarrow \text{Cats},$$

the **indiscrete category functor**, is the functor sending a set to its associated indiscrete category of [Item 1](#).

Proof. Omitted. □

00Y4 8.2.2 Connected Components and Connected Categories

00Y5 8.2.2.1 Connected Components of Categories

Let C be a category.

00Y6 **Definition 8.2.2.1.1.** A **connected component** of C is a full subcategory \mathcal{I} of C satisfying the following conditions:⁹

1. *Non-Emptiness.* We have $\text{Obj}(\mathcal{I}) \neq \emptyset$.
2. *Connectedness.* There exists a zigzag of arrows between any two objects of \mathcal{I} .

00Y7 8.2.2.2 Sets of Connected Components of Categories

Let C be a category.

⁹In other words, a **connected component** of C is an element of the set $\text{Obj}(C)/\sim$ with \sim

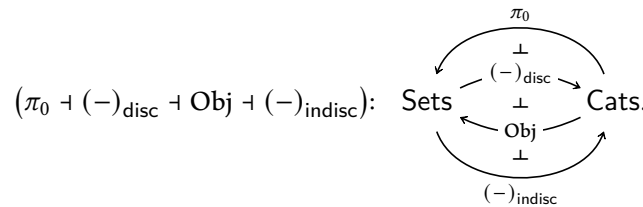
00Y8 Definition 8.2.2.2.1. The **set of connected components of C** is the set $\pi_0(C)$ whose elements are the connected components of C .

00Y9 Proposition 8.2.2.2.2. Let C be a category.

00YA 1. *Functoriality.* The assignment $C \mapsto \pi_0(C)$ defines a functor

$$\pi_0: \text{Cats} \rightarrow \text{Sets}.$$

00YB 2. *Adjointness.* We have a quadruple adjunction



00YC 3. *Interaction With Groupoids.* If C is a groupoid, then we have an isomorphism of categories

$$\pi_0(C) \cong \mathbf{K}(C),$$

where $\mathbf{K}(C)$ is the set of isomorphism classes of C of ??.

00YD 4. *Preservation of Colimits.* The functor π_0 of **Item 1** preserves colimits. In particular, we have bijections of sets

$$\begin{aligned} \pi_0(C \amalg \mathcal{D}) &\cong \pi_0(C) \amalg \pi_0(\mathcal{D}), \\ \pi_0(C \amalg_{\mathcal{E}} \mathcal{D}) &\cong \pi_0(C) \amalg_{\pi_0(\mathcal{E})} \pi_0(\mathcal{D}), \\ \pi_0\left(\text{CoEq}\left(C \begin{array}{c} \xrightarrow{F} \\ \xrightarrow{G} \end{array} \mathcal{D}\right)\right) &\cong \text{CoEq}\left(\pi_0(C) \begin{array}{c} \xrightarrow{\pi_0(F)} \\ \xrightarrow{\pi_0(G)} \end{array} \pi_0(\mathcal{D})\right), \end{aligned}$$

natural in $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$.

00YE 5. *Symmetric Strong Monoidality With Respect to Coproducts.* The connected components functor of **Item 1** has a symmetric strong monoidal structure

$$\left(\pi_0, \pi_0 \amalg, \pi_0 \amalg_{\mathbb{1}}\right): (\text{Cats}, \amalg, \emptyset_{\text{cat}}) \rightarrow (\text{Sets}, \amalg, \emptyset),$$

the equivalence relation generated by the relation \sim' obtained by declaring $A \sim' B$ iff there exists a morphism of C from A to B .

being equipped with isomorphisms

$$\begin{aligned}\pi_{0|C,\mathcal{D}}^{\amalg} : \pi_0(C) \amalg \pi_0(\mathcal{D}) &\xrightarrow{\cong} \pi_0(C \amalg \mathcal{D}), \\ \pi_{0|\mathbb{1}}^{\amalg} : \emptyset &\xrightarrow{\cong} \pi_0(\emptyset_{\text{cat}}),\end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$.

- 00YF** 6. *Symmetric Strong Monoidality With Respect to Products.* The connected components functor of **Item 1** has a symmetric strong monoidal structure

$$\left(\pi_0, \pi_0^\times, \pi_{0|\mathbb{1}}^\times\right) : (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Sets}, \times, \text{pt}),$$

being equipped with isomorphisms

$$\begin{aligned}\pi_{0|C,\mathcal{D}}^\times : \pi_0(C) \times \pi_0(\mathcal{D}) &\xrightarrow{\cong} \pi_0(C \times \mathcal{D}), \\ \pi_{0|\mathbb{1}}^\times : \text{pt} &\xrightarrow{\cong} \pi_0(\text{pt}),\end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$.

Proof. **Item 1, Functoriality:** Clear.

Item 2, Adjointness: This is proved in **Proposition 8.2.1.1.1**.

Item 3, Interaction With Groupoids: Clear.

Item 4, Preservation of Colimits: This follows from **Item 2** and ?? of ??.

Item 5, Symmetric Strong Monoidality With Respect to Coproducts: Clear.

Item 6, Symmetric Strong Monoidality With Respect to Products: Clear. \square

00YG 8.2.2.3 Connected Categories

00YH **Definition 8.2.2.3.1.** A category C is **connected** if $\pi_0(C) \cong \text{pt}$.^{10,11}

00YJ 8.2.3 Discrete Categories

00YK **Definition 8.2.3.1.1.** Let X be a set.

00YL 1. The **discrete category on X** is the category X_{disc} where

- *Objects.* We have

$$\text{Obj}(X_{\text{disc}}) \stackrel{\text{def}}{=} X.$$

¹⁰*Further Terminology:* A category is **disconnected** if it is not connected.

¹¹*Example:* A groupoid is connected iff any two of its objects are isomorphic.

- *Morphisms.* For each $A, B \in \text{Obj}(X_{\text{disc}})$, we have

$$\text{Hom}_{X_{\text{disc}}}(A, B) \stackrel{\text{def}}{=} \begin{cases} \text{id}_A & \text{if } A = B, \\ \emptyset & \text{if } A \neq B. \end{cases}$$

- *Identities.* For each $A \in \text{Obj}(X_{\text{disc}})$, the unit map

$$\mathbb{1}_A^{X_{\text{disc}}} : \text{pt} \rightarrow \text{Hom}_{X_{\text{disc}}}(A, A)$$

of X_{disc} at A is defined by

$$\text{id}_A^{X_{\text{disc}}} \stackrel{\text{def}}{=} \text{id}_A.$$

- *Composition.* For each $A, B, C \in \text{Obj}(X_{\text{disc}})$, the composition map

$$\circ_{A,B,C}^{X_{\text{disc}}} : \text{Hom}_{X_{\text{disc}}}(B, C) \times \text{Hom}_{X_{\text{disc}}}(A, B) \rightarrow \text{Hom}_{X_{\text{disc}}}(A, C)$$

of X_{disc} at (A, B, C) is defined by

$$\text{id}_A \circ \text{id}_B \stackrel{\text{def}}{=} \text{id}_A.$$

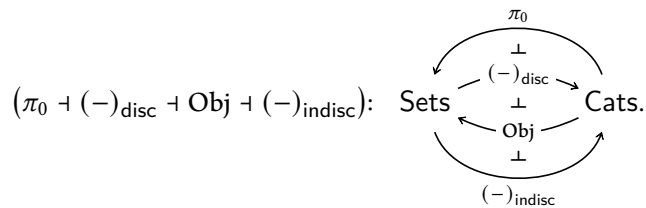
00YM 2. A category C is **discrete** if it is equivalent to X_{disc} for some set X .

00YN **Proposition 8.2.3.1.2.** Let X be a set.

00YP 1. *Functoriality.* The assignment $X \mapsto X_{\text{disc}}$ defines a functor

$$(-)_{\text{disc}} : \text{Sets} \rightarrow \text{Cats}.$$

00YQ 2. *Adjointness.* We have a quadruple adjunction



00YR 3. *Symmetric Strong Monoidality With Respect to Coproducts.* The functor of **Item 1** has a symmetric strong monoidal structure

$$\left((-)_{\text{disc}}, (-)_{\text{disc}}, (-)_{\text{disc}|_{\mathbb{1}}} \right) : (\text{Sets}, \coprod, \emptyset) \rightarrow (\text{Cats}, \coprod, \emptyset_{\text{cat}}),$$

being equipped with isomorphisms

$$\begin{aligned} (-)_{\text{disc}|X,Y}^{\amalg} : X_{\text{disc}} \amalg Y_{\text{disc}} &\xrightarrow{\cong} (X \amalg Y)_{\text{disc}}, \\ (-)_{\text{disc}|\mathbb{1}}^{\amalg} : \mathbb{0}_{\text{cat}} &\xrightarrow{\cong} \mathbb{0}_{\text{disc}}, \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

- 00YS** 4. *Symmetric Strong Monoidality With Respect to Products.* The functor of **Item 1** has a symmetric strong monoidal structure

$$\left((-)_{\text{disc}}, (-)_{\text{disc}}^{\times}, (-)_{\text{disc}|\mathbb{1}}^{\times} \right) : (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Cats}, \times, \text{pt}),$$

being equipped with isomorphisms

$$\begin{aligned} (-)_{\text{disc}|X,Y}^{\times} : X_{\text{disc}} \times Y_{\text{disc}} &\xrightarrow{\cong} (X \times Y)_{\text{disc}}, \\ (-)_{\text{disc}|\mathbb{1}}^{\times} : \text{pt} &\xrightarrow{\cong} \text{pt}_{\text{disc}}, \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

Proof. Item 1, Functoriality: Clear.

Item 2, Adjointness: This is proved in **Proposition 8.2.1.1.1**.

Item 3, Symmetric Strong Monoidality With Respect to Coproducts: Clear.

Item 4, Symmetric Strong Monoidality With Respect to Products: Clear. \square

00YT 8.2.4 Indiscrete Categories

00YU **Definition 8.2.4.1.1.** Let X be a set.

- 00YV** 1. The **indiscrete category on X** ¹² is the category X_{indisc} where

- *Objects.* We have

$$\text{Obj}(X_{\text{indisc}}) \stackrel{\text{def}}{=} X.$$

- *Morphisms.* For each $A, B \in \text{Obj}(X_{\text{indisc}})$, we have

$$\begin{aligned} \text{Hom}_{X_{\text{disc}}}(A, B) &\stackrel{\text{def}}{=} \{[A] \rightarrow [B]\} \\ &\cong \text{pt}. \end{aligned}$$

¹²*Further Terminology:* Sometimes called the **chaotic category on X** .

- *Identities.* For each $A \in \text{Obj}(X_{\text{indisc}})$, the unit map

$$\mathbb{1}_A^{X_{\text{indisc}}} : \text{pt} \rightarrow \text{Hom}_{X_{\text{indisc}}}(A, A)$$

of X_{indisc} at A is defined by

$$\text{id}_A^{X_{\text{indisc}}} \stackrel{\text{def}}{=} \{[A] \rightarrow [A]\}.$$

- *Composition.* For each $A, B, C \in \text{Obj}(X_{\text{indisc}})$, the composition map

$$\circ_{A,B,C}^{X_{\text{indisc}}} : \text{Hom}_{X_{\text{indisc}}}(B, C) \times \text{Hom}_{X_{\text{indisc}}}(A, B) \rightarrow \text{Hom}_{X_{\text{indisc}}}(A, C)$$

of X_{disc} at (A, B, C) is defined by

$$([B] \rightarrow [C]) \circ ([A] \rightarrow [B]) \stackrel{\text{def}}{=} ([A] \rightarrow [C]).$$

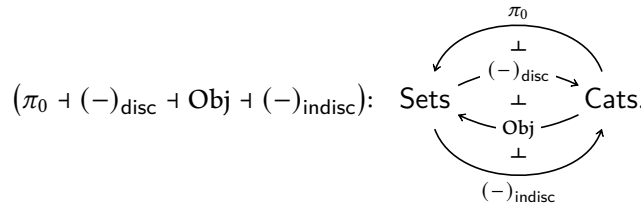
00YW 2. A category C is **indiscrete** if it is equivalent to X_{indisc} for some set X .

00YX **Proposition 8.2.4.1.2.** Let X be a set.

00YY 1. *Functoriality.* The assignment $X \mapsto X_{\text{indisc}}$ defines a functor

$$(-)_{\text{indisc}} : \text{Sets} \rightarrow \text{Cats}.$$

00YZ 2. *Adjointness.* We have a quadruple adjunction



00Z0 3. *Symmetric Strong Monoidality With Respect to Products.* The functor of **Item 1** has a symmetric strong monoidal structure

$$\left((-)_{\text{indisc}}, (-)_{\text{indisc}}^{\times}, (-)_{\text{indisc}|\mathbb{1}}^{\times} \right) : (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Cats}, \times, \text{pt}),$$

being equipped with isomorphisms

$$(-)_{\text{indisc}|\mathbb{1}}^{\times} : X_{\text{indisc}} \times Y_{\text{indisc}} \xrightarrow{\cong} (X \times Y)_{\text{indisc}},$$

$$(-)_{\text{indisc}|\mathbb{1}}^{\times} : \text{pt} \xrightarrow{\cong} \text{pt}_{\text{indisc}},$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

Proof. **Item 1, Functoriality:** Clear.

Item 2, Adjointness: This is proved in **Proposition 8.2.1.1.1**.

Item 3, Symmetric Strong Monoidality With Respect to Products: Clear. □

00Z1 8.3 Groupoids

00Z2 8.3.1 Foundations

Let C be a category.

00Z3 **Definition 8.3.1.1.1.** A morphism $f: A \rightarrow B$ of C is an **isomorphism** if there exists a morphism $f^{-1}: B \rightarrow A$ of C such that

$$\begin{aligned} f \circ f^{-1} &= \text{id}_B, \\ f^{-1} \circ f &= \text{id}_A. \end{aligned}$$

00Z4 **Notation 8.3.1.1.2.** We write $\text{Iso}_C(A, B)$ for the set of all isomorphisms in C from A to B .

00Z5 **Definition 8.3.1.1.3.** A **groupoid** is a category in which every morphism is an isomorphism.

00Z6 8.3.2 The Groupoid Completion of a Category

Let C be a category.

00Z7 **Definition 8.3.2.1.1.** The **groupoid completion** of C ¹³ is the pair $(K_0(C), \iota_C)$ consisting of

- A groupoid $K_0(C)$;
- A functor $\iota_C: C \rightarrow K_0(C)$;

satisfying the following universal property:¹⁴

(UP) Given another such pair (\mathcal{G}, i) , there exists a unique functor $K_0(C) \xrightarrow{\exists!} \mathcal{G}$ making the diagram

$$\begin{array}{ccc} & & K_0(C) \\ & \nearrow \iota_C & \downarrow \exists! \\ C & \xrightarrow{i} & \mathcal{G} \end{array}$$

commute.

¹³*Further Terminology:* Also called the **Grothendieck groupoid** of C or the **Grothendieck groupoid completion** of C .

¹⁴See **Item 5** of **Proposition 8.3.2.1.3** for an explicit construction.

00Z8 Construction 8.3.2.1.2. Concretely, the groupoid completion of C is the Gabriel–Zisman localisation $\text{Mor}(C)^{-1}C$ of C at the set $\text{Mor}(C)$ of all morphisms of C ; see ??.
(To be expanded upon later on.)

Proof. Omitted. □

00Z9 Proposition 8.3.2.1.3. Let C be a category.

00ZA 1. *Functoriality.* The assignment $C \mapsto K_0(C)$ defines a functor

$$K_0: \text{Cats} \rightarrow \text{Grpd}.$$

00ZB 2. *2-Functoriality.* The assignment $C \mapsto K_0(C)$ defines a 2-functor

$$K_0: \text{Cats}_2 \rightarrow \text{Grpd}_2.$$

00ZC 3. *Adjointness.* We have an adjunction

$$(K_0 \dashv \iota): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp \\ \xleftarrow{\iota} \end{array} \text{Grpd},$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Grpd}}(K_0(C), \mathcal{G}) \cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}),$$

natural in $C \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$, forming, together with the functor Core of **Item 1** of **Proposition 8.3.3.1.4**, a triple adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp \\ \xleftarrow{\iota} \\ \perp \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\text{Grpd}}(K_0(C), \mathcal{G}) &\cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}), \\ \text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) &\cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})), \end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

00ZD 4. *2-Adjointness*. We have a 2-adjunction

$$(\mathbb{K}_0 \dashv \iota): \text{Cats} \begin{array}{c} \xrightarrow{\mathbb{K}_0} \\ \xleftarrow{\iota} \\ \xrightarrow{\iota} \\ \xleftarrow{\mathbb{K}_0} \end{array} \text{Grpd},$$

witnessed by an isomorphism of categories

$$\text{Fun}(\mathbb{K}_0(C), \mathcal{G}) \cong \text{Fun}(C, \mathcal{G}),$$

natural in $C \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$, forming, together with the 2-functor Core of **Item 2** of **Proposition 8.3.3.1.4**, a triple 2-adjunction

$$(\mathbb{K}_0 \dashv \iota \dashv \text{Core}): \text{Cats} \begin{array}{c} \xrightarrow{\mathbb{K}_0} \\ \xleftarrow{\iota} \\ \xrightarrow{\iota} \\ \xleftarrow{\mathbb{K}_0} \\ \xrightarrow{\text{Core}} \\ \xleftarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by isomorphisms of categories

$$\begin{aligned} \text{Fun}(\mathbb{K}_0(C), \mathcal{G}) &\cong \text{Fun}(C, \mathcal{G}), \\ \text{Fun}(\mathcal{G}, \mathcal{D}) &\cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})), \end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

00ZE 5. *Interaction With Classifying Spaces*. We have an isomorphism of groupoids

$$\mathbb{K}_0(C) \cong \Pi_{\leq 1}(|\mathbf{N}_\bullet(C)|),$$

natural in $C \in \text{Obj}(\text{Cats})$; i.e. the diagram

$$\begin{array}{ccc} \text{Cats} & \xrightarrow{\mathbb{K}_0} & \text{Grp} \\ \downarrow \mathbf{N}_\bullet & \updownarrow & \uparrow \Pi_{\leq 1} \\ \text{sSets} & \xrightarrow{|\cdot|} & \text{Top} \end{array}$$

commutes up to natural isomorphism.

00ZF 6. *Symmetric Strong Monoidality With Respect to Coproducts*. The groupoid completion functor of **Item 1** has a symmetric strong monoidal structure

$$\left(\mathbb{K}_0, \mathbb{K}_0 \amalg, \mathbb{K}_0 \amalg_{\mathbb{1}}\right): (\text{Cats}, \amalg, \mathbb{0}_{\text{cat}}) \rightarrow (\text{Grpd}, \amalg, \mathbb{0}_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned} K_{0|C,\mathcal{D}}^{\amalg} : K_0(C) \amalg K_0(\mathcal{D}) &\xrightarrow{\cong} K_0(C \amalg \mathcal{D}), \\ K_{0|\mathbb{1}}^{\amalg} : \mathcal{0}_{\text{cat}} &\xrightarrow{\cong} K_0(\mathcal{0}_{\text{cat}}), \end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$.

- 00ZG** 7. *Symmetric Strong Monoidality With Respect to Products.* The groupoid completion functor of **Item 1** has a symmetric strong monoidal structure

$$\left(K_0, K_0^\times, K_{0|\mathbb{1}}^\times \right) : (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned} K_{0|C,\mathcal{D}}^\times : K_0(C) \times K_0(\mathcal{D}) &\xrightarrow{\cong} K_0(C \times \mathcal{D}), \\ K_{0|\mathbb{1}}^\times : \text{pt} &\xrightarrow{\cong} K_0(\text{pt}), \end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$.

Proof. Item 1, Functoriality: Omitted.

Item 2, 2-Functoriality: Omitted.

Item 3, Adjointness: Omitted.

Item 4, 2-Adjointness: Omitted.

Item 5, Interaction With Classifying Spaces: See Corollary 18.33 of <https://web.ma.utexas.edu/users/dafr/M392C-2012/Notes/lecture18.pdf>.

Item 6, Symmetric Strong Monoidality With Respect to Coproducts: Omitted.

Item 7, Symmetric Strong Monoidality With Respect to Products: Omitted. \square

00ZH 8.3.3 The Core of a Category

Let C be a category.

- 00ZJ** **Definition 8.3.3.1.1.** The **core** of C is the pair $(\text{Core}(C), \iota_C)$ consisting of

- A groupoid $\text{Core}(C)$;
- A functor $\iota_C : \text{Core}(C) \hookrightarrow C$;

satisfying the following universal property:

(UP) Given another such pair (\mathcal{G}, i) , there exists a unique functor $\mathcal{G} \xrightarrow{\exists!} \text{Core}(C)$ making the diagram

$$\begin{array}{ccc}
 & \text{Core}(C) & \\
 \exists! \nearrow & \downarrow \iota_C & \\
 \mathcal{G} & \xrightarrow{i} & C
 \end{array}$$

commute.

00ZK Notation 8.3.3.1.2. We also write C^\simeq for $\text{Core}(C)$.

00ZL Construction 8.3.3.1.3. The core of C is the wide subcategory of C spanned by the isomorphisms of C , i.e. the category $\text{Core}(C)$ where¹⁵

1. *Objects.* We have

$$\text{Obj}(\text{Core}(C)) \stackrel{\text{def}}{=} \text{Obj}(C).$$

2. *Morphisms.* The morphisms of $\text{Core}(C)$ are the isomorphisms of C .

Proof. This follows from the fact that functors preserve isomorphisms (**Item 1** of **Proposition 8.4.1.1.6**). □

00ZM Proposition 8.3.3.1.4. Let C be a category.

1. *Functoriality.* The assignment $C \mapsto \text{Core}(C)$ defines a functor

$$\text{Core}: \text{Cats} \rightarrow \text{Grpd}.$$

2. *2-Functoriality.* The assignment $C \mapsto \text{Core}(C)$ defines a 2-functor

$$\text{Core}: \text{Cats}_2 \rightarrow \text{Grpd}_2.$$

3. *Adjointness.* We have an adjunction

$$(\iota \dashv \text{Core}): \text{Grpd} \begin{array}{c} \xrightarrow{\iota} \\ \perp \\ \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) \cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

¹⁵*Slogan:* The groupoid $\text{Core}(C)$ is the maximal subgroupoid of C .

natural in $\mathcal{G} \in \text{Obj}(\text{Grpd})$ and $\mathcal{D} \in \text{Obj}(\text{Cats})$, forming, together with the functor K_0 of **Item 1** of **Proposition 8.3.2.1.3**, a triple adjunction

$$(\mathbb{K}_0 \dashv \iota \dashv \text{Core}): \quad \text{Cats} \begin{array}{c} \xrightarrow{\mathbb{K}_0} \\ \perp \\ \xleftarrow{\iota} \\ \perp \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by bijections of sets

$$\begin{aligned}
 \text{Hom}_{\text{Grpd}}(\mathbb{K}_0(C), \mathcal{G}) &\cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}), \\
 \text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) &\cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})),
 \end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

00ZR 4. *2-Adjointness.* We have an adjunction

$$(\iota \dashv \text{Core}): \quad \text{Grpd} \begin{array}{c} \xrightarrow{\iota} \\ \perp_2 \\ \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

witnessed by an isomorphism of categories

$$\text{Fun}(\mathcal{G}, \mathcal{D}) \cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

natural in $\mathcal{G} \in \text{Obj}(\text{Grpd})$ and $\mathcal{D} \in \text{Obj}(\text{Cats})$, forming, together with the 2-functor K_0 of **Item 2** of **Proposition 8.3.2.1.3**, a triple 2-adjunction

$$(\mathbb{K}_0 \dashv \iota \dashv \text{Core}): \quad \text{Cats} \begin{array}{c} \xrightarrow{\mathbb{K}_0} \\ \perp_2 \\ \xleftarrow{\iota} \\ \perp_2 \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by isomorphisms of categories

$$\begin{aligned}
 \text{Fun}(\mathbb{K}_0(C), \mathcal{G}) &\cong \text{Fun}(C, \mathcal{G}), \\
 \text{Fun}(\mathcal{G}, \mathcal{D}) &\cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})),
 \end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

00ZS 5. *Symmetric Strong Monoidality With Respect to Products.* The core functor of **Item 1** has a symmetric strong monoidal structure

$$(\text{Core}, \text{Core}^\times, \text{Core}_1^\times): (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned}\text{Core}_{C,\mathcal{D}}^{\times} &: \text{Core}(C) \times \text{Core}(\mathcal{D}) \xrightarrow{\cong} \text{Core}(C \times \mathcal{D}), \\ \text{Core}_{\mathbb{1}}^{\times} &: \text{pt} \xrightarrow{\cong} \text{Core}(\text{pt}),\end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$.

- 00ZT** 6. *Symmetric Strong Monoidality With Respect to Coproducts.* The core functor of **Item 1** has a symmetric strong monoidal structure

$$\left(\text{Core}, \text{Core}^{\amalg}, \text{Core}_{\mathbb{1}}^{\amalg} \right) : (\text{Cats}, \amalg, \emptyset_{\text{cat}}) \rightarrow (\text{Grpd}, \amalg, \emptyset_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned}\text{Core}_{C,\mathcal{D}}^{\amalg} &: \text{Core}(C) \amalg \text{Core}(\mathcal{D}) \xrightarrow{\cong} \text{Core}(C \amalg \mathcal{D}), \\ \text{Core}_{\mathbb{1}}^{\amalg} &: \emptyset_{\text{cat}} \xrightarrow{\cong} \text{Core}(\emptyset_{\text{cat}}),\end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$.

Proof. Item 1, Functoriality: Omitted.

Item 2, 2-Functoriality: Omitted.

Item 3, Adjointness: Omitted.

Item 4, 2-Adjointness: Omitted.

Item 5, Symmetric Strong Monoidality With Respect to Products: Omitted.

Item 6, Symmetric Strong Monoidality With Respect to Coproducts: Omitted. \square

00ZU 8.4 Functors

00ZV 8.4.1 Foundations

Let C and \mathcal{D} be categories.

00ZW **Definition 8.4.1.1.1.** A functor $F: C \rightarrow \mathcal{D}$ from C to \mathcal{D} ¹⁶ consists of:

1. *Action on Objects.* A map of sets

$$F: \text{Obj}(C) \rightarrow \text{Obj}(\mathcal{D}),$$

called the **action on objects of F** .

¹⁶*Further Terminology:* Also called a **covariant functor**.

2. *Action on Morphisms.* For each $A, B \in \text{Obj}(C)$, a map

$$F_{A,B} : \text{Hom}_C(A, B) \rightarrow \text{Hom}_D(F(A), F(B)),$$

called the **action on morphisms of F at (A, B)** ¹⁷.

satisfying the following conditions:

1. *Preservation of Identities.* For each $A \in \text{Obj}(C)$, the diagram

$$\begin{array}{ccc} \text{pt} & & \\ \downarrow \mathbb{1}_A^C & \searrow \mathbb{1}_{F(A)}^D & \\ \text{Hom}_C(A, A) & \xrightarrow{F_{A,A}} & \text{Hom}_D(F(A), F(A)) \end{array}$$

commutes, i.e. we have

$$F(\text{id}_A) = \text{id}_{F(A)}.$$

2. *Preservation of Composition.* For each $A, B, C \in \text{Obj}(C)$, the diagram

$$\begin{array}{ccc} \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_C(A, C) \\ \downarrow F_{B,C} \times F_{A,B} & & \downarrow F_{A,C} \\ \text{Hom}_D(F(B), F(C)) \times \text{Hom}_D(F(A), F(B)) & \xrightarrow{\circ_{F(A),F(B),F(C)}^D} & \text{Hom}_D(F(A), F(C)) \end{array}$$

commutes, i.e. for each composable pair (g, f) of morphisms of C , we have

$$F(g \circ f) = F(g) \circ F(f).$$

00ZX Notation 8.4.1.1.2. Let C and D be categories, and write C^{op} for the opposite category of C of ??.

00ZY 1. Given a functor

$$F : C \rightarrow D,$$

we also write F_A for $F(A)$.

00ZZ 2. Given a functor

$$F : C^{\text{op}} \rightarrow D,$$

we also write F^A for $F(A)$.

¹⁷Further Terminology: Also called **action on Hom-sets of F at (A, B)** .

0100 3. Given a functor

$$F: C \times C \rightarrow \mathcal{D},$$

we also write $F_{A,B}$ for $F(A, B)$.

0101 4. Given a functor

$$F: C^{\text{op}} \times C \rightarrow \mathcal{D},$$

we also write F_B^A for $F(A, B)$.

We employ a similar notation for morphisms, writing e.g. F_f for $F(f)$ given a functor $F: C \rightarrow \mathcal{D}$.

0102 **Notation 8.4.1.1.3.** Following the notation $\llbracket x \mapsto f(x) \rrbracket$ for a function $f: X \rightarrow Y$ introduced in **Notation 1.1.1.1.2**, we will sometimes denote a functor $F: C \rightarrow \mathcal{D}$ by

$$F \stackrel{\text{def}}{=} \llbracket A \mapsto F(A) \rrbracket,$$

specially when the action on morphisms of F is clear from its action on objects.

0103 **Example 8.4.1.1.4.** The **identity functor** of a category C is the functor $\text{id}_C: C \rightarrow C$ where

1. *Action on Objects.* For each $A \in \text{Obj}(C)$, we have

$$\text{id}_C(A) \stackrel{\text{def}}{=} A.$$

2. *Action on Morphisms.* For each $A, B \in \text{Obj}(C)$, the action on morphisms

$$(\text{id}_C)_{A,B}: \text{Hom}_C(A, B) \rightarrow \underbrace{\text{Hom}_C(\text{id}_C(A), \text{id}_C(B))}_{\stackrel{\text{def}}{=} \text{Hom}_C(A, B)}$$

of id_C at (A, B) is defined by

$$(\text{id}_C)_{A,B} \stackrel{\text{def}}{=} \text{id}_{\text{Hom}_C(A, B)}.$$

Proof. Preservation of Identities: We have $\text{id}_C(\text{id}_A) \stackrel{\text{def}}{=} \text{id}_A$ for each $A \in \text{Obj}(C)$ by definition.

Preservation of Compositions: For each composable pair $A \xrightarrow{f} B \xrightarrow{g} B$ of morphisms of C , we have

$$\begin{aligned} \text{id}_C(g \circ f) &\stackrel{\text{def}}{=} g \circ f \\ &\stackrel{\text{def}}{=} \text{id}_C(g) \circ \text{id}_C(f). \end{aligned}$$

This finishes the proof. \square

0104 Definition 8.4.1.1.5. The **composition** of two functors $F: C \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{E}$ is the functor $G \circ F$ where

- *Action on Objects.* For each $A \in \text{Obj}(C)$, we have

$$[G \circ F](A) \stackrel{\text{def}}{=} G(F(A)).$$

- *Action on Morphisms.* For each $A, B \in \text{Obj}(C)$, the action on morphisms

$$(G \circ F)_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{E}}(G_{F_A}, G_{F_B})$$

of $G \circ F$ at (A, B) is defined by

$$[G \circ F](f) \stackrel{\text{def}}{=} G(F(f)).$$

Proof. Preservation of Identities: For each $A \in \text{Obj}(C)$, we have

$$\begin{aligned} G_{F_{\text{id}_A}} &= G_{\text{id}_{F_A}} && \text{(functoriality of } F) \\ &= \text{id}_{G_{F_A}}. && \text{(functoriality of } G) \end{aligned}$$

Preservation of Composition: For each composable pair (g, f) of morphisms of C , we have

$$\begin{aligned} G_{F_{g \circ f}} &= G_{F_g \circ F_f} && \text{(functoriality of } F) \\ &= G_{F_g} \circ G_{F_f}. && \text{(functoriality of } G) \end{aligned}$$

This finishes the proof. \square

0105 Proposition 8.4.1.1.6. Let $F: C \rightarrow \mathcal{D}$ be a functor.

0106 1. *Preservation of Isomorphisms.* If f is an isomorphism in C , then $F(f)$ is an isomorphism in \mathcal{D} .¹⁸

Proof. Item 1, Preservation of Isomorphisms: Indeed, we have

$$\begin{aligned} F(f)^{-1} \circ F(f) &= F(f^{-1} \circ f) \\ &= F(\text{id}_A) \\ &= \text{id}_{F(A)} \end{aligned}$$

and

$$\begin{aligned} F(f) \circ F(f)^{-1} &= F(f \circ f^{-1}) \\ &= F(\text{id}_B) \\ &= \text{id}_{F(B)}, \end{aligned}$$

showing $F(f)$ to be an isomorphism. \square

¹⁸When the converse holds, we call F *conservative*, see [Definition 8.5.4.1.1](#).

0107 **8.4.2 Contravariant Functors**

Let \mathcal{C} and \mathcal{D} be categories, and let \mathcal{C}^{op} denote the opposite category of \mathcal{C} of ??.

0108 **Definition 8.4.2.1.1.** A **contravariant functor** from \mathcal{C} to \mathcal{D} is a functor from \mathcal{C}^{op} to \mathcal{D} .

0109 **Remark 8.4.2.1.2.** In detail, a **contravariant functor** from \mathcal{C} to \mathcal{D} consists of:

1. *Action on Objects.* A map of sets

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D}),$$

called the **action on objects of F** .

2. *Action on Morphisms.* For each $A, B \in \text{Obj}(\mathcal{C})$, a map

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(B), F(A)),$$

called the **action on morphisms of F at (A, B)** .

satisfying the following conditions:

1. *Preservation of Identities.* For each $A \in \text{Obj}(\mathcal{C})$, the diagram

$$\begin{array}{ccc} \text{pt} & & \\ \downarrow \mathbb{1}_A^{\mathcal{C}} & \searrow \mathbb{1}_{F(A)}^{\mathcal{D}} & \\ \text{Hom}_{\mathcal{C}}(A, A) & \xrightarrow{F_{A,A}} & \text{Hom}_{\mathcal{D}}(F(A), F(A)) \end{array}$$

commutes, i.e. we have

$$F(\text{id}_A) = \text{id}_{F(A)}.$$

2. *Preservation of Composition.* For each $A, B, C \in \text{Obj}(\mathcal{C})$, the diagram

$$\begin{array}{ccc} & \text{Hom}_{\mathcal{D}}(F(C), F(B)) \times \text{Hom}_{\mathcal{D}}(F(B), F(A)) & \\ & \nearrow F_{B,C} \times F_{A,B} & \searrow \sigma_{\text{Hom}_{\mathcal{D}}(F(C), F(B)), \text{Hom}_{\mathcal{D}}(F(B), F(A))}^{\text{Sets}} \\ \text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(A, B) & & \text{Hom}_{\mathcal{D}}(F(B), F(A)) \times \text{Hom}_{\mathcal{D}}(F(C), F(B)) \\ \downarrow \circ_{A,B,C}^{\mathcal{C}} & & \downarrow \circ_{F(C), F(B), F(A)}^{\mathcal{D}} \\ \text{Hom}_{\mathcal{C}}(A, C) & \xrightarrow{F_{A,C}} & \text{Hom}_{\mathcal{D}}(F(C), F(A)) \end{array}$$

commutes, i.e. for each composable pair (g, f) of morphisms of C , we have

$$F(g \circ f) = F(f) \circ F(g).$$

010A Remark 8.4.2.1.3. Throughout this work we will not use the term “contravariant” functor, speaking instead simply of functors $F: C^{\text{op}} \rightarrow \mathcal{D}$. We will usually, however, write

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(B), F(A))$$

for the action on morphisms

$$F_{A,B}: \text{Hom}_{C^{\text{op}}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(A), F(B))$$

of F , as well as write $F(g \circ f) = F(f) \circ F(g)$.

010B 8.4.3 Forgetful Functors

010C Definition 8.4.3.1.1. There isn’t a precise definition of a **forgetful functor**.

010D Remark 8.4.3.1.2. Despite there not being a formal or precise definition of a forgetful functor, the term is often very useful in practice, similarly to the word “canonical”. The idea is that a “forgetful functor” is a functor that forgets structure or properties, and is best explained through examples, such as the ones below (see [Examples 8.4.3.1.3](#) and [8.4.3.1.4](#)).

010E Example 8.4.3.1.3. Examples of forgetful functors that forget structure include:

010F 1. *Forgetting Group Structures.* The functor $\text{Grp} \rightarrow \text{Sets}$ sending a group (G, μ_G, η_G) to its underlying set G , forgetting the multiplication and unit maps μ_G and η_G of G .

010G 2. *Forgetting Topologies.* The functor $\text{Top} \rightarrow \text{Sets}$ sending a topological space (X, \mathcal{T}_X) to its underlying set X , forgetting the topology \mathcal{T}_X .

010H 3. *Forgetting Fibrations.* The functor $\text{FibSets}(K) \rightarrow \text{Sets}$ sending a K -fibred set $\phi_X: X \rightarrow K$ to the set X , forgetting the map ϕ_X and the base set K .

010J Example 8.4.3.1.4. Examples of forgetful functors that forget properties include:

010K 1. *Forgetting Commutativity.* The inclusion functor $\iota: \text{CMon} \hookrightarrow \text{Mon}$ which forgets the property of being commutative.

010L 2. *Forgetting Inverses.* The inclusion functor $\iota: \text{Grp} \hookrightarrow \text{Mon}$ which forgets the property of having inverses.

010M **Notation 8.4.3.1.5.** Throughout this work, we will denote forgetful functors that forget structure by $\overset{\circ}{\text{忘}}$, e.g. as in

$$\overset{\circ}{\text{忘}}: \text{Grp} \rightarrow \text{Sets}.$$

The symbol $\overset{\circ}{\text{忘}}$, pronounced *wasureru* (see **Item 1** of **Remark 8.4.3.1.6** below), means *to forget*, and is a kanji found in the following words in Japanese and Chinese:

- 010N 1. 忘れる, transcribed as *wasureru*, meaning *to forget*.
 2. 忘却関手, transcribed as *boukyaku kanshu*, meaning *forgetful functor*.

010P

- 010Q 3. 忘记 or 忘記, transcribed as *wàngjì*, meaning *to forget*.
 4. 遗忘函子 or 遺忘函子, transcribed as *yíwàng hánzǐ*, meaning *forgetful functor*.

010R

010S **Remark 8.4.3.1.6.** Here we collect the pronunciation of the words in **Notation 8.4.3.1.5** for accuracy and completeness.

010T 1. Pronunciation of 忘れる:

- Audio: see <https://topological-modular-forms.github.io/the-clowder-project/static/sounds/wasureru-01.mp3>
- IPA broad transcription: [wäsureru].
- IPA narrow transcription: [ʷäsiʳɛɾu].

010U 2. Pronunciation of 忘却関手: Pronunciation:

- Audio: see <https://topological-modular-forms.github.io/the-clowder-project/static/sounds/wasureru-02.mp3>
- IPA broad transcription: [bɔ:kjaku kãũɕɯ].
- IPA narrow transcription: [bɔ:kjaku kãũɕɯ].

010V 3. Pronunciation of 忘记:

- Audio: see <https://topological-modular-forms.github.io/the-clowder-project/static/sounds/wasureru-03.ogg>

- Broad IPA transcription: [wɑŋtɕi].
- Sinological IPA transcription: [wɑŋ⁵¹⁻⁵³tɕi⁵¹].

010W 4. Pronunciation of 遗忘函数:

- Audio: see <https://topological-modular-forms.github.io/the-clowder-project/static/sounds/wasureru-04.mp3>
- Broad IPA transcription: [iwɑŋ xänfʅzɿ].
- Sinological IPA transcription: [i³⁵wɑŋ⁵¹ xän³⁵fʅzɿ²¹⁴⁻²¹⁽⁴⁾].

010X 8.4.4 The Natural Transformation Associated to a Functor

010Y **Definition 8.4.4.1.1.** Every functor $F: C \rightarrow D$ defines a natural transformation¹⁹

$$F^\dagger: \text{Hom}_C \implies \text{Hom}_D \circ (F^{\text{op}} \times F),$$

called the **natural transformation associated to F** , consisting of the collection

$$\left\{ F_{A,B}^\dagger: \text{Hom}_C(A, B) \rightarrow \text{Hom}_D(F_A, F_B) \right\}_{(A,B) \in \text{Obj}(C^{\text{op}} \times C)}$$

with

$$F_{A,B}^\dagger \stackrel{\text{def}}{=} F_{A,B}.$$

Proof. The naturality condition for F^\dagger is the requirement that for each morphism

$$(\phi, \psi): (X, Y) \rightarrow (A, B)$$

of $C^{\text{op}} \times C$, the diagram

$$\begin{array}{ccc} \text{Hom}_C(X, Y) & \xrightarrow{\phi^* \circ \psi_* = \psi_* \circ \phi^*} & \text{Hom}_C(A, B) \\ F_{X,Y} \downarrow & & \downarrow F_{A,B} \\ \text{Hom}_D(F_X, F_Y) & \xrightarrow{F(\phi)^* \circ F(\psi)_* = F(\psi)_* \circ F(\phi)^*} & \text{Hom}_D(F_A, F_B), \end{array}$$

¹⁹This is the 1-categorical version of **Item 1** of **Proposition 2.4.1.1.3**.

acting on elements as

$$\begin{array}{ccc}
 f & \xrightarrow{\quad} & \psi \circ f \circ \phi \\
 \downarrow & & \downarrow \\
 F(f) & \xrightarrow{\quad} & F(\psi) \circ F(f) \circ F(\psi) = F(\psi \circ f \circ \phi)
 \end{array}$$

commutes, which follows from the functoriality of F . □

010Z Proposition 8.4.4.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{E}$ be functors.

0110 1. *Interaction With Natural Isomorphisms.* The following conditions are equivalent:

(a) The natural transformation $F^\dagger: \text{Hom}_{\mathcal{C}} \Rightarrow \text{Hom}_{\mathcal{D}} \circ (F^{\text{op}} \times F)$

0111 associated to F is a natural isomorphism.

0112 (b) The functor F is fully faithful.

0113 2. *Interaction With Composition.* We have an equality of pasting diagrams

$$\begin{array}{ccc}
 \mathcal{C}^{\text{op}} \times \mathcal{C} & \xrightarrow{F^{\text{op}} \times F} & \mathcal{D}^{\text{op}} \times \mathcal{D} & \xrightarrow{G^{\text{op}} \times G} & \mathcal{E}^{\text{op}} \times \mathcal{E} & & \mathcal{C}^{\text{op}} \times \mathcal{C} & \xrightarrow{(G \circ F)^{\text{op}} \times (G \circ F)} & \mathcal{E}^{\text{op}} \times \mathcal{E} \\
 \searrow & \swarrow F^\dagger & \downarrow & \swarrow G^\dagger & \searrow & = & \searrow & \swarrow (G \circ F)^\dagger & \searrow \\
 \text{Hom}_{\mathcal{C}} & & \text{Hom}_{\mathcal{D}} & & \text{Hom}_{\mathcal{E}} & & \text{Hom}_{\mathcal{C}} & & \text{Hom}_{\mathcal{E}} \\
 & & \downarrow & & & & & & \\
 & & \text{Sets} & & & & & & \text{Sets}
 \end{array}$$

in Cats_2 , i.e. we have

$$(G \circ F)^\dagger = (G^\dagger \star \text{id}_{F^{\text{op}} \times F}) \circ F^\dagger.$$

0114 3. *Interaction With Identities.* We have

$$\text{id}_{\mathcal{C}}^\dagger = \text{id}_{\text{Hom}_{\mathcal{C}}(-1, -2)},$$

i.e. the natural transformation associated to $\text{id}_{\mathcal{C}}$ is the identity natural transformation of the functor $\text{Hom}_{\mathcal{C}}(-1, -2)$.

Proof. Item 1, Interaction With Natural Isomorphisms: Clear.

Item 2, Interaction With Composition: Clear.

Item 3, Interaction With Identities: Clear. □

0115 8.5 Conditions on Functors

0116 8.5.1 Faithful Functors

Let C and \mathcal{D} be categories.

0117 Definition 8.5.1.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **faithful** if, for each $A, B \in \text{Obj}(C)$, the action on morphisms

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is injective.

0118 Proposition 8.5.1.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor.

0119 1. *Interaction With Postcomposition.* The following conditions are equivalent:

011A (a) The functor $F: C \rightarrow \mathcal{D}$ is faithful.

011B (b) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is faithful.

011C (c) The functor $F: C \rightarrow \mathcal{D}$ is a representably faithful morphism in Cats_2 in the sense of **Definition 9.1.1.1.1.**

011D 2. *Interaction With Precomposition I.* Let $F: C \rightarrow \mathcal{D}$ be a functor.

011E (a) If F is faithful, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

can fail to be faithful.

011F (b) Conversely, if the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is faithful, then F can fail to be faithful.

011G 3. *Interaction With Precomposition II.* If F is essentially surjective, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is faithful.

011H 4. *Interaction With Precomposition III.* The following conditions are equivalent:

011J (a) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is faithful.

011K (b) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is conservative.

011L (c) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is monadic.

011M (d) The functor $F : \mathcal{C} \rightarrow \mathcal{D}$ is a corepresentably faithful morphism in Cats_2 in the sense of [Definition 9.2.1.1.1](#).

011N (e) The components

$$\eta_G : G \Longrightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta : \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})} \Longrightarrow \text{Ran}_F \circ F^*$$

of the adjunction $F^* \dashv \text{Ran}_F$ are all monomorphisms.

011P (f) The components

$$\epsilon_G : \text{Lan}_F(G \circ F) \Longrightarrow G$$

of the counit

$$\epsilon : \text{Lan}_F \circ F^* \Longrightarrow \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction $\text{Lan}_F \dashv F^*$ are all epimorphisms.

011Q (g) The functor F is dominant ([Definition 8.6.1.1.1](#)), i.e. every object of \mathcal{D} is a retract of some object in $\text{Im}(F)$:

- (★) For each $B \in \text{Obj}(\mathcal{D})$, there exist:
- An object A of \mathcal{C} ;
 - A morphism $s : B \rightarrow F(A)$ of \mathcal{D} ;

- A morphism $r: F(A) \rightarrow B$ of \mathcal{D} ;
- such that $r \circ s = \text{id}_B$.

Proof. Item 1, Interaction With Postcomposition: Omitted.

Item 2, Interaction With Precomposition I: See [MSE 733163] for *Item 2a*. *Item 2b* follows from *Item 3* and the fact that there are essentially surjective functors that are not faithful.

Item 3, Interaction With Precomposition II: Omitted, but see https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.precomp_fully_faithful.html for a formalised proof.

Item 4, Interaction With Precomposition III: We claim *Items 4a* to *4g* are equivalent:

- *Items 4a* and *4d* Are Equivalent: This is true by the definition of corepresentably faithful morphism; see [Definition 9.2.1.1.1](#).
- *Items 4a* to *4c* and *4g* Are Equivalent: See [Adá+01, Proposition 4.1] or alternatively [Fre09, Lemmas 3.1 and 3.2] for the equivalence between *Items 4a* and *4g*.
- *Items 4a*, *4e* and *4f* Are Equivalent: See ?? of ??.

This finishes the proof. □

011R 8.5.2 Full Functors

Let C and \mathcal{D} be categories.

011S Definition 8.5.2.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **full** if, for each $A, B \in \text{Obj}(C)$, the action on morphisms

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is surjective.

011T Proposition 8.5.2.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor.

011U 1. *Interaction With Postcomposition.* The following conditions are equivalent:

- 011V** (a) The functor $F: C \rightarrow \mathcal{D}$ is full.
- 011W** (b) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is full.

011X (c) The functor $F: C \rightarrow \mathcal{D}$ is a representably full morphism in Cats_2 in the sense of [Definition 9.1.2.1.1](#).

011Y 2. *Interaction With Precomposition I*. If F is full, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

can fail to be full.

011Z 3. *Interaction With Precomposition II*. If the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is full, then F can fail to be full.

0120 4. *Interaction With Precomposition III*. If F is essentially surjective and full, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is full (and also faithful by [Item 3](#) of [Proposition 8.5.1.1.2](#)).

0121 5. *Interaction With Precomposition IV*. The following conditions are equivalent:

0122 (a) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is full.

0123 (b) The functor $F: C \rightarrow \mathcal{D}$ is a corepresentably full morphism in Cats_2 in the sense of [Definition 9.2.1.1.1](#).

0124 (c) The components

$$\eta_G: G \Longrightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta: \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})} \Longrightarrow \text{Ran}_F \circ F^*$$

of the adjunction $F^* \dashv \text{Ran}_F$ are all retractions/split epimorphisms.

0125 (d) The components

$$\epsilon_G : \text{Lan}_F(G \circ F) \implies G$$

of the counit

$$\epsilon : \text{Lan}_F \circ F^* \implies \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction $\text{Lan}_F \dashv F^*$ are all sections/split monomorphisms.

0126 (e) For each $B \in \text{Obj}(\mathcal{D})$, there exist:

- An object A_B of \mathcal{C} ;
- A morphism $s_B : B \rightarrow F(A_B)$ of \mathcal{D} ;
- A morphism $r_B : F(A_B) \rightarrow B$ of \mathcal{D} ;

satisfying the following condition:

(★) For each $A \in \text{Obj}(\mathcal{C})$ and each pair of morphisms

$$\begin{aligned} r : F(A) &\rightarrow B, \\ s : B &\rightarrow F(A) \end{aligned}$$

of \mathcal{D} , we have

$$\begin{aligned} [(A_B, s_B, r_B)] &= [(A, s, r \circ s_B \circ r_B)] \\ \text{in } \int^{A \in \mathcal{C}} h_{F_A}^{B'} \times h_B^{F_A}. \end{aligned}$$

Proof. **Item 1, Interaction With Postcomposition:** Omitted.

Item 2, Interaction With Precomposition I: Omitted.

Item 3, Interaction With Precomposition II: See [BS10, p. 47].

Item 4, Interaction With Precomposition III: Omitted, but see https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.y.precomp_fully_faithful.html for a formalised proof.

Item 5, Interaction With Precomposition IV: We claim **Items 5a to 5e** are equivalent:

- **Items 5a and 5b Are Equivalent:** This is true by the definition of corepresentably full morphism; see **Definition 9.2.2.1.1**.
- **Items 5a, 5c and 5d Are Equivalent:** See ?? of ??.
- **Items 5a and 5e Are Equivalent:** See [Adá+01, Item (b) of Remark 4.3].

This finishes the proof. \square

0127 **Question 8.5.2.1.3.** **Item 5** of **Proposition 8.5.2.1.2** gives a characterisation of the functors F for which F^* is full, but the characterisations given there are really messy. Are there better ones?

This question also appears as [MO 468121b].

0128 8.5.3 Fully Faithful Functors

Let C and \mathcal{D} be categories.

0129 Definition 8.5.3.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **fully faithful** if F is full and faithful, i.e. if, for each $A, B \in \text{Obj}(C)$, the action on morphisms

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is bijective.

012A Proposition 8.5.3.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor.

012B 1. *Characterisations.* The following conditions are equivalent:

012C (a) The functor F is fully faithful.

012D (b) We have a pullback square

$$\text{Arr}(C) \cong (C \times C) \times_{\mathcal{D} \times \mathcal{D}} \text{Arr}(\mathcal{D}), \quad \begin{array}{ccc} \text{Arr}(C) & \xrightarrow{\text{Arr}(F)} & \text{Arr}(\mathcal{D}) \\ \text{src} \times \text{tgt} \downarrow & \lrcorner & \downarrow \text{src} \times \text{tgt} \\ C \times C & \xrightarrow{F \times F} & \mathcal{D} \times \mathcal{D} \end{array}$$

in Cats .

012E 2. *Conservativity.* If F is fully faithful, then F is conservative.

012F 3. *Essential Injectivity.* If F is fully faithful, then F is essentially injective.

012G 4. *Interaction With Co/Limits.* If F is fully faithful, then F reflects co/limits.

012H 5. *Interaction With Postcomposition.* The following conditions are equivalent:

012J (a) The functor $F: C \rightarrow \mathcal{D}$ is fully faithful.

012K (b) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is fully faithful.

(c) The functor $F: C \rightarrow \mathcal{D}$ is a representably fully faithful morphism in Cats_2 in the sense of **Definition 9.1.3.1.1**.

012L

- 012M 6. *Interaction With Precomposition I.* If F is fully faithful, then the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

can fail to be fully faithful.

- 012N 7. *Interaction With Precomposition II.* If the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is fully faithful, then F *can fail* to be fully faithful (and in fact it can also fail to be either full or faithful).

- 012P 8. *Interaction With Precomposition III.* If F is essentially surjective and full, then the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is fully faithful.

- 012Q 9. *Interaction With Precomposition IV.* The following conditions are equivalent:

- 012R (a) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is fully faithful.

- 012S (b) The precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \text{Sets}) \rightarrow \text{Fun}(\mathcal{C}, \text{Sets})$$

is fully faithful.

- 012T (c) The functor

$$\text{Lan}_F : \text{Fun}(\mathcal{C}, \text{Sets}) \rightarrow \text{Fun}(\mathcal{D}, \text{Sets})$$

is fully faithful.

- 012U (d) The functor F is a corepresentably fully faithful morphism in Cats_2 in the sense of [Definition 9.2.3.1.1](#).

- 012V (e) The functor F is absolutely dense.

012W (f) The components

$$\eta_G : G \Longrightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta : \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})} \Longrightarrow \text{Ran}_F \circ F^*$$

of the adjunction $F^* \dashv \text{Ran}_F$ are all isomorphisms.

012X (g) The components

$$\epsilon_G : \text{Lan}_F(G \circ F) \Longrightarrow G$$

of the counit

$$\epsilon : \text{Lan}_F \circ F^* \Longrightarrow \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction $\text{Lan}_F \dashv F^*$ are all isomorphisms.

012Y (h) The natural transformation

$$\alpha : \text{Lan}_{h_F}(h^F) \Longrightarrow h$$

with components

$$\alpha_{B', B} : \int^{A \in C} h_{F_A}^{B'} \times h_B^{F_A} \rightarrow h_B^{B'}$$

given by

$$\alpha_{B', B}([\phi, \psi]) = \psi \circ \phi$$

is a natural isomorphism.

012Z (i) For each $B \in \text{Obj}(\mathcal{D})$, there exist:

- An object A_B of C ;
- A morphism $s_B : B \rightarrow F(A_B)$ of \mathcal{D} ;
- A morphism $r_B : F(A_B) \rightarrow B$ of \mathcal{D} ;

satisfying the following conditions:

i. The triple $(F(A_B), r_B, s_B)$ is a retract of B , i.e. we have $r_B \circ s_B = \text{id}_B$.

0130

0131

ii. For each morphism $f : B' \rightarrow B$ of \mathcal{D} , we have

$$[(A_B, s_{B'}, f \circ r_{B'})] = [(A_B, s_B \circ f, r_B)]$$

$$\text{in } \int^{A \in C} h_{F_A}^{B'} \times h_B^{F_A}.$$

Proof. Item 1, Characterisations: Omitted.

Item 2, Conservativity: This is a repetition of *Item 2* of [Proposition 8.5.4.1.2](#), and is proved there.

Item 3, Essential Injectivity: Omitted.

Item 4, Interaction With Co/Limits: Omitted.

Item 5, Interaction With Postcomposition: This follows from *Item 1* of [Proposition 8.5.1.1.2](#) and *Item 1* of [Proposition 8.5.2.1.2](#).

Item 6, Interaction With Precomposition I: See [\[MSE 733161\]](#) for an example of a fully faithful functor whose precomposition with which fails to be full.

Item 7, Interaction With Precomposition II: See [\[MSE 749304, Item 3\]](#).

Item 8, Interaction With Precomposition III: Omitted, but see https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.y.precomp_fully_faithful.html for a formalised proof.

Item 9, Interaction With Precomposition IV: We claim *Items 9a* to *9i* are equivalent:

- *Items 9a and 9d Are Equivalent:* This is true by the definition of corepresentably fully faithful morphism; see [Definition 9.2.3.1.1](#).
- *Items 9a, 9f and 9g Are Equivalent:* See ?? of ??.
- *Items 9a to 9c Are Equivalent:* This follows from [\[Low15, Proposition A.1.5\]](#).
- *Items 9a, 9e, 9h and 9i Are Equivalent:* See [\[Fre09, Theorem 4.1\]](#) and [\[Adá+01, Theorem 1.1\]](#).

This finishes the proof. □

0132 8.5.4 Conservative Functors

Let C and \mathcal{D} be categories.

0133 **Definition 8.5.4.1.1.** A functor $F: C \rightarrow \mathcal{D}$ is **conservative** if it satisfies the following condition:²⁰

- (★) For each $f \in \text{Mor}(C)$, if $F(f)$ is an isomorphism in \mathcal{D} , then f is an isomorphism in C .

0134 **Proposition 8.5.4.1.2.** Let $F: C \rightarrow \mathcal{D}$ be a functor.

0135 1. *Characterisations.* The following conditions are equivalent:

0136 (a) The functor F is conservative.

²⁰*Slogan:* A functor F is **conservative** if it reflects isomorphisms.

- 0137 (b) For each $f \in \text{Mor}(C)$, the morphism $F(f)$ is an isomorphism in \mathcal{D} iff f is an isomorphism in C .
- 0138 2. *Interaction With Fully Faithfulness.* Every fully faithful functor is conservative.
- 0139 3. *Interaction With Precomposition.* The following conditions are equivalent:
- 013A (a) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor
- $$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$
- is conservative.
- 013B (b) The equivalent conditions of [Item 4 of Proposition 8.5.1.1.2](#) are satisfied.

Proof. Item 1, Characterisations: This follows from [Item 1 of Proposition 8.4.1.1.6](#).
Item 2, Interaction With Fully Faithfulness: Let $F : C \rightarrow \mathcal{D}$ be a fully faithful functor, let $f : A \rightarrow B$ be a morphism of C , and suppose that F_f is an isomorphism. We have

$$\begin{aligned} F(\text{id}_B) &= \text{id}_{F(B)} \\ &= F(f) \circ F(f)^{-1} \\ &= F(f \circ f^{-1}). \end{aligned}$$

Similarly, $F(\text{id}_A) = F(f^{-1} \circ f)$. But since F is fully faithful, we must have

$$\begin{aligned} f \circ f^{-1} &= \text{id}_B, \\ f^{-1} \circ f &= \text{id}_A, \end{aligned}$$

showing f to be an isomorphism. Thus F is conservative. \square

- 013C **Question 8.5.4.1.3.** Is there a characterisation of functors $F : C \rightarrow \mathcal{D}$ satisfying the following condition:

- (\star) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is conservative?

This question also appears as [\[MO 468121a\]](#).

013D 8.5.5 Essentially Injective Functors

Let C and \mathcal{D} be categories.

013E Definition 8.5.5.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **essentially injective** if it satisfies the following condition:

(★) For each $A, B \in \text{Obj}(C)$, if $F(A) \cong F(B)$, then $A \cong B$.

013F Question 8.5.5.1.2. Is there a characterisation of functors $F: C \rightarrow \mathcal{D}$ such that:

013G 1. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is essentially injective, i.e. if $\phi \circ F \cong \psi \circ F$, then $\phi \cong \psi$ for all functors ϕ and ψ ?

013H 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is essentially injective, i.e. if $F \circ \phi \cong F \circ \psi$, then $\phi \cong \psi$?

This question also appears as [MO 468121a].

013J 8.5.6 Essentially Surjective Functors

Let C and \mathcal{D} be categories.

013K Definition 8.5.6.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **essentially surjective**²¹ if it satisfies the following condition:

(★) For each $D \in \text{Obj}(\mathcal{D})$, there exists some object A of C such that $F(A) \cong D$.

013L Question 8.5.6.1.2. Is there a characterisation of functors $F: C \rightarrow \mathcal{D}$ such that:

013M 1. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is essentially surjective?

013N 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is essentially surjective?

This question also appears as [MO 468121a].

²¹*Further Terminology:* Also called an **eso** functor, where the name “eso” comes from

013P 8.5.7 Equivalences of Categories**013Q Definition 8.5.7.1.1.** Let C and \mathcal{D} be categories.**013R** 1. An **equivalence of categories** between C and \mathcal{D} consists of a pair of functors

$$F: C \rightarrow \mathcal{D},$$

$$G: \mathcal{D} \rightarrow C$$

together with natural isomorphisms

$$\eta: \text{id}_C \xrightarrow{\sim} G \circ F,$$

$$\epsilon: F \circ G \xrightarrow{\sim} \text{id}_{\mathcal{D}}.$$

013S 2. An **adjoint equivalence of categories** between C and \mathcal{D} is an equivalence (F, G, η, ϵ) between C and \mathcal{D} which is also an adjunction.**013T Proposition 8.5.7.1.2.** Let $F: C \rightarrow \mathcal{D}$ be a functor.**013U** 1. *Characterisations.* If C and \mathcal{D} are small²², then the following conditions are equivalent:²³**013V** (a) The functor F is an equivalence of categories.**013W** (b) The functor F is fully faithful and essentially surjective.**013X** (c) The induced functor

$$\uparrow F\text{Sk}(C): \text{Sk}(C) \rightarrow \text{Sk}(\mathcal{D})$$

is an *isomorphism* of categories.**013Y** (d) For each $X \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(C, X)$$

is an equivalence of categories.

*essentially surjective on objects.*²²Otherwise there will be size issues. One can also work with large categories and universes, or require F to be *constructively* essentially surjective; see [MSE 1465107].²³In ZFC, the equivalence between **Item 1a** and **Item 1b** is equivalent to the axiom of choice; see [MO 119454].

In Univalent Foundations, this is true without requiring neither the axiom of choice nor the law of excluded middle.

- 013Z (e) For each $X \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is an equivalence of categories.

- 0140 2. *Two-Out-of-Three*. Let

$$\begin{array}{ccc} C & \xrightarrow{G \circ F} & \mathcal{E} \\ & \searrow F & \nearrow G \\ & \mathcal{D} & \end{array}$$

be a diagram in Cats . If two out of the three functors among F , G , and $G \circ F$ are equivalences of categories, then so is the third.

- 0141 3. *Stability Under Composition*. Let

$$C \begin{array}{c} \xrightarrow{F} \\ \xleftarrow{G} \end{array} \mathcal{D} \begin{array}{c} \xrightarrow{F'} \\ \xleftarrow{G'} \end{array} \mathcal{E}$$

be a diagram in Cats . If (F, G) and (F', G') are equivalences of categories, then so is their composite $(F' \circ F, G' \circ G)$.

- 0142 4. *Equivalences vs. Adjoint Equivalences*. Every equivalence of categories can be promoted to an adjoint equivalence.²⁴

- 0143 5. *Interaction With Groupoids*. If C and \mathcal{D} are groupoids, then the following conditions are equivalent:

0144 (a) The functor F is an equivalence of groupoids.

0145 (b) The following conditions are satisfied:

0146 i. The functor F induces a bijection

$$\pi_0(F) : \pi_0(C) \rightarrow \pi_0(\mathcal{D})$$

of sets.

0147 ii. For each $A \in \text{Obj}(C)$, the induced map

$$F_{x,x} : \text{Aut}_C(A) \rightarrow \text{Aut}_{\mathcal{D}}(F_A)$$

is an isomorphism of groups.

²⁴More precisely, we can promote an equivalence of categories (F, G, η, ϵ) to adjoint equivalences (F, G, η', ϵ) and (F, G, η, ϵ') .

Proof. Item 1, Characterisations: We claim that **Items 1a to 1e** are indeed equivalent:

1. **Item 1a** \implies **Item 1b**: Clear.
2. **Item 1b** \implies **Item 1a**: Since F is essentially surjective and C and \mathcal{D} are small, we can choose, using the axiom of choice, for each $B \in \text{Obj}(\mathcal{D})$, an object j_B of C and an isomorphism $i_B: B \rightarrow F_{j_B}$ of \mathcal{D} .
Since F is fully faithful, we can extend the assignment $B \mapsto j_B$ to a *unique* functor $j: \mathcal{D} \rightarrow C$ such that the isomorphisms $i_B: B \rightarrow F_{j_B}$ assemble into a natural isomorphism $\eta: \text{id}_{\mathcal{D}} \xrightarrow{\sim} F \circ j$, with a similar natural isomorphism $\epsilon: \text{id}_C \xrightarrow{\sim} j \circ F$. Hence F is an equivalence.
3. **Item 1a** \implies **Item 1c**: This follows from **Item 4** of **Proposition 8.1.5.1.3**.
4. **Item 1c** \implies **Item 1a**: Omitted.
5. **Items 1a, 1d and 1e Are Equivalent**: This follows from ??.

This finishes the proof of **Item 1**.

Item 2, Two-Out-of-Three: Omitted.

Item 3, Stability Under Composition: Clear.

Item 4, Equivalences vs. Adjoint Equivalences: See [Rie17, Proposition 4.4.5].

Item 5, Interaction With Groupoids: See [nLa24, Proposition 4.4]. \square

0148 8.5.8 Isomorphisms of Categories

0149 **Definition 8.5.8.1.1.** An **isomorphism of categories** is a pair of functors

$$\begin{aligned} F: C &\rightarrow \mathcal{D}, \\ G: \mathcal{D} &\rightarrow C \end{aligned}$$

such that we have

$$G \circ F = \text{id}_C,$$

$$F \circ G = \text{id}_{\mathcal{D}}.$$

014A **Example 8.5.8.1.2.** Categories can be equivalent but non-isomorphic. For example, the category consisting of two isomorphic objects is equivalent to pt , but not isomorphic to it.

014B **Proposition 8.5.8.1.3.** Let $F: C \rightarrow \mathcal{D}$ be a functor.

014C 1. *Characterisations.* If C and \mathcal{D} are small, then the following conditions are equivalent:

014D (a) The functor F is an isomorphism of categories.

014E (b) The functor F is fully faithful and bijective on objects.

014F (c) For each $X \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(C, X)$$

is an isomorphism of categories.

014G (d) For each $X \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_* : \text{Fun}(X, C) \rightarrow \text{Fun}(X, \mathcal{D})$$

is an isomorphism of categories.

Proof. *Item 1, Characterisations:* We claim that **Items 1a to 1d** are indeed equivalent:

1. *Items 1a and 1b Are Equivalent:* Omitted, but similar to **Item 1** of **Proposition 8.5.7.1.2.**

2. *Items 1a, 1c and 1d Are Equivalent:* This follows from ??.

This finishes the proof. \square

014H 8.6 More Conditions on Functors

014J 8.6.1 Dominant Functors

Let C and \mathcal{D} be categories.

014K **Definition 8.6.1.1.1.** A functor $F: C \rightarrow \mathcal{D}$ is **dominant** if every object of \mathcal{D} is a retract of some object in $\text{Im}(F)$, i.e.:

(\star) For each $B \in \text{Obj}(\mathcal{D})$, there exist:

- An object A of C ;
- A morphism $r: F(A) \rightarrow B$ of \mathcal{D} ;
- A morphism $s: B \rightarrow F(A)$ of \mathcal{D} ;

such that we have

$$r \circ s = \text{id}_B,$$

$$\begin{array}{ccc} B & \xrightarrow{s} & F(A) \\ & \searrow \text{id}_B & \downarrow r \\ & & B. \end{array}$$

014L Proposition 8.6.1.1.2. Let $F, G: C \rightrightarrows \mathcal{D}$ be functors and let $I: \mathcal{X} \rightarrow C$ be a functor.

014M 1. *Interaction With Right Whiskering.* If I is full and dominant, then the map

$$- \star \text{id}_I: \text{Nat}(F, G) \rightarrow \text{Nat}(F \circ I, G \circ I)$$

is a bijection.

014N 2. *Interaction With Adjunctions.* Let $(F, G): C \rightleftarrows \mathcal{D}$ be an adjunction.

014P (a) If F is dominant, then G is faithful.

014Q (b) The following conditions are equivalent:

014R i. The functor G is full.

014S ii. The restriction

$$\uparrow G \text{Im}_F: \text{Im}(F) \rightarrow C$$

of G to $\text{Im}(F)$ is full.

Proof. **Item 1, Interaction With Right Whiskering:** See [DFH75, Proposition 1.4].

Item 2, Interaction With Adjunctions: See [DFH75, Proposition 1.7]. \square

014T Question 8.6.1.1.3. Is there a characterisation of functors $F: C \rightarrow \mathcal{D}$ such that:

014U 1. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is dominant?

014V 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is dominant?

This question also appears as [MO 468121a].

014W 8.6.2 Monomorphisms of Categories

Let C and \mathcal{D} be categories.

014X Definition 8.6.2.1.1. A functor $F: C \rightarrow \mathcal{D}$ is a **monomorphism of categories** if it is a monomorphism in \mathbf{Cats} (see ??).

014Y Proposition 8.6.2.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor.

014Z 1. *Characterisations.* The following conditions are equivalent:

0150 (a) The functor F is a monomorphism of categories.

(b) The functor F is injective on objects and morphisms, i.e. F is

0151 injective on objects and the map

$$F: \text{Mor}(C) \rightarrow \text{Mor}(\mathcal{D})$$

is injective.

Proof. Item 1, Characterisations: Omitted. \square

0152 Question 8.6.2.1.3. Is there a characterisation of functors $F: C \rightarrow \mathcal{D}$ such that:

0153 1. For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is a monomorphism of categories?

0154 2. For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is a monomorphism of categories?

This question also appears as [MO 468121a].

0155 8.6.3 Epimorphisms of Categories

Let C and \mathcal{D} be categories.

0156 Definition 8.6.3.1.1. A functor $F: C \rightarrow \mathcal{D}$ is a **epimorphism of categories** if it is an epimorphism in \mathbf{Cats} (see ??).

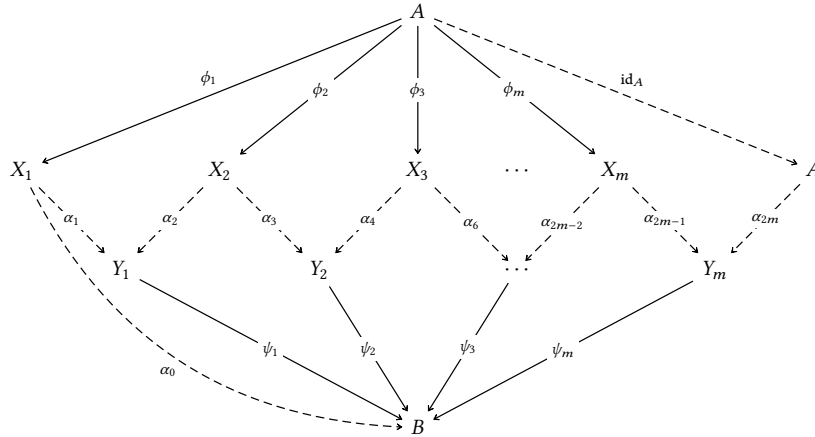
0157 Proposition 8.6.3.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor.

0158 1. *Characterisations.* The following conditions are equivalent:²⁵

0159 (a) The functor F is an epimorphism of categories.

²⁵*Further Terminology:* This statement is known as **Isbell's zigzag theorem**.

015A (b) For each morphism $f : A \rightarrow B$ of \mathcal{D} , we have a diagram



in \mathcal{D} satisfying the following conditions:

- 015B i. We have $f = \alpha_0 \circ \phi_1$.
- 015C ii. We have $f = \psi_m \circ \alpha_{2m}$.
- 015D iii. For each $0 \leq i \leq 2m$, we have $\alpha_i \in \text{Mor}(\text{Im}(F))$.

015E 2. *Surjectivity on Objects.* If F is an epimorphism of categories, then F is surjective on objects.

Proof. Item 1, Characterisations: See [Isb68].

Item 2, Surjectivity on Objects: Omitted. □

015F **Question 8.6.3.1.3.** Is there a characterisation of functors $F : \mathcal{C} \rightarrow \mathcal{D}$ such that:

015G 1. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is an epimorphism of categories?

015H 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is an epimorphism of categories?

This question also appears as [MO 468121a].

015J 8.6.4 Pseudomononic Functors

Let \mathcal{C} and \mathcal{D} be categories.

015K Definition 8.6.4.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **pseudomononic** if it satisfies the following conditions:

015L 1. For all diagrams of the form

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D},$$

if we have

$$\text{id}_F \star \alpha = \text{id}_F \star \beta,$$

then $\alpha = \beta$.

015M 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$ and each natural isomorphism

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C}$$

such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams, i.e. such that we have

$$\beta = \text{id}_F \star \alpha.$$

015N Proposition 8.6.4.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

015P 1. *Characterisations.* The following conditions are equivalent:

015Q (a) The functor F is pseudomononic.

- 015R (b) The functor F satisfies the following conditions:
- 015S i. The functor F is faithful, i.e. for each $A, B \in \text{Obj}(C)$, the action on morphisms

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_D(F_A, F_B)$$

of F at (A, B) is injective.

- 015T ii. For each $A, B \in \text{Obj}(C)$, the restriction

$$F_{A,B}^{\text{iso}}: \text{Iso}_C(A, B) \rightarrow \text{Iso}_D(F_A, F_B)$$

of the action on morphisms of F at (A, B) to isomorphisms is surjective.

- 015U (c) We have an isocomma square of the form

$$C \stackrel{\text{eq.}}{\cong} C \overset{\leftrightarrow}{\times}_D C, \quad \begin{array}{ccc} C & \xrightarrow{\text{id}_C} & C \\ \text{id}_C \downarrow & \swarrow \text{dashed} & \downarrow F \\ C & \xrightarrow{F} & D \end{array}$$

in Cats_2 up to equivalence.

- 015V (d) We have an isocomma square of the form

$$C \stackrel{\text{eq.}}{\cong} C \overset{\leftrightarrow}{\times}_{\text{Arr}(D)} D, \quad \begin{array}{ccc} C & \hookrightarrow & \text{Arr}(C) \\ F \downarrow & \swarrow \text{dashed} & \downarrow \text{Arr}(F) \\ D & \hookrightarrow & \text{Arr}(D) \end{array}$$

in Cats_2 up to equivalence.

- 015W (e) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition²⁶ functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, D)$$

is pseudomonadic.

- 015X 2. *Conservativity.* If F is pseudomonadic, then F is conservative.
- 015Y 3. *Essential Injectivity.* If F is pseudomonadic, then F is essentially injective.

Proof. Item 1, Characterisations: Omitted.

Item 2, Conservativity: Omitted.

Item 3, Essential Injectivity: Omitted. □

²⁶Asking the precomposition functors

$$F^*: \text{Fun}(D, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

015Z 8.6.5 Pseudoepic Functors

Let C and \mathcal{D} be categories.

0160 Definition 8.6.5.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **pseudoepic** if it satisfies the following conditions:

0161 1. For all diagrams of the form

$$C \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{X},$$

if we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then $\alpha = \beta$.

0162 2. For each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad C \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} \mathcal{X}$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{X}$$

of C such that we have an equality

$$C \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{X} = C \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} \mathcal{X}$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

0163 Proposition 8.6.5.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor.

0164 1. *Characterisations.* The following conditions are equivalent:

to be pseudomonadic leads to pseudoepic functors; see [Item 1b](#) of [Item 1](#) of [Proposition 8.6.5.1.2](#).

- 0165 (a) The functor F is pseudoepic.
- 0166 (b) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

given by precomposition by F is pseudomonic.

- 0167 (c) We have an isococomma square of the form

$$\mathcal{D} \xrightarrow{\text{eq.}} \mathcal{D} \amalg_{\mathcal{C}} \mathcal{D}, \quad \begin{array}{ccc} \mathcal{D} & \xleftarrow{\text{id}_{\mathcal{D}}} & \mathcal{D} \\ \uparrow \text{id}_{\mathcal{D}} & \nearrow & \uparrow F \\ \mathcal{D} & \xleftarrow{F} & \mathcal{C} \end{array}$$

in Cats_2 up to equivalence.

- 0168 2. *Dominance.* If F is pseudoepic, then F is dominant (Definition 8.6.1.1.1).

Proof. **Item 1, Characterisations:** Omitted.

Item 2, Dominance: If F is pseudoepic, then

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is pseudomonic for all $\mathcal{X} \in \text{Obj}(\text{Cats})$, and thus in particular faithful. By **Item 4g of Item 4 of Proposition 8.5.1.1.2**, this is equivalent to requiring F to be dominant. □

- 0169 **Question 8.6.5.1.3.** Is there a nice characterisation of the pseudoepic functors, similarly to the characterisation of pseudomonic functors given in **Item 1b of Item 1 of Proposition 8.6.4.1.2**?

This question also appears as [MO 321971].

- 016A **Question 8.6.5.1.4.** A pseudomonic and pseudoepic functor is dominant, faithful, essentially injective, and full on isomorphisms. Is it necessarily an equivalence of categories? If not, how bad can this fail, i.e. how far can a pseudomonic and pseudoepic functor be from an equivalence of categories? This question also appears as [MO 468334].

- 016B **Question 8.6.5.1.5.** Is there a characterisation of functors $F : \mathcal{C} \rightarrow \mathcal{D}$ such that:

- 016C 1. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is pseudoepic?

016D 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is pseudoepic?

This question also appears as [MO 468121a].

016E 8.7 Even More Conditions on Functors

016F 8.7.1 Injective on Objects Functors

Let C and \mathcal{D} be categories.

016G **Definition 8.7.1.1.1.** A functor $F: C \rightarrow \mathcal{D}$ is **injective on objects** if the action on objects

$$F: \text{Obj}(C) \rightarrow \text{Obj}(\mathcal{D})$$

of F is injective.

016H **Proposition 8.7.1.1.2.** Let $F: C \rightarrow \mathcal{D}$ be a functor.

016J 1. *Characterisations.* The following conditions are equivalent:

016K (a) The functor F is injective on objects.

016L (b) The functor F is an isofibration in Cats_2 .

Proof. *Item 1, Characterisations:* Omitted. □

016M 8.7.2 Surjective on Objects Functors

Let C and \mathcal{D} be categories.

016N **Definition 8.7.2.1.1.** A functor $F: C \rightarrow \mathcal{D}$ is **surjective on objects** if the action on objects

$$F: \text{Obj}(C) \rightarrow \text{Obj}(\mathcal{D})$$

of F is surjective.

016P 8.7.3 Bijective on Objects Functors

Let C and \mathcal{D} be categories.

016Q **Definition 8.7.3.1.1.** A functor $F: C \rightarrow \mathcal{D}$ is **bijective on objects**²⁷ if the action on objects

$$F: \text{Obj}(C) \rightarrow \text{Obj}(\mathcal{D})$$

of F is a bijection.

²⁷*Further Terminology:* Also called a **bo** functor.

016R 8.7.4 Functors Representably Faithful on Cores

Let \mathcal{C} and \mathcal{D} be categories.

016S Definition 8.7.4.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **representably faithful on cores** if, for each $X \in \text{Obj}(\text{Cats})$, the postcomposition by F functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is faithful.

016T Remark 8.7.4.1.2. In detail, a functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **representably faithful on cores** if, given a diagram of the form

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D},$$

if α and β are natural isomorphisms and we have

$$\text{id}_F \star \alpha = \text{id}_F \star \beta,$$

then $\alpha = \beta$.

016U Question 8.7.4.1.3. Is there a characterisation of functors representably faithful on cores?

016V 8.7.5 Functors Representably Full on Cores

Let \mathcal{C} and \mathcal{D} be categories.

016W Definition 8.7.5.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **representably full on cores** if, for each $X \in \text{Obj}(\text{Cats})$, the postcomposition by F functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is full.

016X Remark 8.7.5.1.2. In detail, a functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **representably full on cores** if, for each $X \in \text{Obj}(\text{Cats})$ and each natural isomorphism

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C}$$

such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in Cats_2 , i.e. such that we have

$$\beta = \text{id}_F \star \alpha.$$

016Y Question 8.7.5.1.3. Is there a characterisation of functors representably full on cores?

This question also appears as [MO 468121a].

016Z 8.7.6 Functors Representably Fully Faithful on Cores

Let \mathcal{C} and \mathcal{D} be categories.

0170 Definition 8.7.6.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **representably fully faithful on cores** if, for each $X \in \text{Obj}(\text{Cats})$, the postcomposition by F functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is fully faithful.

0171 Remark 8.7.6.1.2. In detail, a functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **representably fully faithful on cores** if it satisfies the conditions in **Remarks 8.7.4.1.2** and **8.7.5.1.2**, i.e.:

0172 1. For all diagrams of the form

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D},$$

with α and β natural isomorphisms, if we have $\text{id}_F \star \alpha = \text{id}_F \star \beta$, then $\alpha = \beta$.

0173 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$ and each natural isomorphism

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of \mathcal{C} , there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C}$$

of \mathcal{C} such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in Cats_2 , i.e. such that we have

$$\beta = \text{id}_F \star \alpha.$$

0174 **Question 8.7.6.1.3.** Is there a characterisation of functors representably fully faithful on cores?

0175 **8.7.7 Functors Corepresentably Faithful on Cores**

Let \mathcal{C} and \mathcal{D} be categories.

0176 **Definition 8.7.7.1.1.** A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **corepresentably faithful on cores** if, for each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition by F functor

$$F_*: \text{Core}(\text{Fun}(\mathcal{X}, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(\mathcal{X}, \mathcal{D}))$$

is faithful.

0177 **Remark 8.7.7.1.2.** In detail, a functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **corepresentably faithful on cores** if, given a diagram of the form

$$\mathcal{C} \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{X},$$

if α and β are natural isomorphisms and we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then $\alpha = \beta$.

0178 **Question 8.7.7.1.3.** Is there a characterisation of functors corepresentably faithful on cores?

0179 8.7.8 Functors Corepresentably Full on Cores

Let \mathcal{C} and \mathcal{D} be categories.

017A Definition 8.7.8.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **corepresentably full on cores** if, for each $X \in \text{Obj}(\text{Cats})$, the postcomposition by F functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is full.

017B Remark 8.7.8.1.2. In detail, a functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **corepresentably full on cores** if, for each $X \in \text{Obj}(\text{Cats})$ and each natural isomorphism

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad \mathcal{C} \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} X,$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = X \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in Cats_2 , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

017C Question 8.7.8.1.3. Is there a characterisation of functors corepresentably full on cores?

This question also appears as [MO 468121a].

017D 8.7.9 Functors Corepresentably Fully Faithful on Cores

Let \mathcal{C} and \mathcal{D} be categories.

017E Definition 8.7.9.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **corepresentably fully faithful on cores** if, for each $X \in \text{Obj}(\text{Cats})$, the postcomposition by F functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is fully faithful.

017F Remark 8.7.9.1.2. In detail, a functor $F: C \rightarrow \mathcal{D}$ is **corepresentably fully faithful on cores** if it satisfies the conditions in **Remarks 8.7.7.1.2** and **8.7.8.1.2**, i.e.:

017G 1. For all diagrams of the form

$$C \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{X},$$

if α and β are natural isomorphisms and we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then $\alpha = \beta$.

017H 2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$ and each natural isomorphism

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad C \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} \mathcal{X},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{X}$$

such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \\ \xrightarrow{\psi} \end{array} C \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in Cats_2 , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

017J Question 8.7.9.1.3. Is there a characterisation of functors corepresentably fully faithful on cores?

017K 8.8 Natural Transformations**017L 8.8.1 Transformations**

Let C and \mathcal{D} be categories and $F, G: C \Rightarrow \mathcal{D}$ be functors.

017M Definition 8.8.1.1.1. A transformation²⁸ $\alpha: F \Rightarrow G$ from F to G is a collection

$$\{\alpha_A: F(A) \rightarrow G(A)\}_{A \in \text{Obj}(C)}$$

of morphisms of \mathcal{D} .

017N Notation 8.8.1.1.2. We write $\text{Trans}(F, G)$ for the set of transformations from F to G .

017P 8.8.2 Natural Transformations

Let C and \mathcal{D} be categories and $F, G: C \Rightarrow \mathcal{D}$ be functors.

017Q Definition 8.8.2.1.1. A natural transformation $\alpha: F \Rightarrow G$ from F to G is a transformation

$$\{\alpha_A: F(A) \rightarrow G(A)\}_{A \in \text{Obj}(C)}$$

from F to G such that, for each morphism $f: A \rightarrow B$ of C , the diagram

$$\begin{array}{ccc} F(A) & \xrightarrow{F(f)} & F(B) \\ \alpha_A \downarrow & & \downarrow \alpha_B \\ G(A) & \xrightarrow{G(f)} & G(B) \end{array}$$

commutes.²⁹

017R Remark 8.8.2.1.2. We denote natural transformations in diagrams as

$$C \begin{array}{c} \xrightarrow{F} \\ \alpha \Downarrow \\ \xrightarrow{G} \end{array} \mathcal{D}.$$

017S Notation 8.8.2.1.3. We write $\text{Nat}(F, G)$ for the set of natural transformations from F to G .

²⁸Further Terminology: Also called an **unnatural transformation** for emphasis.

²⁹Further Terminology: The morphism $\alpha_A: F_A \rightarrow G_A$ is called the **component of α at A** .

017T Example 8.8.2.1.4. The **identity natural transformation** $\text{id}_F: F \Longrightarrow F$ of F is the natural transformation consisting of the collection

$$\{\text{id}_{F(A)}: F(A) \rightarrow F(A)\}_{A \in \text{Obj}(C)}.$$

Proof. The naturality condition for id_F is the requirement that, for each morphism $f: A \rightarrow B$ of C , the diagram

$$\begin{array}{ccc} F(A) & \xrightarrow{F(f)} & F(B) \\ \text{id}_{F(A)} \downarrow & & \downarrow \text{id}_{F(B)} \\ F(A) & \xrightarrow{F(f)} & F(B) \end{array}$$

commutes, which follows from unitality of the composition of C . \square

017U Definition 8.8.2.1.5. Two natural transformations $\alpha, \beta: F \Longrightarrow G$ are **equal** if we have

$$\alpha_A = \beta_A$$

for each $A \in \text{Obj}(C)$.

017V 8.8.3 Vertical Composition of Natural Transformations

017W Definition 8.8.3.1.1. The **vertical composition** of two natural transformations $\alpha: F \Longrightarrow G$ and $\beta: G \Longrightarrow H$ as in the diagram

$$\begin{array}{ccc} & F & \\ \curvearrowright & \downarrow \alpha & \curvearrowright \\ C & \xrightarrow{G} & D \\ \curvearrowleft & \downarrow \beta & \curvearrowleft \\ & H & \end{array}$$

is the natural transformation $\beta \circ \alpha: F \Longrightarrow H$ consisting of the collection

$$\{(\beta \circ \alpha)_A: F(A) \rightarrow H(A)\}_{A \in \text{Obj}(C)}$$

with

$$(\beta \circ \alpha)_A \stackrel{\text{def}}{=} \beta_A \circ \alpha_A$$

for each $A \in \text{Obj}(C)$.

Proof. The naturality condition for $\beta \circ \alpha$ is the requirement that the boundary

of the diagram

$$\begin{array}{ccc}
 F(A) & \xrightarrow{F(f)} & F(B) \\
 \alpha_A \downarrow & (1) & \downarrow \alpha_B \\
 G(A) & \xrightarrow{G(f)} & G(B) \\
 \beta_A \downarrow & (2) & \downarrow \beta_B \\
 H(A) & \xrightarrow{H(f)} & H(B)
 \end{array}$$

commutes. Since

1. Subdiagram (1) commutes by the naturality of α .
2. Subdiagram (2) commutes by the naturality of β .

so does the boundary diagram. Hence $\beta \circ \alpha$ is a natural transformation. \square

017X Proposition 8.8.3.1.2. Let \mathcal{C} , \mathcal{D} , and \mathcal{E} be categories.

017Y 1. *Functionality.* The assignment $(\beta, \alpha) \mapsto \beta \circ \alpha$ defines a function

$$\circ_{F,G,H} : \text{Nat}(G, H) \times \text{Nat}(F, G) \rightarrow \text{Nat}(F, H).$$

017Z 2. *Associativity.* Let $F, G, H, K : \mathcal{C} \rightrightarrows \mathcal{D}$ be functors. The diagram

$$\begin{array}{ccc}
 & \text{Nat}(H, K) \times (\text{Nat}(G, H) \times \text{Nat}(F, G)) & \\
 \alpha_{\text{Nat}(H,K), \text{Nat}(G,H), \text{Nat}(F,G)}^{\text{Sets}} \swarrow & & \searrow \text{id}_{\text{Nat}(H,K)} \times \circ_{F,G,H} \\
 (\text{Nat}(H, K) \times \text{Nat}(G, H)) \times \text{Nat}(F, G) & & \text{Nat}(H, K) \times \text{Nat}(F, H) \\
 \downarrow \circ_{G,H,K} \times \text{id}_{\text{Nat}(F,G)} & & \downarrow \circ_{F,H,K} \\
 \text{Nat}(G, K) \times \text{Nat}(F, G) & \xrightarrow{\circ_{F,G,K}} & \text{Nat}(F, K)
 \end{array}$$

commutes, i.e. given natural transformations

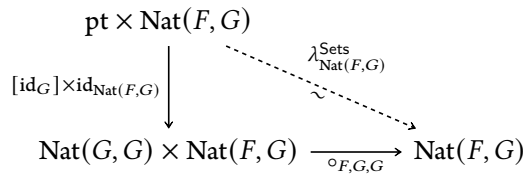
$$F \xrightarrow{\alpha} G \xrightarrow{\beta} H \xrightarrow{\gamma} K,$$

we have

$$(\gamma \circ \beta) \circ \alpha = \gamma \circ (\beta \circ \alpha).$$

0180 3. *Unitality.* Let $F, G: C \rightrightarrows D$ be functors.

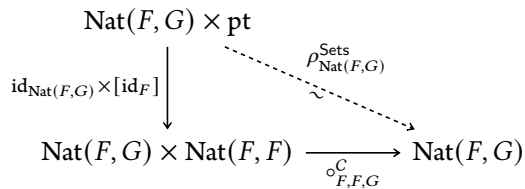
(a) *Left Unitality.* The diagram



commutes, i.e. given a natural transformation $\alpha: F \rightrightarrows G$, we have

$$\text{id}_G \circ \alpha = \alpha.$$

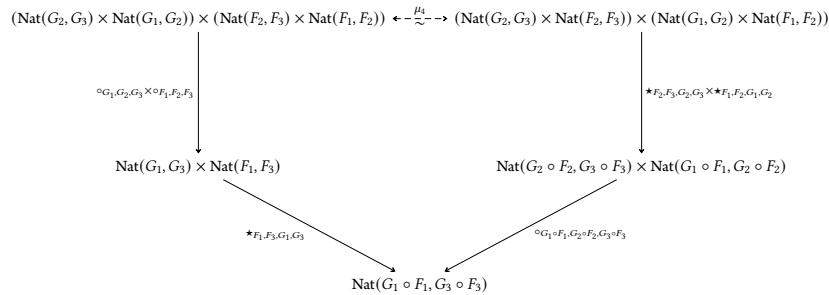
(b) *Right Unitality.* The diagram



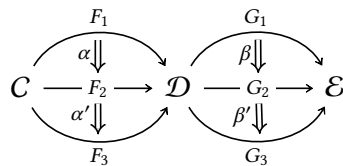
commutes, i.e. given a natural transformation $\alpha: F \rightrightarrows G$, we have

$$\alpha \circ \text{id}_F = \alpha.$$

0181 4. *Middle Four Exchange.* Let $F_1, F_2, F_3: C \rightarrow D$ and $G_1, G_2, G_3: D \rightarrow E$ be functors. The diagram



commutes, i.e. given a diagram



in Cats_2 , we have

$$(\beta' \star \alpha') \circ (\beta \star \alpha) = (\beta' \circ \beta) \star (\alpha' \circ \alpha).$$

Proof. Item 1, Functionality: Clear.

Item 2, Associativity: Indeed, we have

$$\begin{aligned} ((\gamma \circ \beta) \circ \alpha)_A &\stackrel{\text{def}}{=} (\gamma \circ \beta)_A \circ \alpha_A \\ &\stackrel{\text{def}}{=} (\gamma_A \circ \beta_A) \circ \alpha_A \\ &= \gamma_A \circ (\beta_A \circ \alpha_A) \\ &\stackrel{\text{def}}{=} \gamma_A \circ (\beta \circ \alpha)_A \\ &\stackrel{\text{def}}{=} (\gamma \circ (\beta \circ \alpha))_A \end{aligned}$$

for each $A \in \text{Obj}(C)$, showing the desired equality.

Item 3, Unitality: We have

$$\begin{aligned} (\text{id}_G \circ \alpha)_A &= \text{id}_G \circ \alpha_A \\ &= \alpha_A, \\ (\alpha \circ \text{id}_F)_A &= \alpha_A \circ \text{id}_F \\ &= \alpha_A \end{aligned}$$

for each $A \in \text{Obj}(C)$, showing the desired equality.

Item 4, Middle Four Exchange: This is proved in *Item 4* of [Proposition 8.8.4.1.3](#). \square

0182 8.8.4 Horizontal Composition of Natural Transformations

0183 **Definition 8.8.4.1.1.** The **horizontal composition**^{30,31} of two natural transformations $\alpha: F \Rightarrow G$ and $\beta: H \Rightarrow K$ as in the diagram

$$\begin{array}{ccc} C & \begin{array}{c} \xrightarrow{F} \\ \alpha \Downarrow \\ \xrightarrow{G} \end{array} & \mathcal{D} & \begin{array}{c} \xrightarrow{H} \\ \beta \Downarrow \\ \xrightarrow{K} \end{array} & \mathcal{E} \end{array}$$

of α and β is the natural transformation

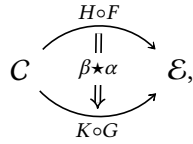
$$\beta \star \alpha: (H \circ F) \Rightarrow (K \circ G),$$

³⁰*Further Terminology:* Also called the **Godement product** of α and β .

³¹Horizontal composition forms a map

$$\star_{(F,H),(G,K)}: \text{Nat}(H, K) \times \text{Nat}(F, G) \rightarrow \text{Nat}(H \circ F, K \circ G).$$

as in the diagram



consisting of the collection

$$\{(\beta \star \alpha)_A : H(F(A)) \rightarrow K(G(A))\}_{A \in \text{Obj}(C)},$$

of morphisms of \mathcal{E} with

$$\begin{array}{ccc}
 H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\
 \beta_{F(A)} \downarrow & & \downarrow \beta_{G(A)} \\
 K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)).
 \end{array}$$

$(\beta \star \alpha)_A \stackrel{\text{def}}{=} \beta_{G(A)} \circ H(\alpha_A)$
 $= K(\alpha_A) \circ \beta_{F(A)},$

Proof. First, we claim that we indeed have

$$\begin{array}{ccc}
 H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\
 \beta_{F(A)} \downarrow & & \downarrow \beta_{G(A)} \\
 K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)).
 \end{array}$$

$\beta_{G(A)} \circ H(\alpha_A) = K(\alpha_A) \circ \beta_{F(A)},$

This is, however, simply the naturality square for β applied to the morphism $\alpha_A : F(A) \rightarrow G(A)$. Next, we check the naturality condition for $\beta \star \alpha$, which is the requirement that the boundary of the diagram

$$\begin{array}{ccc}
 H(F(A)) & \xrightarrow{H(F(f))} & H(F(B)) \\
 H(\alpha_A) \downarrow & (1) & \downarrow H(\alpha_B) \\
 H(G(A)) & \xrightarrow{H(G(f))} & H(G(B)) \\
 \beta_{G(A)} \downarrow & (2) & \downarrow \beta_{G(B)} \\
 K(G(A)) & \xrightarrow{K(G(f))} & K(G(B))
 \end{array}$$

commutes. Since

1. Subdiagram (1) commutes by the naturality of α .
2. Subdiagram (2) commutes by the naturality of β .

so does the boundary diagram. Hence $\beta \circ \alpha$ is a natural transformation.³² \square

0184 Definition 8.8.4.1.2. Let

$$\mathcal{X} \xrightarrow{F} \mathcal{C} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{D} \xrightarrow{G} \mathcal{Y}$$

be a diagram in Cats_2 .

0185 1. The **left whiskering of α with G** is the natural transformation³³

$$\text{id}_G \star \alpha: G \circ \phi \Longrightarrow G \circ \psi.$$

0186 2. The **right whiskering of α with F** is the natural transformation³⁴

$$\alpha \star \text{id}_F: \phi \circ F \Longrightarrow \psi \circ F.$$

0187 Proposition 8.8.4.1.3. Let \mathcal{C} , \mathcal{D} , and \mathcal{E} be categories.

0188 1. *Functionality.* The assignment $(\beta, \alpha) \mapsto \beta \star \alpha$ defines a function

$$\star_{(F,G),(H,K)}: \text{Nat}(H, K) \times \text{Nat}(F, G) \rightarrow \text{Nat}(H \circ F, K \circ G).$$

0189 2. *Associativity.* Let

$$\mathcal{C} \begin{array}{c} \xrightarrow{F_1} \\ \xrightarrow{G_1} \end{array} \mathcal{D} \begin{array}{c} \xrightarrow{F_2} \\ \xrightarrow{G_2} \end{array} \mathcal{E} \begin{array}{c} \xrightarrow{F_3} \\ \xrightarrow{G_3} \end{array} \mathcal{F}$$

be a diagram in Cats_2 . The diagram

$$\begin{array}{ccc} \text{Nat}(F_3, G_3) \times \text{Nat}(F_2, G_2) \times \text{Nat}(F_1, G_1) & \xrightarrow{\star_{(F_2, G_2), (F_3, G_3)} \times \text{id}} & \text{Nat}(F_3 \circ F_2, G_3 \circ G_2) \times \text{Nat}(F_1, G_1) \\ \downarrow \text{id} \times \star_{(F_1, G_1), (F_2, G_2)} & & \downarrow \star_{(F_3 \circ F_2), (G_3 \circ G_2, F_1, G_1)} \\ \text{Nat}(F_3, G_3) \times \text{Nat}(F_2 \circ F_1, G_2 \circ G_1) & \xrightarrow{\star_{(F_2 \circ F_1), (G_2 \circ G_1, F_3, G_3)}} & \text{Nat}(F_3 \circ F_2 \circ F_1, G_3 \circ G_2 \circ G_1) \end{array}$$

³²Reference: [Bor94, Proposition 1.3.4].

³³Further Notation: Also written $G\alpha$ or $G \star \alpha$, although we won't use either of these notations in this work.

³⁴Further Notation: Also written αF or $\alpha \star F$, although we won't use either of these notations

commutes, i.e. given natural transformations

$$C \begin{array}{c} \xrightarrow{F_1} \\ \alpha \Downarrow \\ \xrightarrow{G_1} \end{array} \mathcal{D} \begin{array}{c} \xrightarrow{F_2} \\ \beta \Downarrow \\ \xrightarrow{G_2} \end{array} \mathcal{E} \begin{array}{c} \xrightarrow{F_3} \\ \gamma \Downarrow \\ \xrightarrow{G_3} \end{array} \mathcal{F},$$

we have

$$(\gamma \star \beta) \star \alpha = \gamma \star (\beta \star \alpha).$$

- 018A 3. *Interaction With Identities.* Let $F: C \rightarrow D$ and $G: D \rightarrow E$ be functors. The diagram

$$\begin{array}{ccc} \text{pt} \times \text{pt} & \xrightarrow{[\text{id}_G] \times [\text{id}_F]} & \text{Nat}(G, G) \times \text{Nat}(F, F) \\ \uparrow \text{?} & & \downarrow \star_{(F,F),(G,G)} \\ \text{pt} & \xrightarrow{[\text{id}_{G \circ F}]} & \text{Nat}(G \circ F, G \circ F) \end{array}$$

commutes, i.e. we have

$$\text{id}_G \star \text{id}_F = \text{id}_{G \circ F}.$$

- 018B 4. *Middle Four Exchange.* Let $F_1, F_2, F_3: C \rightarrow D$ and $G_1, G_2, G_3: D \rightarrow E$ be functors. The diagram

$$\begin{array}{ccc} (\text{Nat}(G_2, G_3) \times \text{Nat}(G_1, G_2)) \times (\text{Nat}(F_2, F_3) \times \text{Nat}(F_1, F_2)) & \xleftarrow{\mu} & (\text{Nat}(G_2, G_3) \times \text{Nat}(F_2, F_3)) \times (\text{Nat}(G_1, G_2) \times \text{Nat}(F_1, F_2)) \\ \downarrow \circ_{G_1, G_2, G_3} \times \circ_{F_1, F_2, F_3} & & \downarrow \star_{F_2, F_3, G_2, G_3} \times \star_{F_1, F_2, G_1, G_2} \\ \text{Nat}(G_1, G_3) \times \text{Nat}(F_1, F_3) & & \text{Nat}(G_2 \circ F_2, G_3 \circ F_3) \times \text{Nat}(G_1 \circ F_1, G_2 \circ F_2) \\ \searrow \star_{F_1, F_3, G_1, G_3} & & \swarrow \circ_{G_1 \circ F_1, G_2 \circ F_2, G_3 \circ F_3} \\ & \text{Nat}(G_1 \circ F_1, G_3 \circ F_3) & \end{array}$$

commutes, i.e. given a diagram

$$C \begin{array}{c} \xrightarrow{F_1} \\ \alpha \Downarrow \\ \xrightarrow{F_2} \\ \alpha' \Downarrow \\ \xrightarrow{F_3} \end{array} \mathcal{D} \begin{array}{c} \xrightarrow{G_1} \\ \beta \Downarrow \\ \xrightarrow{G_2} \\ \beta' \Downarrow \\ \xrightarrow{G_3} \end{array} \mathcal{E}$$

in Cats_2 , we have

$$(\beta' \star \alpha') \circ (\beta \star \alpha) = (\beta' \circ \beta) \star (\alpha' \circ \alpha).$$

Proof. Item 1, Functionality: Clear.

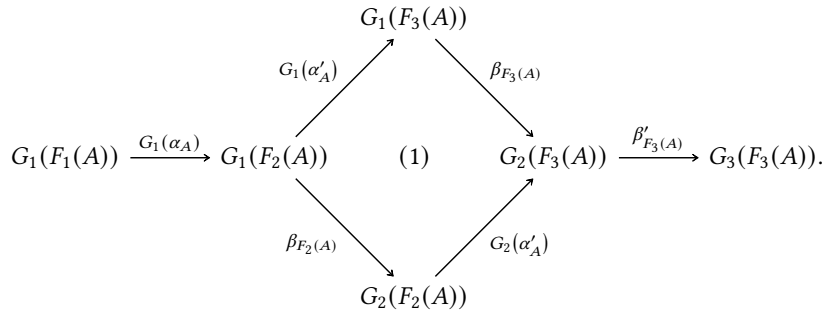
Item 2, Associativity: Omitted.

Item 3, Interaction With Identities: We have

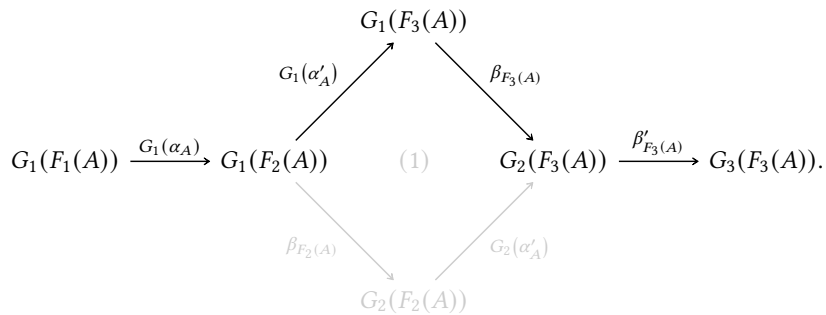
$$\begin{aligned}
 (\text{id}_G \star \text{id}_F)_A &\stackrel{\text{def}}{=} (\text{id}_G)_{F_A} \circ G_{(\text{id}_F)_A} \\
 &\stackrel{\text{def}}{=} \text{id}_{G_{F_A}} \circ G_{\text{id}_{F_A}} \\
 &= \text{id}_{G_{F_A}} \circ \text{id}_{G_{F_A}} \\
 &= \text{id}_{G_{F_A}} \\
 &\stackrel{\text{def}}{=} (\text{id}_{G \circ F})_A
 \end{aligned}$$

for each $A \in \text{Obj}(C)$, showing the desired equality.

Item 4, Middle Four Exchange: Let $A \in \text{Obj}(C)$ and consider the diagram

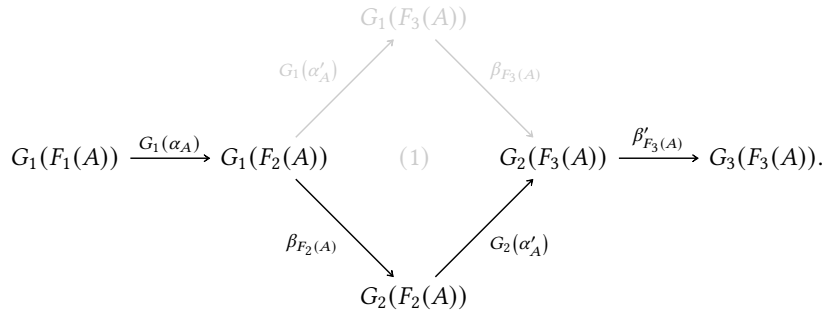


The top composition



in this work.

is given by $((\beta' \circ \beta) \star (\alpha' \circ \alpha))_A$, while the bottom composition



is given by $((\beta' \star \alpha') \circ (\beta \star \alpha))_A$. Now, Subdiagram (1) corresponds to the naturality condition

$$G_2(\alpha'_A) \circ \beta_{F_2(A)} = \beta_{F_3(A)} \circ G_1(\alpha'_A),$$

$$\begin{array}{ccc}
 G_1(F_2(A)) & \xrightarrow{G_1(\alpha'_A)} & G_1(F_3(A)) \\
 \beta_{F_2(A)} \downarrow & & \downarrow \beta_{F_3(A)} \\
 G_2(F_2(A)) & \xrightarrow{G_2(\alpha'_A)} & G_2(F_3(A))
 \end{array}$$

for $\beta: G_1 \Rightarrow G_2$ at $\alpha'_A: F_2(A) \rightarrow F_3(A)$, and thus commutes. Thus we have

$$((\beta' \circ \beta) \star (\alpha' \circ \alpha))_A = ((\beta' \star \alpha') \circ (\beta \star \alpha))_A$$

for each $A \in \text{Obj}(C)$ and therefore

$$(\beta' \star \alpha') \circ (\beta \star \alpha) = (\beta' \circ \beta) \star (\alpha' \circ \alpha).$$

This finishes the proof. □

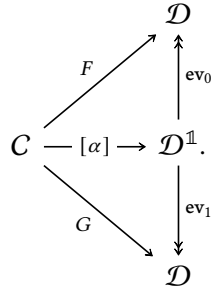
018C 8.8.5 Properties of Natural Transformations

018D Proposition 8.8.5.1.1. Let $F, G: C \Rightarrow D$ be functors. The following data are equivalent:³⁵

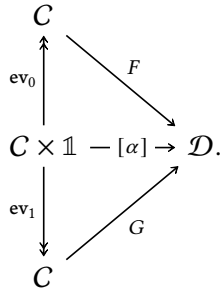
- 018E** 1. A natural transformation $\alpha: F \Rightarrow G$.

³⁵Taken from [MO 64365].

018F 2. A functor $[\alpha]: C \rightarrow \mathcal{D}^{\mathbb{1}}$ filling the diagram



018G 3. A functor $[\alpha]: C \times \mathbb{1} \rightarrow \mathcal{D}$ filling the diagram



Proof. From Item 1 to Item 2 and Back: We may identify $\mathcal{D}^{\mathbb{1}}$ with $\text{Arr}(\mathcal{D})$. Given a natural transformation $\alpha: F \Rightarrow G$, we have a functor

$$\begin{array}{ccc}
 [\alpha]: C & \longrightarrow & \mathcal{D}^{\mathbb{1}} \\
 A & \longmapsto & \alpha_A \\
 (f: A \rightarrow B) & \longmapsto & \left(\begin{array}{ccc} F_A & \xrightarrow{F_f} & F_B \\ \alpha_A \downarrow & & \downarrow \alpha_B \\ G_A & \xrightarrow{G_f} & G_B \end{array} \right)
 \end{array}$$

making the diagram in **Item 2** commute. Conversely, every such functor gives rise to a natural transformation from F to G , and these constructions are inverse to each other.

From Item 2 to Item 3 and Back: This follows from **Item 3** of **Proposition 8.9.1.1.2**.

□

018H 8.8.6 Natural Isomorphisms

Let C and \mathcal{D} be categories and let $F, G: C \Rightarrow \mathcal{D}$ be functors.

018J Definition 8.8.6.1.1. A natural transformation $\alpha: F \Rightarrow G$ is a **natural isomorphism** if there exists a natural transformation $\alpha^{-1}: G \Rightarrow F$ such that

$$\begin{aligned}\alpha^{-1} \circ \alpha &= \text{id}_F, \\ \alpha \circ \alpha^{-1} &= \text{id}_G.\end{aligned}$$

018K Proposition 8.8.6.1.2. Let $\alpha: F \Rightarrow G$ be a natural transformation.

018L 1. *Characterisations.* The following conditions are equivalent:

- 018M** (a) The natural transformation α is a natural isomorphism.
018N (b) For each $A \in \text{Obj}(C)$, the morphism $\alpha_A: F_A \rightarrow G_A$ is an isomorphism.

018P 2. *Componentwise Inverses of Natural Transformations Assemble Into Natural Transformations.* Let $\alpha^{-1}: G \Rightarrow F$ be a transformation such that, for each $A \in \text{Obj}(C)$, we have

$$\begin{aligned}\alpha_A^{-1} \circ \alpha_A &= \text{id}_{F(A)}, \\ \alpha_A \circ \alpha_A^{-1} &= \text{id}_{G(A)}.\end{aligned}$$

Then α^{-1} is a natural transformation.

Proof. Item 1, Characterisations: The implication **Item 1a** \implies **Item 1b** is clear, whereas the implication **Item 1b** \implies **Item 1a** follows from **Item 2**.

Item 2, Componentwise Inverses of Natural Transformations Assemble Into Natural Transformations: The naturality condition for α^{-1} corresponds to the commutativity of the diagram

$$\begin{array}{ccc} G(A) & \xrightarrow{G(f)} & G(B) \\ \alpha_A^{-1} \downarrow & & \downarrow \alpha_B^{-1} \\ F(A) & \xrightarrow{F(f)} & F(B) \end{array}$$

for each $A, B \in \text{Obj}(C)$ and each $f \in \text{Hom}_C(A, B)$. Considering the dia-

gram

$$\begin{array}{ccc}
 G(A) & \xrightarrow{G(f)} & G(B) \\
 \alpha_A^{-1} \downarrow & (1) & \downarrow \alpha_B^{-1} \\
 F(A) & \xrightarrow{F(f)} & F(B) \\
 \alpha_A \downarrow & (2) & \downarrow \alpha_B \\
 G(A) & \xrightarrow{G(f)} & G(B),
 \end{array}$$

where the boundary diagram as well as Subdiagram (2) commute, we have

$$\begin{aligned}
 G(f) &= G(f) \circ \text{id}_{G(A)} \\
 &= G(f) \circ \alpha_A \circ \alpha_A^{-1} \\
 &= \alpha_B \circ F(f) \circ \alpha_A^{-1}.
 \end{aligned}$$

Postcomposing both sides with α_B^{-1} , we get

$$\begin{aligned}
 \alpha_B^{-1} \circ G(f) &= \alpha_B^{-1} \circ \alpha_B \circ F(f) \circ \alpha_A^{-1} \\
 &= \text{id}_{F(B)} \circ F(f) \circ \alpha_A^{-1} \\
 &= F(f) \circ \alpha_A^{-1},
 \end{aligned}$$

which is the naturality condition we wanted to show. Thus α^{-1} is a natural transformation. \square

018Q 8.9 Categories of Categories

018R 8.9.1 Functor Categories

Let \mathcal{C} be a category and \mathcal{D} be a small category.

018S Definition 8.9.1.1.1. The **category of functors from \mathcal{C} to \mathcal{D}** ³⁶ is the category $\text{Fun}(\mathcal{C}, \mathcal{D})$ ³⁷ where

- *Objects.* The objects of $\text{Fun}(\mathcal{C}, \mathcal{D})$ are functors from \mathcal{C} to \mathcal{D} .
- *Morphisms.* For each $F, G \in \text{Obj}(\text{Fun}(\mathcal{C}, \mathcal{D}))$, we have

$$\text{Hom}_{\text{Fun}(\mathcal{C}, \mathcal{D})}(F, G) \stackrel{\text{def}}{=} \text{Nat}(F, G).$$

³⁶Further Terminology: Also called the **functor category** $\text{Fun}(\mathcal{C}, \mathcal{D})$.

³⁷Further Notation: Also written $\mathcal{D}^{\mathcal{C}}$ and $[\mathcal{C}, \mathcal{D}]$.

- *Identities.* For each $F \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$, the unit map

$$\mathbb{1}_F^{\text{Fun}(C, \mathcal{D})} : \text{pt} \rightarrow \text{Nat}(F, F)$$

of $\text{Fun}(C, \mathcal{D})$ at F is given by

$$\text{id}_F^{\text{Fun}(C, \mathcal{D})} \stackrel{\text{def}}{=} \text{id}_F,$$

where $\text{id}_F : F \Rightarrow F$ is the identity natural transformation of F of [Example 8.8.2.1.4](#).

- *Composition.* For each $F, G, H \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$, the composition map

$$\circ_{F, G, H}^{\text{Fun}(C, \mathcal{D})} : \text{Nat}(G, H) \times \text{Nat}(F, G) \rightarrow \text{Nat}(F, H)$$

of $\text{Fun}(C, \mathcal{D})$ at (F, G, H) is given by

$$\beta \circ_{F, G, H}^{\text{Fun}(C, \mathcal{D})} \alpha \stackrel{\text{def}}{=} \beta \circ \alpha,$$

where $\beta \circ \alpha$ is the vertical composition of α and β of [Item 1 of Proposition 8.8.3.1.2](#).

018T Proposition 8.9.1.1.2. Let C and \mathcal{D} be categories and let $F : C \rightarrow \mathcal{D}$ be a functor.

- 018U** 1. *Functoriality.* The assignments $C, \mathcal{D}, (C, \mathcal{D}) \mapsto \text{Fun}(C, \mathcal{D})$ define functors

$$\begin{aligned} \text{Fun}(C, -_2) &: \text{Cats} \rightarrow \text{Cats}, \\ \text{Fun}(-_1, \mathcal{D}) &: \text{Cats}^{\text{op}} \rightarrow \text{Cats}, \\ \text{Fun}(-_1, -_2) &: \text{Cats}^{\text{op}} \times \text{Cats} \rightarrow \text{Cats}. \end{aligned}$$

- 018V** 2. *2-Functoriality.* The assignments $C, \mathcal{D}, (C, \mathcal{D}) \mapsto \text{Fun}(C, \mathcal{D})$ define 2-functors

$$\begin{aligned} \text{Fun}(C, -_2) &: \text{Cats}_2 \rightarrow \text{Cats}_2, \\ \text{Fun}(-_1, \mathcal{D}) &: \text{Cats}_2^{\text{op}} \rightarrow \text{Cats}_2, \\ \text{Fun}(-_1, -_2) &: \text{Cats}_2^{\text{op}} \times \text{Cats}_2 \rightarrow \text{Cats}_2. \end{aligned}$$

- 018W** 3. *Adjointness.* We have adjunctions

$$\begin{aligned} (C \times - \dashv \text{Fun}(C, -)) &: \text{Cats} \begin{array}{c} \xrightarrow{C \times -} \\ \perp \\ \xleftarrow{\text{Fun}(C, -)} \end{array} \text{Cats}, \\ (- \times \mathcal{D} \dashv \text{Fun}(\mathcal{D}, -)) &: \text{Cats} \begin{array}{c} \xrightarrow{- \times \mathcal{D}} \\ \perp \\ \xleftarrow{\text{Fun}(\mathcal{D}, -)} \end{array} \text{Cats}, \end{aligned}$$

witnessed by bijections of sets

$$\begin{aligned}\mathrm{Hom}_{\mathrm{Cats}}(C \times \mathcal{D}, \mathcal{E}) &\cong \mathrm{Hom}_{\mathrm{Cats}}(\mathcal{D}, \mathrm{Fun}(C, \mathcal{E})), \\ \mathrm{Hom}_{\mathrm{Cats}}(C \times \mathcal{D}, \mathcal{E}) &\cong \mathrm{Hom}_{\mathrm{Cats}}(C, \mathrm{Fun}(\mathcal{D}, \mathcal{E})),\end{aligned}$$

natural in $C, \mathcal{D}, \mathcal{E} \in \mathrm{Obj}(\mathrm{Cats})$.

018X 4. *2-Adjointness*. We have 2-adjunctions

$$\begin{aligned}(C \times - \dashv \mathrm{Fun}(C, -)) &: \mathrm{Cats}_2 \begin{array}{c} \xrightarrow{C \times -} \\ \dashv_2 \\ \xleftarrow{\mathrm{Fun}(C, -)} \end{array} \mathrm{Cats}_2, \\ (- \times \mathcal{D} \dashv \mathrm{Fun}(\mathcal{D}, -)) &: \mathrm{Cats}_2 \begin{array}{c} \xrightarrow{- \times \mathcal{D}} \\ \dashv_2 \\ \xleftarrow{\mathrm{Fun}(\mathcal{D}, -)} \end{array} \mathrm{Cats}_2,\end{aligned}$$

witnessed by isomorphisms of categories

$$\begin{aligned}\mathrm{Fun}(C \times \mathcal{D}, \mathcal{E}) &\cong \mathrm{Fun}(\mathcal{D}, \mathrm{Fun}(C, \mathcal{E})), \\ \mathrm{Fun}(C \times \mathcal{D}, \mathcal{E}) &\cong \mathrm{Fun}(C, \mathrm{Fun}(\mathcal{D}, \mathcal{E})),\end{aligned}$$

natural in $C, \mathcal{D}, \mathcal{E} \in \mathrm{Obj}(\mathrm{Cats}_2)$.

018Y 5. *Interaction With Punctual Categories*. We have a canonical isomorphism of categories

$$\mathrm{Fun}(\mathrm{pt}, C) \cong C,$$

natural in $C \in \mathrm{Obj}(\mathrm{Cats})$.

018Z 6. *Objectwise Computation of Co/Limits*. Let

$$D: I \rightarrow \mathrm{Fun}(C, \mathcal{D})$$

be a diagram in $\mathrm{Fun}(C, \mathcal{D})$. We have isomorphisms

$$\begin{aligned}\lim(D)_A &\cong \lim_{i \in I}(D_i(A)), \\ \mathrm{colim}(D)_A &\cong \mathrm{colim}_{i \in I}(D_i(A)),\end{aligned}$$

naturally in $A \in \mathrm{Obj}(C)$.

0190 7. *Interaction With Co/Completeness*. If \mathcal{E} is co/complete, then so is $\mathrm{Fun}(C, \mathcal{E})$.

0191 8. *Monomorphisms and Epimorphisms.* Let $\alpha: F \Rightarrow G$ be a morphism of $\text{Fun}(C, \mathcal{D})$. The following conditions are equivalent:

0192 (a) The natural transformation

$$\alpha: F \Rightarrow G$$

is a monomorphism (resp. epimorphism) in $\text{Fun}(C, \mathcal{D})$.

0193 (b) For each $A \in \text{Obj}(C)$, the morphism

$$\alpha_A: F_A \rightarrow G_A$$

is a monomorphism (resp. epimorphism) in \mathcal{D} .

Proof. **Item 1, Functoriality:** Omitted.

Item 2, 2-Functoriality: Omitted.

Item 3, Adjointness: Omitted.

Item 4, 2-Adjointness: Omitted.

Item 5, Interaction With Punctual Categories: Omitted.

Item 6, Objectwise Computation of Co/Limits: Omitted.

Item 7, Interaction With Co/Completeness: This follows from ??.

Item 8, Monomorphisms and Epimorphisms: Omitted. \square

0194 8.9.2 The Category of Categories and Functors

0195 **Definition 8.9.2.1.1.** The **category of (small) categories and functors** is the category Cats where

- *Objects.* The objects of Cats are small categories.
- *Morphisms.* For each $C, \mathcal{D} \in \text{Obj}(\text{Cats})$, we have

$$\text{Hom}_{\text{Cats}}(C, \mathcal{D}) \stackrel{\text{def}}{=} \text{Obj}(\text{Fun}(C, \mathcal{D})).$$

- *Identities.* For each $C \in \text{Obj}(\text{Cats})$, the unit map

$$\mathbb{1}_C^{\text{Cats}}: \text{pt} \rightarrow \text{Hom}_{\text{Cats}}(C, C)$$

of Cats at C is defined by

$$\text{id}_C^{\text{Cats}} \stackrel{\text{def}}{=} \text{id}_C,$$

where $\text{id}_C: C \rightarrow C$ is the identity functor of C of **Example 8.4.1.1.4**.

- *Composition.* For each $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$, the composition map

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\text{Cats}} : \text{Hom}_{\text{Cats}}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}}(C, \mathcal{D}) \rightarrow \text{Hom}_{\text{Cats}}(C, \mathcal{E})$$

of Cats at $(C, \mathcal{D}, \mathcal{E})$ is given by

$$G \circ_{C, \mathcal{D}, \mathcal{E}}^{\text{Cats}} F \stackrel{\text{def}}{=} G \circ F,$$

where $G \circ F : C \rightarrow \mathcal{E}$ is the composition of F and G of **Definition 8.4.1.1.5**.

0196 Proposition 8.9.2.1.2. Let C be a category.

0197 1. *Co/Completeness.* The category Cats is complete and cocomplete.

0198 2. *Cartesian Monoidal Structure.* The quadruple $(\text{Cats}, \times, \text{pt}, \text{Fun})$ is a Cartesian closed monoidal category.

Proof. **Item 1, Co/Completeness:** Omitted.

Item 2, Cartesian Monoidal Structure: Omitted. \square

8.9.3 The 2-Category of Categories, Functors, and Natural Transformations

0199

019A Definition 8.9.3.1.1. The 2-category of (small) categories, functors, and natural transformations is the 2-category Cats_2 where

- *Objects.* The objects of Cats_2 are small categories.
- *Hom-Categories.* For each $C, \mathcal{D} \in \text{Obj}(\text{Cats}_2)$, we have

$$\text{Hom}_{\text{Cats}_2}(C, \mathcal{D}) \stackrel{\text{def}}{=} \text{Fun}(C, \mathcal{D}).$$

- *Identities.* For each $C \in \text{Obj}(\text{Cats}_2)$, the unit functor

$$\mathbb{1}_C^{\text{Cats}_2} : \text{pt} \rightarrow \text{Fun}(C, C)$$

of Cats_2 at C is the functor picking the identity functor $\text{id}_C : C \rightarrow C$ of C .

- *Composition.* For each $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats}_2)$, the composition bifunctor

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\text{Cats}_2} : \text{Hom}_{\text{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}_2}(C, \mathcal{D}) \rightarrow \text{Hom}_{\text{Cats}_2}(C, \mathcal{E})$$

of Cats_2 at $(C, \mathcal{D}, \mathcal{E})$ is the functor where

- *Action on Objects.* For each object $(G, F) \in \text{Obj}(\text{Hom}_{\text{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}_2}(C, \mathcal{D}))$, we have

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\text{Cats}_2}(G, F) \stackrel{\text{def}}{=} G \circ F.$$

- *Action on Morphisms.* For each morphism $(\beta, \alpha): (K, H) \implies (G, F)$ of $\text{Hom}_{\text{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}_2}(C, \mathcal{D})$, we have

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\text{Cats}_2}(\beta, \alpha) \stackrel{\text{def}}{=} \beta \star \alpha,$$

where $\beta \star \alpha$ is the horizontal composition of α and β of [Definition 8.8.4.1.1](#).

019B Proposition 8.9.3.1.2. Let C be a category.

019C 1. *2-Categorical Co/Completeness.* The 2-category Cats_2 is complete and cocomplete as a 2-category, having all 2-categorical and bicategorical co/limits.

Proof. *Item 1, Co/Completeness:* Omitted. □

019D 8.9.4 The Category of Groupoids

019E Definition 8.9.4.1.1. The **category of (small) groupoids** is the full subcategory Grpd of Cats spanned by the groupoids.

019F 8.9.5 The 2-Category of Groupoids

019G Definition 8.9.5.1.1. The **2-category of (small) groupoids** is the full sub-2-category Grpd_2 of Cats_2 spanned by the groupoids.

Appendices

8.A Other Chapters

Sets

1. [Sets](#)
2. [Constructions With Sets](#)
3. [Pointed Sets](#)
4. [Tensor Products of Pointed Sets](#)

Relations

5. [Relations](#)
6. [Constructions With Relations](#)
7. [Equivalence Relations and Apartness Relations](#)

Category Theory

8. **Categories
Bicategories**

9. **Types of Morphisms in Bicat-
egories**

Part IV

Bicategories

Chapter 9

Types of Morphisms in Bicategories

Ø19H In this chapter, we study special kinds of morphisms in bicategories:

1. *Monomorphisms and Epimorphisms in Bicategories* (Sections 9.1 and 9.2).

There is a large number of different notions capturing the idea of a “monomorphism” or of an “epimorphism” in a bicategory.

Arguably, the notion that best captures these concepts is that of a *pseudomonadic morphism* (Definition 9.1.10.1.1) and of a *pseudoepic morphism* (Definition 9.2.10.1.1), although the other notions introduced in Sections 9.1 and 9.2 are also interesting on their own.

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019J 9.1 Monomorphisms in Bicategories

019K 9.1.1 Representably Faithful Morphisms

Let C be a bicategory.

019L Definition 9.1.1.1.1. A 1-morphism $f: A \rightarrow B$ of C is **representably faithful**¹ if, for each $X \in \text{Obj}(C)$, the functor

$$f_* : \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is faithful.

019M Remark 9.1.1.1.2. In detail, f is representably faithful if, for all diagrams in C of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B,$$

if we have

$$\text{id}_f \star \alpha = \text{id}_f \star \beta,$$

then $\alpha = \beta$.

¹*Further Terminology:* Also called simply a **faithful morphism**, based on [Item 1](#) of

019N Example 9.1.1.1.3. Here are some examples of representably faithful morphisms.

019P 1. *Representably Faithful Morphisms in \mathbf{Cats}_2 .* The representably faithful morphisms in \mathbf{Cats}_2 are precisely the faithful functors; see **Item 1** of **Proposition 8.5.1.1.2**.

019Q 2. *Representably Faithful Morphisms in \mathbf{Rel} .* Every morphism of \mathbf{Rel} is representably faithful; see **Item 1** of **Proposition 5.3.8.1.1**.

019R 9.1.2 Representably Full Morphisms

Let C be a bicategory.

019S Definition 9.1.2.1.1. A 1-morphism $f: A \rightarrow B$ of C is **representably full**² if, for each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is full.

019T Remark 9.1.2.1.2. In detail, f is representably full if, for each $X \in \text{Obj}(C)$ and each 2-morphism

$$\beta: f \circ \phi \Longrightarrow f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of C , there exists a 2-morphism

$$\alpha: \phi \Longrightarrow \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A$$

of C such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B = X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

Example 9.1.1.1.3.

²*Further Terminology:* Also called simply a **full morphism**, based on **Item 1** of

019U **Example 9.1.2.1.3.** Here are some examples of representably full morphisms.

019V 1. *Representably Full Morphisms in \mathbf{Cats}_2 .* The representably full morphisms in \mathbf{Cats}_2 are precisely the full functors; see **Item 1** of **Proposition 8.5.2.1.2**.

019W 2. *Representably Full Morphisms in \mathbf{Rel} .* The representably full morphisms in \mathbf{Rel} are characterised in **Item 2** of **Proposition 5.3.8.1.1**.

019X 9.1.3 Representably Fully Faithful Morphisms

Let C be a bicategory.

019Y **Definition 9.1.3.1.1.** A 1-morphism $f: A \rightarrow B$ of C is **representably fully faithful**³ if the following equivalent conditions are satisfied:

- 019Z 1. The 1-morphism f is representably faithful (**Definition 9.1.1.1.1**) and representably full (**Definition 9.1.2.1.1**).
- 01A0 2. For each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is fully faithful.

01A1 **Remark 9.1.3.1.2.** In detail, f is representably fully faithful if the conditions in **Remark 9.1.1.1.2** and **Remark 9.1.2.1.2** hold:

1. For all diagrams in C of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B,$$

if we have

$$\text{id}_f \star \alpha = \text{id}_f \star \beta,$$

then $\alpha = \beta$.

Example 9.1.2.1.3.

³*Further Terminology:* Also called simply a **fully faithful morphism**, based on **Item 1** of **Example 9.1.3.1.3**.

2. For each $X \in \text{Obj}(C)$ and each 2-morphism

$$\beta: f \circ \phi \Longrightarrow f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of C , there exists a 2-morphism

$$\alpha: \phi \Longrightarrow \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A$$

of C such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B = X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

01A2 Example 9.1.3.1.3. Here are some examples of representably fully faithful morphisms.

01A3 1. *Representably Fully Faithful Morphisms in \mathbf{Cats}_2 .* The representably fully faithful morphisms in \mathbf{Cats}_2 are precisely the fully faithful functors; see **Item 5 of Proposition 8.5.3.1.2.**

01A4 2. *Representably Fully Faithful Morphisms in \mathbf{Rel} .* The representably fully faithful morphisms of \mathbf{Rel} coincide (**Item 3 of Proposition 5.3.8.1.1**) with the representably full morphisms in \mathbf{Rel} , which are characterised in **Item 2 of Proposition 5.3.8.1.1.**

01A5 9.1.4 Morphisms Representably Faithful on Cores

Let C be a bicategory.

01A6 Definition 9.1.4.1.1. A 1-morphism $f: A \rightarrow B$ of C is **representably faithful on cores** if, for each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Core}(\text{Hom}_C(X, A)) \rightarrow \text{Core}(\text{Hom}_C(X, B))$$

given by postcomposition by f is faithful.

01A7 Remark 9.1.4.1.2. In detail, f is representably faithful on cores if, for all diagrams in C of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B,$$

if α and β are 2-isomorphisms and we have

$$\text{id}_f \star \alpha = \text{id}_f \star \beta,$$

then $\alpha = \beta$.

01A8 9.1.5 Morphisms Representably Full on Cores

Let C be a bicategory.

01A9 Definition 9.1.5.1.1. A 1-morphism $f: A \rightarrow B$ of C is **representably full on cores** if, for each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Core}(\text{Hom}_C(X, A)) \rightarrow \text{Core}(\text{Hom}_C(X, B))$$

given by postcomposition by f is full.

01AA Remark 9.1.5.1.2. In detail, f is representably full on cores if, for each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: f \circ \phi \xrightarrow{\sim} f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A$$

of C such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B = X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

01AB 9.1.6 Morphisms Representably Fully Faithful on Cores

Let C be a bicategory.

01AC Definition 9.1.6.1.1. A 1-morphism $f: A \rightarrow B$ of C is **representably fully faithful on cores** if the following equivalent conditions are satisfied:

1. The 1-morphism f is representably faithful on cores (**Definition 9.1.5.1.1**)

01AD and representably full on cores (**Definition 9.1.4.1.1**).

01AE 2. For each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Core}(\text{Hom}_C(X, A)) \rightarrow \text{Core}(\text{Hom}_C(X, B))$$

given by postcomposition by f is fully faithful.

01AF Remark 9.1.6.1.2. In detail, f is representably fully faithful on cores if the conditions in **Remark 9.1.4.1.2** and **Remark 9.1.5.1.2** hold:

1. For all diagrams in C of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B,$$

if α and β are 2-isomorphisms and we have

$$\text{id}_f \star \alpha = \text{id}_f \star \beta,$$

then $\alpha = \beta$.

2. For each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: f \circ \phi \xrightarrow{\sim} f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A$$

of C such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B = X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

01AG 9.1.7 Representably Essentially Injective Morphisms

Let C be a bicategory.

01AH Definition 9.1.7.1.1. A 1-morphism $f: A \rightarrow B$ of C is **representably essentially injective** if, for each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is essentially injective.

01AJ Remark 9.1.7.1.2. In detail, f is representably essentially injective if, for each pair of morphisms $\phi, \psi: X \rightrightarrows A$ of C , the following condition is satisfied:

$$(\star) \text{ If } f \circ \phi \cong f \circ \psi, \text{ then } \phi \cong \psi.$$

01AK 9.1.8 Representably Conservative Morphisms

Let C be a bicategory.

01AL Definition 9.1.8.1.1. A 1-morphism $f: A \rightarrow B$ of C is **representably conservative** if, for each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is conservative.

01AM Remark 9.1.8.1.2. In detail, f is representably conservative if, for each pair of morphisms $\phi, \psi: X \rightrightarrows A$ and each 2-morphism

$$\alpha: \phi \rightrightarrows \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A$$

of C , if the 2-morphism

$$\text{id}_f \star \alpha: f \circ \phi \rightrightarrows f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \parallel \\ \text{id}_f \star \alpha \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

is a 2-isomorphism, then so is α .

01AN 9.1.9 Strict Monomorphisms

Let C be a bicategory.

01AP Definition 9.1.9.1.1. A 1-morphism $f: A \rightarrow B$ of C is a **strict monomorphism** if, for each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is injective on objects, i.e. its action on objects

$$f_*: \text{Obj}(\text{Hom}_C(X, A)) \rightarrow \text{Obj}(\text{Hom}_C(X, B))$$

is injective.

01AQ Remark 9.1.9.1.2. In detail, f is a strict monomorphism in C if, for each diagram in C of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B,$$

if $f \circ \phi = f \circ \psi$, then $\phi = \psi$.

01AR Example 9.1.9.1.3. Here are some examples of strict monomorphisms.

01AS 1. *Strict Monomorphisms in Cats_2 .* The strict monomorphisms in Cats_2 are precisely the functors which are injective on objects and injective on morphisms; see **Item 1** of **Proposition 8.6.2.1.2**.

01AT 2. *Strict Monomorphisms in Rel .* The strict monomorphisms in Rel are characterised in **Proposition 5.3.7.1.1**.

01AU 9.1.10 Pseudomonic Morphisms

Let C be a bicategory.

01AV Definition 9.1.10.1.1. A 1-morphism $f: A \rightarrow B$ of C is **pseudomonic** if, for each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is pseudomonic.

01AW Remark 9.1.10.1.2. In detail, a 1-morphism $f: A \rightarrow B$ of C is pseudomonic if it satisfies the following conditions:

01AX 1. For all diagrams in C of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B,$$

if we have

$$\text{id}_f \star \alpha = \text{id}_f \star \beta,$$

then $\alpha = \beta$.

01AY 2. For each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: f \circ \phi \xrightarrow{\sim} f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A$$

of C such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} A \xrightarrow{f} B = X \begin{array}{c} \xrightarrow{f \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{f \circ \psi} \end{array} B$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

01AZ **Proposition 9.1.10.1.3.** Let $f: A \rightarrow B$ be a 1-morphism of C .

01B0 1. *Characterisations.* The following conditions are equivalent:

- 01B1 (a) The morphism f is pseudomonic.
- 01B2 (b) The morphism f is representably full on cores and representably faithful.
- 01B3 (c) We have an isocomma square of the form

$$A \xrightarrow{\text{eq.}} A \overset{\leftrightarrow}{\times}_B A, \quad \begin{array}{ccc} A & \xrightarrow{\text{id}_A} & A \\ \text{id}_A \downarrow & \nearrow \text{---} & \downarrow F \\ A & \xrightarrow{F} & B \end{array}$$

in C up to equivalence.

01B4 2. *Interaction With Cotensors.* If C has cotensors with $\mathbb{1}$, then the following conditions are equivalent:

- (a) The morphism f is pseudomonic.
- (b) We have an isocomma square of the form

$$A \xrightarrow{\text{eq.}} A \times_{\mathbb{1} \pitchfork F} B, \quad \begin{array}{ccc} A & \longrightarrow & \mathbb{1} \pitchfork A \\ F \downarrow & \dashrightarrow & \downarrow \mathbb{1} \pitchfork F \\ B & \longrightarrow & \mathbb{1} \pitchfork B \end{array}$$

in C up to equivalence.

Proof. Item 1, Characterisations: Omitted.

Item 2, Interaction With Cotensors: Omitted. □

01B5 9.2 Epimorphisms in Bicategories

01B6 9.2.1 Corepresentably Faithful Morphisms

Let C be a bicategory.

01B7 **Definition 9.2.1.1.1.** A 1-morphism $f: A \rightarrow B$ of C is **corepresentably faithful** if, for each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is faithful.

01B8 **Remark 9.2.1.1.2.** In detail, f is corepresentably faithful if, for all diagrams in C of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} X,$$

if we have

$$\alpha \star \text{id}_f = \beta \star \text{id}_f,$$

then $\alpha = \beta$.

01B9 **Example 9.2.1.1.3.** Here are some examples of corepresentably faithful morphisms.

01BA 1. *Corepresentably Faithful Morphisms in Cats_2 .* The corepresentably faithful morphisms in Cats_2 are characterised in **Item 4** of **Proposition 8.5.1.1.2**.

01BB 2. *Corepresentably Faithful Morphisms in Rel .* Every morphism of Rel is corepresentably faithful; see **Item 1** of **Proposition 5.3.10.1.1**.

01BC 9.2.2 Corepresentably Full Morphisms

Let C be a bicategory.

01BD Definition 9.2.2.1.1. A 1-morphism $f: A \rightarrow B$ of C is **corepresentably full** if, for each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is full.

01BE Remark 9.2.2.1.2. In detail, f is corepresentably full if, for each $X \in \text{Obj}(C)$ and each 2-morphism

$$\beta: \phi \circ f \Rightarrow \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of C , there exists a 2-morphism

$$\alpha: \phi \Rightarrow \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

of C such that we have an equality

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X = A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

01BF Example 9.2.2.1.3. Here are some examples of corepresentably full morphisms.

01BG 1. *Corepresentably Full Morphisms in Cats_2 .* The corepresentably full morphisms in Cats_2 are characterised in **Item 5** of **Proposition 8.5.2.1.2**.

01BH 2. *Corepresentably Full Morphisms in \mathbf{Rel} .* The corepresentably full morphisms in \mathbf{Rel} are characterised in **??** of **Proposition 5.3.8.1.1**.

01BJ 9.2.3 Corepresentably Fully Faithful Morphisms

Let C be a bicategory.

01BK Definition 9.2.3.1.1. A 1-morphism $f: A \rightarrow B$ of C is **corepresentably fully faithful**⁴ if the following equivalent conditions are satisfied:

- 1. The 1-morphism f is corepresentably full (Definition 9.2.2.1.1) and corepresentably faithful (Definition 9.2.1.1.1).
- 2. For each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is fully faithful.

01BN Remark 9.2.3.1.2. In detail, f is corepresentably fully faithful if the conditions in Remark 9.2.1.1.2 and Remark 9.2.2.1.2 hold:

- 1. For all diagrams in C of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} X,$$

if we have

$$\alpha \star \text{id}_f = \beta \star \text{id}_f,$$

then $\alpha = \beta$.

- 2. For each $X \in \text{Obj}(C)$ and each 2-morphism

$$\beta: \phi \circ f \Longrightarrow \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of C , there exists a 2-morphism

$$\alpha: \phi \Longrightarrow \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

⁴*Further Terminology:* Corepresentably fully faithful morphisms have also been called **lax epimorphisms** in the literature (e.g. in [Adá+01]), though we will always use the name “corepresentably fully faithful morphism” instead in this work.

of C such that we have an equality

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X = A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

01BP Example 9.2.3.1.3. Here are some examples of corepresentably fully faithful morphisms.

01BQ 1. *Corepresentably Fully Faithful Morphisms in Cats_2 .* The fully faithful epimorphisms in Cats_2 are characterised in **Item 9** of **Proposition 8.5.3.1.2**.

01BR 2. *Corepresentably Fully Faithful Morphisms in \mathbf{Rel} .* The corepresentably fully faithful morphisms of \mathbf{Rel} coincide (**Item 3** of **Proposition 5.3.10.1.1**) with the corepresentably full morphisms in \mathbf{Rel} , which are characterised in **Item 2** of **Proposition 5.3.10.1.1**.

01BS 9.2.4 Morphisms Corepresentably Faithful on Cores

Let C be a bicategory.

01BT Definition 9.2.4.1.1. A 1-morphism $f : A \rightarrow B$ of C is **corepresentably faithful on cores** if, for each $X \in \text{Obj}(C)$, the functor

$$f^* : \text{Core}(\text{Hom}_C(B, X)) \rightarrow \text{Core}(\text{Hom}_C(A, X))$$

given by precomposition by f is faithful.

01BU Remark 9.2.4.1.2. In detail, f is corepresentably faithful on cores if, for all diagrams in C of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} X,$$

if α and β are 2-isomorphisms and we have

$$\alpha \star \text{id}_f = \beta \star \text{id}_f,$$

then $\alpha = \beta$.

01BV 9.2.5 Morphisms Corepresentably Full on Cores

Let C be a bicategory.

01BW Definition 9.2.5.1.1. A 1-morphism $f: A \rightarrow B$ of C is **corepresentably full on cores** if, for each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Core}(\text{Hom}_C(B, X)) \rightarrow \text{Core}(\text{Hom}_C(A, X))$$

given by precomposition by f is full.

01BX Remark 9.2.5.1.2. In detail, f is corepresentably full on cores if, for each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: \phi \circ f \xrightarrow{\sim} \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

of C such that we have an equality

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X = A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

01BY 9.2.6 Morphisms Corepresentably Fully Faithful on Cores

Let C be a bicategory.

01BZ Definition 9.2.6.1.1. A 1-morphism $f: A \rightarrow B$ of C is **corepresentably fully faithful on cores** if the following equivalent conditions are satisfied:

1. The 1-morphism f is corepresentably full on cores (**Definition 9.2.5.1.1**) and corepresentably faithful on cores (**Definition 9.2.1.1.1**).
2. For each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Core}(\text{Hom}_C(B, X)) \rightarrow \text{Core}(\text{Hom}_C(A, X))$$

given by precomposition by f is fully faithful.

01C2 Remark 9.2.6.1.2. In detail, f is corepresentably fully faithful on cores if the conditions in **Remark 9.2.4.1.2** and **Remark 9.2.5.1.2** hold:

1. For all diagrams in C of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} X,$$

if α and β are 2-isomorphisms and we have

$$\alpha \star \text{id}_f = \beta \star \text{id}_f,$$

then $\alpha = \beta$.

2. For each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: \phi \circ f \xrightarrow{\sim} \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

of C such that we have an equality

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X = A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

01C3 9.2.7 Corepresentably Essentially Injective Morphisms

Let C be a bicategory.

01C4 Definition 9.2.7.1.1. A 1-morphism $f: A \rightarrow B$ of C is **corepresentably essentially injective** if, for each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is essentially injective.

01C5 Remark 9.2.7.1.2. In detail, f is corepresentably essentially injective if, for each pair of morphisms $\phi, \psi: B \rightrightarrows X$ of C , the following condition is satisfied:

(\star) If $\phi \circ f \cong \psi \circ f$, then $\phi \cong \psi$.

01C6 9.2.8 Corepresentably Conservative Morphisms

Let C be a bicategory.

01C7 Definition 9.2.8.1.1. A 1-morphism $f: A \rightarrow B$ of C is **corepresentably conservative** if, for each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is conservative.

01C8 Remark 9.2.8.1.2. In detail, f is corepresentably conservative if, for each pair of morphisms $\phi, \psi: B \rightrightarrows X$ and each 2-morphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

of C , if the 2-morphism

$$\alpha \star \text{id}_f: \phi \circ f \xrightarrow{\sim} \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \alpha \star \text{id}_f \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

is a 2-isomorphism, then so is α .

01C9 9.2.9 Strict Epimorphisms

Let C be a bicategory.

01CA Definition 9.2.9.1.1. A 1-morphism $f: A \rightarrow B$ is a **strict epimorphism in C** if, for each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is injective on objects, i.e. its action on objects

$$f_*: \text{Obj}(\text{Hom}_C(B, X)) \rightarrow \text{Obj}(\text{Hom}_C(A, X))$$

is injective.

01CB Remark 9.2.9.1.2. In detail, f is a strict epimorphism if, for each diagram in C of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \psi \\ \xrightarrow{\psi} \end{array} X,$$

if $\phi \circ f = \psi \circ f$, then $\phi = \psi$.

01CC **Example 9.2.9.1.3.** Here are some examples of strict epimorphisms.

01CD 1. *Strict Epimorphisms in \mathbf{Cats}_2 .* The strict epimorphisms in \mathbf{Cats}_2 are characterised in **Item 1** of **Proposition 8.6.3.1.2**.

01CE 2. *Strict Epimorphisms in \mathbf{Rel} .* The strict epimorphisms in \mathbf{Rel} are characterised in **Proposition 5.3.9.1.1**.

01CF **9.2.10 Pseudoepic Morphisms**

Let C be a bicategory.

01CG **Definition 9.2.10.1.1.** A 1-morphism $f: A \rightarrow B$ of C is **pseudoepic** if, for each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is pseudomonic.

01CH **Remark 9.2.10.1.2.** In detail, a 1-morphism $f: A \rightarrow B$ of C is pseudoepic if it satisfies the following conditions:

01CJ 1. For all diagrams in C of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \beta \\ \xrightarrow{\psi} \end{array} X,$$

if we have

$$\alpha \star \text{id}_f = \beta \star \text{id}_f,$$

then $\alpha = \beta$.

01CK 2. For each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: \phi \circ f \xrightarrow{\sim} \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

of C such that we have an equality

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X = A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ f} \end{array} X$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

01CL Proposition 9.2.10.1.3. Let $f: A \rightarrow B$ be a 1-morphism of C .

01CM 1. *Characterisations.* The following conditions are equivalent:

- 01CN** (a) The morphism f is pseudoepic.
- (b) The morphism f is corepresentably full on cores and corepresentably faithful.
- 01CP**
- 01CQ** (c) We have an isococoma square of the form

$$B \xrightarrow{\text{eq.}} B \coprod_A B, \quad \begin{array}{ccc} B & \xleftarrow{\text{id}_B} & B \\ \text{id}_B \uparrow & \dashrightarrow & \uparrow F \\ B & \xleftarrow{F} & A \end{array}$$

in C up to equivalence.

Proof. **Item 1, Characterisations:** Omitted. □

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01CS **10.1 To Do List**

01CT **10.1.1 Omitted Proofs To Add**

Не так благотворна истина, как
зловредна ее видимость.

Даниил Данковский

Truth does not do as much good in
the world as the appearance of truth
does evil.

Daniil Dankovsky

There's a very large number of omitted proofs throughout these notes. Here I list them in decreasing order of how nice it would be to add them.

01CU **Remark 10.1.1.1.1.** Proofs that *need* to be added at some point:

1. ??.
2. ??.
3. Horizontal composition of natural transformations is associative: ?? of ??.
4. Fully faithful functors are essentially injective: ?? of ??.

Proofs that *would be very nice* to be added at some point:

1. Properties of pseudomonadic functors: ??.
2. Characterisation of fully faithful functors: ?? of ??.

Proofs that *would be nice* to be added at some point:

1. Properties of posetal categories: ??.
2. The quadruple adjunction between categories and sets: ??.
3. Properties of groupoid completions: ??.
4. Properties of cores: ??.
5. F_* faithful iff F faithful: ?? of ??.
6. F_* full iff F full: ?? of ??.
7. Injective on objects functors are precisely the isofibrations in \mathbf{Cats}_2 : ?? of ??.
8. Characterisations of monomorphisms of categories: ?? of ??.
9. Epimorphisms of categories are surjective on objects: ?? of ??.
10. Properties of pseudoepic functors: ??.

01CV 10.1.2 Things To Explore/Add

Here we list things to be explored/added to this work in the future.

01CW Remark 10.1.2.1.1. Set theory through a category theory lens:

1. Isbell duality for sets.
2. Density comonads and codensity monads for sets.

Relations:

1. 2-Categorical monomorphisms and epimorphisms in **Rel**.
2. Co/limits in **Rel**.
3. Apartness composition, categorical properties of **Rel** with apartness, and apartness relations.

4. Apartness defines a composition for relations, but its analogue

$$q \square p \stackrel{\text{def}}{=} \int_{A \in C} p_A^{-1} \amalg q_{-2}^A$$

fails to be unital for profunctors. Is there a less obvious analogue of apartness composition for profunctors?

5. Codensity monad $\text{Ran}_J(J)$ of a relation (What about $\text{Rift}_J(J)$?)
6. Relative comonads in the 2-category of relations
7. Discrete fibrations and Street fibrations in **Rel**.
8. Consider adding the sections
- The Monoidal Bicategory of Relations
 - The Monoidal Double Category of Relations

to **Relations**.

Spans:

1. Universal property of the bicategory of spans, <https://ncatlab.org/nlab/show/span>
2. Write about cospans.

Un/Straightening:

1. Write proper sections on straightening for lax functors from sets to Rel or Span (displayed sets)

Categories:

1. Expand ?? and add a proof to it.
2. Sections and retractions; retracts, <https://ncatlab.org/nlab/show/retract>.
3. Regular categories: <https://arxiv.org/pdf/2004.08964.pdf>.
4. Are pseudoepic functors those functors whose restricted Yoneda embedding is pseudomonadic and Yoneda preserves absolute colimits?
5. Absolutely dense functors enriched over \mathbb{R}^+ apparently reduce to topological density

Types of Morphisms in Categories:

1. Behaviour in $\text{Fun}(C, \mathcal{D})$, e.g. pointwise sections vs. sections in $\text{Fun}(C, \mathcal{D})$.
2. A faithful functor from balanced category is conservative

Yoneda stuff:

1. Properties of restricted Yoneda embedding, e.g. if the restricted Yoneda embedding is full, then what can we conclude? Related: <https://qchu.wordpress.com/2015/05/17/generators/>

Adjunctions:

1. Adjunctions, units, counits, and fully faithfulness as in <https://mathoverflow.net/questions/100808/properties-of-functors-and-their-adjoints>.
2. Morphisms between adjunctions and bicategory $\text{Adj}(C)$.
3. <https://ncatlab.org/nlab/show/transformation+of+adjoints>

Constructions With Categories:

1. Comparison between pseudopullbacks and isocomma categories: the “evident” functor $C \times_{\mathcal{E}}^{\text{ps}} \mathcal{D} \rightarrow C \times_{\mathcal{E}} \mathcal{D}$ is essentially surjective and full, but not faithful in general.

Co/limits:

1. Add the characterisations of absolutely dense functors given in ?? to ??.
2. Absolutely dense functors, <https://ncatlab.org/nlab/show/absolutely+dense+functor>. Also theorem 1.1 here: <http://www.tac.mta.ca/tac/volumes/8/n20/n20.pdf>.
3. Dense functors, codense functors, and absolutely codense functors.

Co/ends:

1. Examples of co/ends: <https://mathoverflow.net/a/461814>
2. Cofinality for co/ends, <https://mathoverflow.net/questions/353876>

Fibred category theory:

1. Internal **Hom** in categories of co/Cartesian fibrations.
2. *Tensor structures on fibered categories* by Luca Terenzi: <https://arxiv.org/abs/2401.13491>. Check also the other papers by Luca Terenzi.
3. <https://ncatlab.org/nlab/show/cartesian+natural+transformation> (this is a cartesian morphism in $\text{Fun}(C, \mathcal{D})$ apparently)
4. CoCartesian fibration classifying $\text{Fun}(F, G)$, <https://mathoverflow.net/questions/457533/cocartesian-fibration-classifying-mathrmfunf-g>

Monoidal categories:

1. Free braided monoidal category with a braided monoid: <https://ncatlab.org/nlab/show/vine>

Skew monoidal categories:

1. Does the \mathbb{E}_1 tensor product of monoids admit a skew monoidal category structure?
2. Is there a (right?) skew monoidal category structure on $\text{Fun}(C, \mathcal{D})$ using right Kan extensions instead of left Kan extensions?
3. Similarly, are there skew monoidal category structures on the subcategory of $\mathbf{Rel}(A, B)$ spanned by the functions using left Kan extensions and left Kan lifts?

Higher categories:

1. Internal adjunctions in Mod as in [JY21, Section 6.3]; see [JY21, Example 6.2.6].
2. Comonads in the bicategory of profunctors.

Monoids:

1. Isbell's zigzag theorem for semigroups: the following conditions are equivalent:
 - (a) A morphism $f: A \rightarrow B$ of semigroups is an epimorphism.
 - (b) For each $b \in B$, one of the following conditions is satisfied:
 - We have $f(a) = b$.

- There exist some $m \in \mathbb{N}_{\geq 1}$ and two factorisations

$$b = a_0 y_1,$$

$$b = x_m a_{2m}$$

connected by relations

$$a_0 = x_1 a_1,$$

$$a_1 y_1 = a_2 y_2,$$

$$x_1 a_2 = x_2 a_3,$$

$$a_{2m-1} y_m = a_{2m}$$

such that, for each $1 \leq i \leq m$, we have $a_i \in \text{Im}(f)$.

Wikipedia says in https://en.wikipedia.org/wiki/Isbell%27s_zigzag_theorem:

For monoids, this theorem can be written more concisely:

Types of morphisms in bicategories:

1. Behaviour in 2-categories of pseudofunctors (or lax functors, etc.), e.g. pointwise pseudoepic morphisms in vs. pseudoepic morphisms in 2-categories of pseudofunctors.
2. Statements like “coequifiers are lax epimorphisms”, Item 2 of Examples 2.4 of <https://arxiv.org/abs/2109.09836>, along with most of the other statements/examples there.
3. Dense, absolutely dense, etc. morphisms in bicategories

Other:

1. <https://qchu.wordpress.com/>
2. <https://aroundtoposes.com/>
3. <https://ncatlab.org/nlab/show/essentially+surjective+and+full+functor>
4. <https://mathoverflow.net/questions/415363/objects-with-representable-presheaf-is-a-fibration>
5. <https://mathoverflow.net/questions/460146/universal-property-of-isbell-duality>

6. <http://www.tac.mta.ca/tac/volumes/36/12/36-12abs.html> (Isbell conjugacy and the reflexive completion)
7. <https://ncatlab.org/nlab/show/enrichment+versus+internalisation>
8. The works of Philip Saville, <https://philipsaville.co.uk/>
9. https://golem.ph.utexas.edu/category/2024/02/from_cartesian_to_symmetric_monoidal.html
10. <https://mathoverflow.net/q/463855> (One-object lax transformations)
11. <https://ncatlab.org/nlab/show/analytic+completion+of+a+ring>
12. https://en.wikipedia.org/wiki/Quaternionic_analysis
13. <https://arxiv.org/abs/2401.15051> (The Norm Functor over Schemes)
14. [https://mathoverflow.net/questions/407291/](https://mathoverflow.net/questions/407291) (Adjunctions with respect to profunctors)
15. <https://mathoverflow.net/a/462726> (Prof is free completion of Cats under right extensions)
16. there's some cool stuff in <https://arxiv.org/abs/2312.00990> (Polynomial Functors: A Mathematical Theory of Interaction), e.g. on cofunctors.
17. <https://ncatlab.org/nlab/show/adjoint+lifting+theorem>
18. <https://ncatlab.org/nlab/show/Gabriel%E2%80%93Ulmer+duality>

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