

The Clowder Project

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The Clowder Project Authors

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Part I

Sets

Chapter 1

Sets

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

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1.1 Sets and Functions

1.1.1 Functions

Definition 1.1.1.1. A **function** is a functional and total relation.

Notation 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

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

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](#).

1.2 The Enrichment of Sets in Classical Truth Values

1.2.1 (-2) -Categories

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

1.2.2 (-1) -Categories

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

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

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

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].

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

- *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

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

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

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

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

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

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

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

Here:

⁶This partial order coincides with logical implication.

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

1. If $P_1 = \text{t}$, then $p_1^1 = p_2^1 = \text{id}_\text{t}$, and there's indeed a unique morphism from P_1 to t making the diagram commute, namely id_t ;
2. If $P_1 = \text{f}$, 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 $P_2 = \text{t}$, then there is no morphism p_2^2 .
4. If $P_2 = \text{f}$, then p_1^2 is the unique morphism from f to t while $p_2^2 = \text{id}_\text{f}$, 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 $P_4 = \text{t}$, then there is no morphism p_1^4 or p_2^4 .
7. If $P_4 = \text{f}$, then $p_1^4 = p_2^4 = \text{id}_\text{f}$, 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

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

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

- For $(A, B, C) = (\text{t}, \text{t}, \text{t})$, we have

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

- For $(A, B, C) = (\text{t}, \text{t}, \text{f})$, we have

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

- For $(A, B, C) = (\text{t}, \text{f}, \text{t})$, we have

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

- For $(A, B, C) = (\text{t}, \text{f}, \text{f})$, we have

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

- For $(A, B, C) = (\text{f}, \text{t}, \text{t})$, we have

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

- For $(A, B, C) = (\text{f}, \text{t}, \text{f})$, we have

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

- For $(A, B, C) = (\text{f}, \text{f}, \text{t})$, we have

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

- For $(A, B, C) = (\text{f}, \text{f}, \text{f})$, we have

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

The proof of naturality is omitted. \square

the logical implication operator.

1.2.3 0-Categories

Definition 1.2.3.1.1. A **0-category** is a poset.⁸

Definition 1.2.3.1.2. A **0-groupoid** is a 0-category in which every morphism is invertible.⁹

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 {true, false} | Enrichment in Sets |
| Set X | Category \mathcal{C} |
| Element $x \in X$ | Object $X \in \text{Obj}(\mathcal{C})$ |
| Function | Functor |
| Function $X \rightarrow \{\text{true, false}\}$ | Functor $\mathcal{C} \rightarrow \text{Sets}$ |
| Function $X \rightarrow \{\text{true, false}\}$ | 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 $\mathbf{PSh}(\mathcal{C})$ |
| Characteristic function $\chi_{\{x\}}$ | Representable presheaf h_X |
| Characteristic embedding $\chi_{(-)}: X \hookrightarrow \mathcal{P}(X)$ | Yoneda embedding $\mathfrak{J}: \mathcal{C}^{\text{op}} \hookrightarrow \mathbf{PSh}(\mathcal{C})$ |
| Characteristic relation $\chi_X(-_1, -_2)$ | Hom profunctor $\text{Hom}_{\mathcal{C}}(-_1, -_2)$ |
| 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, $\text{Nat}(h_X, h_Y) \cong \text{Hom}_{\mathcal{C}}(X, Y)$ |
| Subsets are unions of their elements $U = \bigcup_{x \in U} \{x\}$ or $\chi_U = \text{colim}_{x \in \mathbf{Sets}(U, \{\text{t}, \text{f}\})} (\chi_x)$ | Presheaves are colimits of representables, $\mathcal{F} \cong \text{colim}_{h_X \in \int_{\mathcal{C}} \mathcal{F}} (h_X)$ |

Categories of elements:

| Set Theory | Category Theory |
|---|--|
| Assignment $U \mapsto \chi_U$ | Assignment $\mathcal{F} \mapsto \int_{\mathcal{C}} \mathcal{F}$ (the category of elements) |
| Assignment $U \mapsto \chi_U$ giving an isomorphism $\mathcal{P}(X) \cong \mathbf{Sets}(X, \{\text{t}, \text{f}\})$ | Assignment $\mathcal{F} \mapsto \int_{\mathcal{C}} \mathcal{F}$ giving an equivalence $\mathbf{PSh}(\mathcal{C}) \cong \mathbf{DFib}(\mathcal{C})$ |

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

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

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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2.1 Limits of Sets

2.1.1 The Terminal Set

Definition 2.1.1.1. The **terminal set** is the pair $(\text{pt}, \{\text{!}_A\}_{A \in \text{Obj}(\text{Sets})})$ 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

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

commute, namely $!_A$. □

2.1.2 Products of Families of Sets

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

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

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

- *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 $i \in I$.

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 $(a_i)_{i \in I}$

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

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

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 $x \in P$. □

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

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

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

where

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

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

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

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

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

- *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 ??.

□

2.1.3 Binary Products of Sets

Let A and B be sets.

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

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

- *The Cone.* The maps

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

³Further 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 $a \in A$

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

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

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

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

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 $x \in P$. □

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

1. *Functionality.* 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 $(A, B), (X, Y) \in \text{Obj}(\mathbf{Sets})$, the action on Hom-sets

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

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

2. *Adjointness.* We have adjunctions

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

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

witnessed by bijections

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

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

3. *Associativity.* We have an isomorphism of sets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

11. *Distributivity Over Symmetric Differences.* We have isomorphisms of sets

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

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

12. *Symmetric Monoidality.* The triple $(\text{Sets}, \times, \text{pt})$ is a symmetric monoidal category.

13. *Symmetric Bimonoidality.* The quintuple $(\mathbf{Sets}, \coprod, \emptyset, \times, \text{pt})$ is a symmetric bimonoidal category.

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

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

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

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

- *Map I.* We define a map

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

by sending a function

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

to the function

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

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

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

given by sending a function

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

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

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

- *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

$$\begin{aligned} [\Phi_{B,C} \circ (\text{id}_A \times g^*)](\xi) &= \Phi_{B,C}([\text{id}_A \times g^*](\xi)) \\ &= \Phi_{B,C}(\xi(-_1, g(-_2))) \\ &= [\xi(-_1, g(-_2))]^\dagger \\ &= \xi_{-1}^\dagger(g(-_2)) \\ &= (g^*)_*(\xi^\dagger) \\ &= (g^*)_*(\Phi_{B',C}(\xi)) \\ &= [(g^*)_* \circ \Phi_{B',C}](\xi). \end{aligned}$$

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

and $b \in B$ as in [Definition 2.3.4.1.1](#)

$h: C \rightarrow C'$, the diagram

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

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. □

2.1.4 Pullbacks

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

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

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

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

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 diagram commutes, i.e. that we have

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

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 $A \times_C B$

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

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

satisfies the universal property of the pullback. Suppose we have a diagram of the form

$$\begin{array}{ccccc}
 P & \xrightarrow{\quad p_2 \quad} & A \times_C B & \xrightarrow{\quad \text{pr}_2 \rightarrow B \quad} & B \\
 \downarrow p_1 & \nearrow \lrcorner & \downarrow \text{pr}_1 & \lrcorner \downarrow g & \downarrow g \\
 A & \xrightarrow{\quad f \quad} & C & &
 \end{array}$$

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

$$\begin{array}{ccccc}
 P & \xrightarrow{\quad p_2 \quad} & A \times_C B & \xrightarrow{\quad \text{pr}_2 \rightarrow B \quad} & B \\
 \downarrow p_1 & \nearrow \lrcorner \quad \exists! \phi \quad \lrcorner & \downarrow \text{pr}_1 & \lrcorner \downarrow g & \downarrow g \\
 A & \xrightarrow{\quad f \quad} & C & &
 \end{array}$$

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 $x \in P$, 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 $(p_1(x), p_2(x)) \in A \times_C B$. \square

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

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

sets

$$\begin{array}{ccc} A \cap B & \longrightarrow & B \\ \downarrow \lrcorner & & \downarrow \iota_B \\ A \cap B & \cong & A \times_{A \cup B} B, \\ & & \downarrow \\ & & A \xrightarrow{\iota_A} A \cup B. \end{array}$$

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. \square

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

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

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

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

$$\begin{array}{ccccc} A \times_C B & \longrightarrow & B & & \\ \downarrow & \lrcorner & \downarrow g & \searrow \psi & \\ A' \times_{C'} B' & \longrightarrow & B' & & \\ \downarrow & \lrcorner & \downarrow & & \downarrow g' \\ A & \xrightarrow{f} & C & & \\ \phi \searrow & & \chi \swarrow & & \downarrow g' \\ A' & \xrightarrow{f'} & C' & & \end{array}$$

in $\mathbf{Fun}(\mathcal{P}, \mathbf{Sets})$ 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

$$\begin{array}{ccccc}
A \times_C B & \longrightarrow & B & & \\
\downarrow & \lrcorner \searrow & \downarrow g & \searrow \psi & \\
A' \times_{C'} B' & \xrightarrow{\quad} & B' & & \\
\downarrow & \lrcorner & \downarrow & & \downarrow g' \\
A & \xrightarrow{f} & C & & C' \\
\downarrow & \phi \searrow & \downarrow & \searrow \chi & \downarrow \\
A' & \xrightarrow{f'} & C' & &
\end{array}$$

commute.

2. *Associativity.* Given a diagram

$$\begin{array}{ccccc}
A & & B & & C \\
& \searrow f & \swarrow g & \searrow h & \swarrow k \\
& X & Y & &
\end{array}$$

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

$$\begin{array}{ccc}
\begin{array}{c}
(A \times_X B) \times_Y C \\
\downarrow \lrcorner \quad \lrcorner \quad \lrcorner \\
A \times_X B \quad \quad \quad B \times_Y C \\
\downarrow \lrcorner \quad \lrcorner \quad \lrcorner \quad \lrcorner \\
A \quad B \quad C \\
\downarrow f \quad \downarrow g \quad \downarrow h \quad \downarrow k \\
X \quad Y \quad
\end{array} &
\begin{array}{c}
(A \times_X B) \times_B (B \times_Y C) \\
\downarrow \lrcorner \quad \lrcorner \quad \lrcorner \quad \lrcorner \\
A \times_X B \quad B \times_Y C \quad C \\
\downarrow \lrcorner \quad \lrcorner \quad \lrcorner \quad \lrcorner \\
A \quad B \quad C \\
\downarrow f \quad \downarrow g \quad \downarrow h \quad \downarrow k \\
X \quad Y \quad
\end{array} &
\begin{array}{c}
A \times_X (B \times_Y C) \\
\downarrow \lrcorner \quad \lrcorner \quad \lrcorner \\
B \times_Y C \quad C \\
\downarrow \lrcorner \quad \lrcorner \quad \lrcorner \\
B \quad C \\
\downarrow g \quad \downarrow k \\
Y \quad
\end{array}
\end{array}$$

3. *Unitality.* We have isomorphisms of sets

$$\begin{array}{ccc}
\begin{array}{ccc}
A & \xlongequal{\quad} & A \\
\downarrow f & \lrcorner & \downarrow f \\
X & \xlongequal{\quad} & X
\end{array} &
\begin{array}{c}
X \times_X A \cong A, \\
A \times_X X \cong A,
\end{array} &
\begin{array}{c}
A \xrightarrow{f} X \\
\parallel \lrcorner \parallel \\
X \xrightarrow{f} X.
\end{array}
\end{array}$$

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

$$\begin{array}{ccc}
\begin{array}{ccc}
A \times_X B & \longrightarrow & B \\
\downarrow \lrcorner & & \downarrow g \\
A & \xrightarrow{f} & X
\end{array} &
\begin{array}{c}
A \times_X B \cong B \times_X A
\end{array} &
\begin{array}{ccc}
B \times_X A & \longrightarrow & A \\
\downarrow \lrcorner & & \downarrow f \\
B & \xrightarrow{g} & X
\end{array}
\end{array}$$

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

$$\begin{array}{ccc} \emptyset & \xrightarrow{\quad} & \emptyset \\ \downarrow \lrcorner & & \downarrow \\ A & \xrightarrow{f} & X, \end{array} \quad \begin{array}{c} A \times_X \emptyset \cong \emptyset, \\ \emptyset \times_X A \cong \emptyset, \end{array} \quad \begin{array}{ccc} \emptyset & \xrightarrow{\quad} & A \\ \downarrow \lrcorner & & \downarrow f \\ \emptyset & \xrightarrow{\quad} & X. \end{array}$$

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

$$\begin{array}{ccc} A \times B & \xrightarrow{\quad} & B \\ A \times_{\text{pt}} B \cong A \times B, & \downarrow \lrcorner & \downarrow !_B \\ A & \xrightarrow{!_A} & \text{pt.} \end{array}$$

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. □

2.1.5 Equalisers

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

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

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

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

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

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

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

1. *Associativity.* We have isomorphisms of sets⁷

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

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

$$A \begin{array}{c} \xrightarrow{f} \\[-1ex] \xrightarrow[g]{\quad} \\[-1ex] \xrightarrow{h} \end{array} B$$

in **Sets**.

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

$$\text{Eq}(f, g) \xrightarrow{\text{eq}(f, g)} A \begin{array}{c} \xrightarrow{f} \\[-1ex] \xrightarrow[g]{\quad} \end{array} B$$

and then take the equaliser of the composition

$$\text{Eq}(f, g) \xrightarrow{\text{eq}(f, g)} A \begin{array}{c} \xrightarrow{f} \\[-1ex] \xrightarrow[h]{\quad} \end{array} B,$$

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

$$\text{Eq}(g, h) \xrightarrow{\text{eq}(g, h)} A \begin{array}{c} \xrightarrow{g} \\[-1ex] \xrightarrow[h]{\quad} \end{array} B$$

and then take the equaliser of the composition

$$\text{Eq}(g, h) \xrightarrow{\text{eq}(g, h)} A \begin{array}{c} \xrightarrow{f} \\[-1ex] \xrightarrow[g]{\quad} \end{array} B,$$

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

$$\begin{array}{ccc} A & \xrightarrow{\quad f \quad} & B \\ & \xrightarrow{\quad g \quad} & \\ & \xrightarrow{\quad h \quad} & \end{array}$$

in Sets , being explicitly given by

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

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

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

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

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

6. *Interaction With Composition.* Let

$$\begin{array}{ccc} A & \xrightarrow{\quad f \quad} & B & \xrightarrow{\quad h \quad} & C \\ & \xrightarrow{\quad g \quad} & & \xrightarrow{\quad k \quad} & \end{array}$$

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

$$\text{Eq}(f, g) \xrightarrow{\text{eq}(f, g)} A \xrightarrow[\quad g \quad]{\quad f \quad} B \xrightarrow[\quad k \quad]{\quad h \quad} C.$$

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

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

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

2.2 Colimits of Sets

2.2.1 The Initial Set

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

$$\emptyset \qquad A$$

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

$$\emptyset \dashrightarrow^{\phi}_{\exists!} A$$

commute, namely the inclusion map ι_A . □

2.2.2 Coproducts of Families of Sets

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

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 \mathbf{Sets} . Indeed, suppose we have, for each $i \in I$, a diagram of the form

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

in \mathbf{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 $(i, x) \in \coprod_{i \in I} A_i$. □

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

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

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

where

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

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

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 $\coprod_{i \in I}$ 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 ??.

□

2.2.3 Binary Coproducts

Let A and B be sets.

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

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

$$\begin{aligned} A \coprod B &\stackrel{\text{def}}{=} \coprod_{z \in \{A, B\}} z \\ &\cong \{(0, a) \mid a \in A\} \cup \{(1, b) \mid b \in B\}. \end{aligned}$$

- *The Cocone.* The maps

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

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 $A \coprod B$ is the categorical coproduct of A and B in

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

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

Sets. Indeed, suppose we have a diagram of the form

$$\begin{array}{ccc} & C & \\ \iota_A \nearrow & \swarrow \iota_B & \\ A & \xrightarrow{\text{inj}_A} & A \coprod B & \xleftarrow{\text{inj}_B} & B \end{array}$$

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

$$\begin{array}{ccc} & C & \\ \iota_A \nearrow & \uparrow \phi \exists! & \swarrow \iota_B & \\ A & \xrightarrow{\text{inj}_A} & A \coprod B & \xleftarrow{\text{inj}_B} & B \end{array}$$

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 $x \in A \coprod B$. □

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

1. *Functionality.* The assignment $A, B, (A, B) \mapsto A \coprod B$ defines functors

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

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

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

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

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

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

disjoint union of A and B , for emphasis.

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

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

defined by

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

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

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

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

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

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

3. *Unitality.* We have isomorphisms of sets

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

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

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

$$A \coprod B \cong B \coprod A,$$

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

5. *Symmetric Monoidality.* The triple $(\text{Sets}, \coprod, \emptyset)$ 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. □

2.2.4 Pushouts

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

Definition 2.2.4.1.1. The **pushout of A and B over C along f and g**

g^9 is the pair¹⁰ $(A \coprod_C B, \{\text{inj}_1, \text{inj}_2\})$ consisting of:

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

$$A \coprod_C B \stackrel{\text{def}}{=} A \coprod B / \sim_C,$$

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

- *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

$$\begin{array}{ccc} & A \coprod_C B & \xleftarrow{\text{inj}_2} B \\ \text{inj}_1 \circ f = \text{inj}_2 \circ g, & \uparrow \text{inj}_1 & \uparrow g \\ A & \xleftarrow{f} C. & \end{array}$$

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

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

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

pushout. Suppose we have a diagram of the form

$$\begin{array}{ccccc}
 & & P & \leftarrow & \\
 & & \downarrow \iota_2 & & \\
 A \amalg_C B & \leftarrow & \text{inj}_2 - B & & \\
 \uparrow \iota_1 & & \uparrow \text{inj}_1 & & \uparrow g \\
 A & \xleftarrow{f} & C & &
 \end{array}$$

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

$$\begin{array}{ccccc}
 & & P & \leftarrow & \\
 & & \downarrow \iota_2 & & \\
 A \amalg_C B & \xleftarrow{\exists! \phi} & \text{inj}_2 - B & & \\
 \uparrow \iota_1 & & \uparrow \text{inj}_1 & & \uparrow g \\
 A & \xleftarrow{f} & C & &
 \end{array}$$

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 $x \in A \amalg_C B$, 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 $A \amalg B$ 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

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

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

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

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

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 $x_1, \dots, x_n \in A \coprod B$ 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 $x_1, \dots, x_n \in A \coprod B$ 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 $b = f(c_n)$.

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

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

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

Proof. [Item 1](#), *Wedge Sums of Pointed Sets*: Follows by definition.

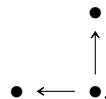
[Item 2](#), *Intersections via Unions*: Indeed, $A \coprod_{A \cap B} B$ is the quotient of $A \coprod B$ by the equivalence relation obtained by declaring $(0, a) \sim (1, b)$ iff $a = b \in A \cap B$, which is in bijection with $A \cup B$ via the map with $[(0, a)] \mapsto a$ and $[(1, b)] \mapsto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

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

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

$$-_1 \coprod_{-_3} -_1 : \mathbf{Fun}(\mathcal{P}, \mathbf{Sets}) \rightarrow \mathbf{Sets},$$

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

$$\begin{array}{ccccc}
 A \coprod_C B & \xleftarrow{\quad \lrcorner \quad} & B & & \\
 \uparrow & & \uparrow \psi & & \\
 A' \coprod_{C'} B' & \xleftarrow{\quad \lrcorner \quad} & B' & & \\
 \uparrow g & & \uparrow & & \\
 A & \xleftarrow{\quad f \quad} & C & & \\
 \downarrow \phi & & \downarrow \chi & & \\
 A' & \xleftarrow{\quad f' \quad} & C' & &
 \end{array}$$

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

$$\begin{array}{ccccc}
 A \coprod_C B & \xleftarrow{\quad \lrcorner \quad} & B & & \\
 \uparrow & \searrow & \uparrow \psi & & \\
 A' \coprod_{C'} B' & \xleftarrow{\quad \lrcorner \quad} & B' & & \\
 \uparrow g & & \uparrow & & \\
 A & \xleftarrow{\quad f \quad} & C & & \\
 \downarrow \phi & & \downarrow \chi & & \\
 A' & \xleftarrow{\quad f' \quad} & C' & &
 \end{array}$$

commute.

2. *Associativity.* Given a diagram

$$\begin{array}{ccccc}
 A & & B & & C \\
 & \swarrow f & \nearrow g & \swarrow h & \nearrow k \\
 X & & Y & &
 \end{array}$$

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

$$\begin{array}{ccc}
 \begin{array}{c} (A \amalg_X B) \amalg_Y C \\ \uparrow \wedge \quad \swarrow \\ A \amalg_X B \end{array} & \begin{array}{c} (A \amalg_X B) \amalg_B (B \amalg_Y C) \\ \uparrow \wedge \quad \swarrow \\ A \amalg_X B \quad B \amalg_Y C \end{array} & \begin{array}{c} A \amalg_X (B \amalg_Y C) \\ \uparrow \wedge \quad \swarrow \\ B \amalg_Y C \end{array} \\
 \begin{array}{ccccc} & & & & \\ A & \nearrow \wedge & B & \nearrow \wedge & C \\ f \downarrow & g \nearrow & h \nearrow & k \nearrow & \\ X & & Y & & \end{array}, & \begin{array}{ccccc} & & & & \\ A & \nearrow \wedge & B & \nearrow \wedge & C \\ f \downarrow & g \nearrow & h \nearrow & k \nearrow & \\ X & & Y & & \end{array}, & \begin{array}{ccccc} & & & & \\ A & \nearrow \wedge & B & \nearrow \wedge & C \\ f \downarrow & g \nearrow & h \nearrow & k \nearrow & \\ X & & Y & & \end{array}.
 \end{array}$$

3. *Unitality.* We have isomorphisms of sets

$$\begin{array}{ccc}
 \begin{array}{c} A \xlongequal{\Gamma} A \\ \uparrow f \quad \uparrow f \\ X \xlongequal{\Gamma} X \end{array} & \begin{array}{c} X \amalg_X A \cong A, \\ A \amalg_X X \cong A, \end{array} & \begin{array}{c} A \xleftarrow{f} X \\ \parallel \Gamma \parallel \\ X \xleftarrow{f} X. \end{array}
 \end{array}$$

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

$$\begin{array}{ccc}
 \begin{array}{c} A \amalg_X B \leftarrow B \\ \uparrow \Gamma \quad \uparrow g \\ A \xleftarrow{f} X, \end{array} & \begin{array}{c} A \amalg_X B \cong B \amalg_X A \end{array}, & \begin{array}{c} B \amalg_X A \leftarrow A \\ \uparrow \Gamma \quad \uparrow f \\ B \xleftarrow{g} X. \end{array}
 \end{array}$$

5. *Interaction With Coproducts.* We have

$$\begin{array}{c} A \amalg B \leftarrow B \\ \uparrow \Gamma \quad \uparrow \iota_B \\ A \amalg_{\emptyset} B \cong A \amalg B, \\ A \xleftarrow{\iota_A} \emptyset. \end{array}$$

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. \square

2.2.5 Coequalisers

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

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 $\pi: B \twoheadrightarrow B/\sim$ 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

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

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

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

commute. \square

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 $b = f(z_n)$.

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

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

$$X/\sim_R \cong \text{CoEq}\left(R \hookrightarrow X \times X \xrightarrow[\text{pr}_2]{\text{pr}_1} X\right).$$

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

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

1. *Associativity.* We have isomorphisms of sets¹¹

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

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

$$A \xrightarrow{\begin{smallmatrix} f \\ -g \\ h \end{smallmatrix}} B$$

in **Sets**.

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

$$A \xrightarrow{\begin{smallmatrix} f \\ -g \\ h \end{smallmatrix}} B$$

in **Sets**.

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

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

and then take the coequaliser of the composition

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

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

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

and then take the coequaliser of the composition

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

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

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

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

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

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

6. *Interaction With Composition.* Let

$$A \xrightarrow[g]{f} B \xrightarrow[k]{h} C$$

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. □

2.3 Operations With Sets

2.3.1 The Empty Set

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 ??.

2.3.2 Singleton Sets

Let X be a set.

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](#)).

2.3.3 Pairings of Sets

Let X and Y be sets.

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 ??.

2.3.4 Ordered Pairs

Let A and B be sets.

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

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

Proposition 2.3.4.1.2. Let A and B be sets.

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

- (a) We have $(A, B) = (C, D)$.
- (b) We have $A = C$ and $B = D$.

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

2.3.5 Sets of Maps

Let A and B be sets.

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 .

Proposition 2.3.5.1.2. Let A and B be sets.

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

$$\begin{aligned} \text{Hom}_{\text{Sets}}(X, -) &: \text{Sets} \rightarrow \text{Sets}, \\ \text{Hom}_{\text{Sets}}(-, Y) &: \text{Sets}^{\text{op}} \rightarrow \text{Sets}, \\ \text{Hom}_{\text{Sets}}(-_1, -_2) &: \text{Sets}^{\text{op}} \times \text{Sets} \rightarrow \text{Sets}. \end{aligned}$$

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

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

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

2.3.6 Unions of Families

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

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 ??.

2.3.7 Binary Unions

Let A and B be sets.

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

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

Proposition 2.3.7.1.2. Let X be a set.

1. *Functionality.* 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

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

(\star) 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 $U, V \in \mathcal{P}(X)$.

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 $U, V \in \mathcal{P}(X)$.

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 $U, V, W \in \mathcal{P}(X)$.

4. *Unitality.* We have equalities of sets

$$\begin{aligned} U \cup \emptyset &= U, \\ \emptyset \cup U &= U \end{aligned}$$

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

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

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

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

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

$$U \cup U = U$$

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

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

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

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

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 $U, V \in \mathcal{P}(X)$.

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 $U, V \in \mathcal{P}(X)$.

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

2.3.8 Intersections of Families

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

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

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

2.3.9 Binary Intersections

Let X and Y be sets.

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

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

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.

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

- (*) If $U \subset U'$ and $V \subset V'$, then $U \cap V \subset U' \cap V'$.

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

2. *Adjointness.* We have adjunctions

$$\begin{aligned} (U \cap - \dashv \mathbf{Hom}_{\mathcal{P}(X)}(U, -)): \quad \mathcal{P}(X) &\xrightleftharpoons[\mathbf{Hom}_{\mathcal{P}(X)}(U, -)]{\perp} \mathcal{P}(X), \\ (- \cap V \dashv \mathbf{Hom}_{\mathcal{P}(X)}(V, -)): \quad \mathcal{P}(X) &\xrightleftharpoons[\mathbf{Hom}_{\mathcal{P}(X)}(V, -)]{\perp} \mathcal{P}(X), \end{aligned}$$

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

$$\begin{aligned} \mathrm{Hom}_{\mathcal{P}(X)}(U \cap V, W) &\cong \mathrm{Hom}_{\mathcal{P}(X)}\left(U, \mathbf{Hom}_{\mathcal{P}(X)}(V, W)\right), \\ \mathrm{Hom}_{\mathcal{P}(X)}(U \cap V, W) &\cong \mathrm{Hom}_{\mathcal{P}(X)}\left(V, \mathbf{Hom}_{\mathcal{P}(X)}(U, W)\right), \end{aligned}$$

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 $V \subset (X \setminus U) \cup W$.

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

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

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

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

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

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

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

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

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

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

$$U \cap U = U$$

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

¹⁶For intuition regarding the expression defining $\mathbf{Hom}_{\mathcal{P}(X)}(U, V)$, see

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 $U, V, W \in \mathcal{P}(X)$.

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 $U \in \mathcal{P}(X)$.

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 $U, V \in \mathcal{P}(X)$.

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 $U, V \in \mathcal{P}(X)$.

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

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

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 $U^c \vee V = (X \setminus U) \cup V$.

2.3.10 Differences

Let X and Y be sets.

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

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

Proposition 2.3.10.1.2. Let X be a set.

1. *Functionality.* 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 $U, V \in \mathcal{P}(X)$.

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 $U, V \in \mathcal{P}(X)$.

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 $U, V, W \in \mathcal{P}(X)$.

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 $U, V, W \in \mathcal{P}(X)$.

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 $U, V, W \in \mathcal{P}(X)$.

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 $U, V, W \in \mathcal{P}(X)$.

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 $U, V, W \in \mathcal{P}(X)$.

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 $U, V \in \mathcal{P}(X)$.

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 $U, V \in \mathcal{P}(X)$.

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 $U, V, W \in \mathcal{P}(X)$.

11. *Left Annihilation.* We have

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

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

12. *Right Unitality.* We have

$$U \setminus \emptyset = U$$

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

13. *Invertibility.* We have

$$U \setminus U = \emptyset$$

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

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

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

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]. \square

2.3.11 Complements

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

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

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

Proposition 2.3.11.1.2. Let X be a set.

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 $V^c \subset U^c$.

Remark 2.3.9.1.3.

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 $U, V \in \mathcal{P}(X)$.

3. *Involutority.* We have

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

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

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 [Pro24i].

Item 4, Interaction With Characteristic Functions: Clear. □

2.3.12 Symmetric Differences

Let A and B be sets.

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

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

Proposition 2.3.12.1.2. Let X be a set.

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

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

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 $U, V \in \mathcal{P}(X)$.

3. *Associativity.* We have¹⁸

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

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

4. *Commutativity.* We have

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

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

5. *Unitality.* We have

$$\begin{aligned} U \Delta \emptyset &= U, \\ \emptyset \Delta U &= U \end{aligned}$$

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

6. *Invertibility.* We have

$$U \Delta U = \emptyset$$

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

7. *Interaction With Unions.* We have

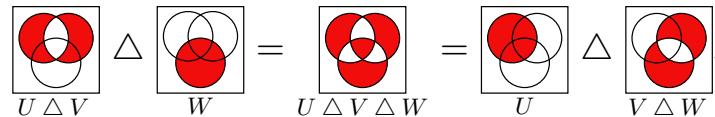
$$(U \Delta V) \cup (V \Delta T) = (U \cup V \cup W) \setminus (U \cap V \cap W)$$

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

¹⁷ Illustration:



¹⁸ Illustration:



8. *Interaction With Complements I.* We have

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

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

9. *Interaction With Complements II.* We have

$$\begin{aligned} U \Delta X &= U^c, \\ X \Delta U &= U^c \end{aligned}$$

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

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 $U, V \in \mathcal{P}(X)$.

11. “Transitivity”. We have

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

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

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 $U, V, W \in \mathcal{P}(X)$.

13. *Distributivity Over Intersections.* We have

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

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

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 $U, V \in \mathcal{P}(X)$.

15. *Bijection.* 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 .

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

- (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).

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

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

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

5. *Interaction With Powersets and Vector Spaces II.* If X is finite, then:

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 $\mathbb{Z}/2 \times \mathbb{Z}/2$:

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

(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

$$\dim(\mathcal{P}(X)) = \#\mathcal{P}(X).$$

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

$$\begin{aligned} (U \Delta V) \Delta (V \Delta W) &= U \Delta (V \Delta (V \Delta W)) && (\text{by } \text{Item 3}) \\ &= U \Delta ((V \Delta V) \Delta W) && (\text{by Item 3}) \\ &= U \Delta (\emptyset \Delta W) && (\text{by Item 6}) \\ &= U \Delta W && (\text{by Item 5}) \end{aligned}$$

[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.

[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 □



²⁰ *Warning:* The analogous statement replacing intersections by unions (i.e. that the quintuple $(\mathcal{P}(X), \Delta, \cap, \emptyset, X)$ is a ring) is false, however. See [Pro24ba] for a proof.

END TEXTDBEND

²¹ Reference: [Pro24av].

²² Reference: [Pro24ay].

2.4 Powersets

2.4.1 Characteristic Functions

Let X be a set.

Definition 2.4.1.1.1. Let $U \subset X$ and let $x \in X$.

1. The **characteristic function of U** ²³ is the function²⁴

$$\chi_U : X \rightarrow \{\text{t}, \text{f}\}$$

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 $x \in X$.

2. The **characteristic function of x** is the function²⁵

$$\chi_x : X \rightarrow \{\text{t}, \text{f}\}$$

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 $y \in X$.

3. The **characteristic relation on X** ²⁶ is the relation²⁷

$$\chi_X(-_1, -_2) : X \times X \rightarrow \{\text{t}, \text{f}\}$$

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 $x, y \in X$.

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_{-2}^{-1} , or \sim_{id} in the context of relations.

²⁸As a subset of $X \times X$, the relation χ_X corresponds to the diagonal $\Delta_X \subset X \times X$ of X .

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 $x \in X$.

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

1. A function

$$f: X \rightarrow \{\text{t}, \text{f}\}$$

is a decategorification of a presheaf

$$\mathcal{F}: \mathcal{C}^{\text{op}} \rightarrow \text{Sets},$$

with the characteristic functions χ_U of the subsets of X being the primordial examples (and, in fact, all examples) of these.

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 $y \in \text{Obj}(X_{\text{disc}})$.

2. The characteristic function

$$\chi_x: X \rightarrow \{\text{t}, \text{f}\}$$

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 .

3. The characteristic relation

$$\chi_X(-_1, -_2): X \times X \rightarrow \{\text{t}, \text{f}\}$$

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 .

4. The characteristic embedding

$$\chi_{(-)}: X \hookrightarrow \mathcal{P}(X)$$

of X into $\mathcal{P}(X)$ is a decategorification of the Yoneda embedding

$$\mathfrak{X}: C^{\text{op}} \hookrightarrow \mathsf{PSh}(C)$$

of a category C into $\mathsf{PSh}(C)$.

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 $\mathsf{PSh}(C)$ is a colimit of objects of C , viewed as representable presheaves $h_X \in \text{Obj}(\mathsf{PSh}(C))$.

Proposition 2.4.1.1.3. Let X be a set.

1. *The Inclusion of Characteristic Relations Associated to a Function.*

Let $f: A \rightarrow B$ be a function. We have an inclusion³¹

$$\begin{array}{ccc} A \times A & \xrightarrow{f \times f} & B \times B \\ \chi_B \circ (f \times f) \subset \chi_A, & \swarrow \curvearrowright \searrow & \\ & \{ \text{t}, \text{f} \}. & \end{array}$$

³¹This is the 0-categorical version of [Definition 8.4.4.1.1](#).

2. *Interaction With Unions I.* We have

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

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

3. *Interaction With Unions II.* We have

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

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

4. *Interaction With Intersections I.* We have

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

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

5. *Interaction With Intersections II.* We have

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

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

6. *Interaction With Differences.* We have

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

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

7. *Interaction With Complements.* We have

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

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

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

9. *Interaction Between the Characteristic Embedding and Morphisms.*

Let $f: X \rightarrow Y$ be a map of sets. The diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & X' \\ f_* \circ \chi_X = \chi_{X'} \circ f, & \downarrow \chi_X & \downarrow \chi_{X'} \\ \mathcal{P}(X) & \xrightarrow{f_*} & \mathcal{P}(X'). \end{array}$$

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: Indeed, 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

2.4.2 The Yoneda Lemma for Sets

Let X be a set and let $U \subset X$ be a subset of X .

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

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

2.4.3 Powersets

Let X be a set.

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 ??.

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

$$\mathbf{Sets}(X, \{\text{t, f}\})$$

of functions from X to the set $\{\text{t, f}\}$ of classical truth values.

- The category of presheaves on a category C is the category

$$\mathbf{Fun}(C^{\text{op}}, \mathbf{Sets})$$

of functors from C^{op} to the category \mathbf{Sets} of sets.

³²This parallel is based on the following comparison:

- A category is enriched over the category

$$\mathbf{Sets} \stackrel{\text{def}}{=} \mathbf{Cats}_0$$

of sets (i.e. “0-categories”), with presheaves taking values on it.

- A set is enriched over the set

$$\{\text{t, f}\} \stackrel{\text{def}}{=} \mathbf{Cats}_{-1}$$

Proposition 2.4.3.1.3. Let X be a set.

1. *Co/Completeness.* The (posetal) category (associated to) $(\mathcal{P}(X), \subset)$ is complete and cocomplete:
 - (a) *Products.* The products in $\mathcal{P}(X)$ are given by intersection of subsets.
 - (b) *Coproducts.* The coproducts in $\mathcal{P}(X)$ are given by union of subsets.
 - (c) *Co/Equalisers.* Being a posetal category, $\mathcal{P}(X)$ only has at most one morphisms between any two objects, so co/equalisers are trivial.
2. *Cartesian Closedness.* The category $\mathcal{P}(X)$ is Cartesian closed with internal Hom

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

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](#). \square

Proposition 2.4.3.1.4. Let X be a set.

1. *Functionality 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

of classical truth values (i.e. “(-1)-categories”), with characteristic functions taking values on it.

³³For intuition regarding the expression defining $\mathbf{Hom}_{\mathcal{P}(X)}(U, V)$, see [Remark 2.3.9.1.3](#).

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](#).

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

$$\mathcal{P}^{-1}(A) \stackrel{\text{def}}{=} \mathcal{P}(A).$$

- *Action on Morphisms.* For each $A, B \in \text{Obj}(\mathbf{Sets})$, the action on morphisms

$$\mathcal{P}_{A,B}^{-1}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Sets}(\mathcal{P}(B), \mathcal{P}(A))$$

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](#).

3. *Functoriality III.* 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 $A, B \in \text{Obj}(\text{Sets})$, 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](#).

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 $B \in \text{Obj}(\text{Sets}^{\text{op}})$.

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

$$\begin{aligned}
 \text{Sets}^{\text{op}}(\mathcal{P}(A), B) &\stackrel{\text{def}}{=} \text{Sets}(B, \mathcal{P}(A)) \\
 &\cong \text{Sets}(B, \text{Sets}(A, \{\text{t}, \text{f}\})) \\
 &\quad (\text{by Item 1 of Proposition 2.4.3.1.6}) \\
 &\cong \text{Sets}(A \times B, \{\text{t}, \text{f}\}) \\
 &\quad (\text{by Item 2 of Proposition 2.1.3.1.2}) \\
 &\cong \text{Sets}(A, \text{Sets}(B, \{\text{t}, \text{f}\})) \\
 &\quad (\text{by Item 2 of Proposition 2.1.3.1.2}) \\
 &\cong \text{Sets}(A, \mathcal{P}(B)) \quad (\text{by Item 1 of Proposition 2.4.3.1.6})
 \end{aligned}$$

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

$$\begin{aligned}
 \text{Rel}(\text{Gr}(A), B) &\cong \mathcal{P}(A \times B) \\
 &\cong \text{Sets}(A \times B, \{\text{t}, \text{f}\}) \\
 &\quad (\text{by Item 1 of Proposition 2.4.3.1.6}) \\
 &\cong \text{Sets}(A, \text{Sets}(B, \{\text{t}, \text{f}\})) \\
 &\quad (\text{by Item 2 of Proposition 2.1.3.1.2}) \\
 &\cong \text{Sets}(A, \mathcal{P}(B)) \quad (\text{by Item 1 of Proposition 2.4.3.1.6})
 \end{aligned}$$

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 $R: \text{Gr}(A) \nrightarrow B$ 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 $R: B \nrightarrow B'$, the diagram

$$\begin{array}{ccc}
 \text{Rel}(\text{Gr}(A), B) & \xrightarrow{R \diamond -} & \text{Rel}(\text{Gr}(A), B') \\
 \downarrow \wr & & \downarrow \wr \\
 \text{Sets}(A, \mathcal{P}(B)) & \xrightarrow{R_*} & \text{Sets}(A, \mathcal{P}(B'))
 \end{array}$$

commutes, which follows from Remark 6.4.1.1.2. \square

Proposition 2.4.3.1.5. Let X be a set.

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

$$\left(\mathcal{P}_*, \mathcal{P}_*^{\coprod}, \mathcal{P}_{*|1}^{\coprod} \right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}, \coprod, \emptyset)$$

being equipped with isomorphisms

$$\begin{aligned}\mathcal{P}_{*|X,Y}^{\coprod}: \mathcal{P}(X) \times \mathcal{P}(Y) &\xrightarrow{\cong} \mathcal{P}(X \coprod Y), \\ \mathcal{P}_{*|\mathbb{1}}^{\coprod}: \text{pt} &\xrightarrow{\cong} \mathcal{P}(\emptyset),\end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

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

$$\left(\mathcal{P}^{-1}, \mathcal{P}^{-1|}\coprod, \mathcal{P}_{\mathbb{1}}^{-1|}\coprod \right): (\text{Sets}^{\text{op}}, \times^{\text{op}}, \text{pt}) \rightarrow (\text{Sets}, \coprod, \emptyset)$$

being equipped with isomorphisms

$$\begin{aligned}\mathcal{P}_{X,Y}^{-1|}\coprod: \mathcal{P}(X) \times \mathcal{P}(Y) &\xrightarrow{\cong} \mathcal{P}(X \coprod Y), \\ \mathcal{P}_{\mathbb{1}}^{-1|}\coprod: \text{pt} &\xrightarrow{\cong} \mathcal{P}(\emptyset),\end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

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

$$\left(\mathcal{P}_!, \mathcal{P}_!^{\coprod}, \mathcal{P}_{|\mathbb{1}}^{\coprod} \right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}, \coprod, \emptyset)$$

being equipped with isomorphisms

$$\begin{aligned}\mathcal{P}_{!|X,Y}^{\coprod}: \mathcal{P}(X) \times \mathcal{P}(Y) &\xrightarrow{\cong} \mathcal{P}(X \coprod Y), \\ \mathcal{P}_{!|\mathbb{1}}^{\coprod}: \text{pt} &\xrightarrow{\cong} \mathcal{P}(\emptyset),\end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

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

$$\left(\mathcal{P}_*, \mathcal{P}_*^{\otimes}, \mathcal{P}_{*|\mathbb{1}}^{\otimes} \right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}, \times, \text{pt})$$

being equipped with morphisms

$$\begin{aligned}\mathcal{P}_{*|X,Y}^{\times}: \mathcal{P}(X) \times \mathcal{P}(Y) &\rightarrow \mathcal{P}(X \times Y), \\ \mathcal{P}_{*|\mathbb{1}}^{\times}: \text{pt} &\rightarrow \mathcal{P}(\text{pt}),\end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$, where

- The map $\mathcal{P}_{*|X,Y}^{\times}$ is given by

$$\mathcal{P}_{*|X,Y}^{\times}(U, V) \stackrel{\text{def}}{=} U \times V$$

for each $(U, V) \in \mathcal{P}(X) \times \mathcal{P}(Y)$,

- The map $\mathcal{P}_{*\mathbb{1}}^{\times}$ is given by

$$\mathcal{P}_{*\mathbb{1}}^{\times}(\star) = \text{pt}.$$

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

$$(\mathcal{P}^{-1}, \mathcal{P}^{-1|\otimes}, \mathcal{P}_{\mathbb{1}}^{-1|\otimes}) : (\mathbf{Sets}^{\text{op}}, \times^{\text{op}}, \text{pt}) \rightarrow (\mathbf{Sets}, \times, \text{pt})$$

being equipped with morphisms

$$\begin{aligned} \mathcal{P}_{X,Y}^{-1|\times} &: \mathcal{P}(X) \times \mathcal{P}(Y) \rightarrow \mathcal{P}(X \times Y), \\ \mathcal{P}_{\mathbb{1}}^{\times} &: \text{pt} \rightarrow \mathcal{P}(\emptyset), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\mathbf{Sets})$, defined as in Item 4.

6. *Symmetric Lax Monoidality With Respect to Products III.* The powerset functor $\mathcal{P}_!$ of Item 3 of Proposition 2.4.3.1.4 has a symmetric lax monoidal structure

$$(\mathcal{P}_!, \mathcal{P}_!^{\otimes}, \mathcal{P}_{!\mathbb{1}}^{\otimes}) : (\mathbf{Sets}, \times, \text{pt}) \rightarrow (\mathbf{Sets}, \times, \text{pt})$$

being equipped with morphisms

$$\begin{aligned} \mathcal{P}_{!|X,Y}^{\times} &: \mathcal{P}(X) \times \mathcal{P}(Y) \rightarrow \mathcal{P}(X \times Y), \\ \mathcal{P}_{!\mathbb{1}}^{\times} &: \text{pt} \rightarrow \mathcal{P}(\emptyset), \end{aligned}$$

natural in $X, Y \in \text{Obj}(\mathbf{Sets})$, defined as in Item 4.

Proof. Item 1, Symmetric Strong Monoidality With Respect to Coproducts I: The isomorphism

$$\mathcal{P}_{*|X,Y}^{\coprod} : \mathcal{P}(X) \times \mathcal{P}(Y) \rightarrow \mathcal{P}(X \coprod Y)$$

is given by sending $(U, V) \in \mathcal{P}(X) \times \mathcal{P}(Y)$ to $U \coprod V$, with inverse given by sending a subset S of $X \coprod Y$ 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 $\mathcal{P}_{*|X,Y}^{\coprod}$ is the statement that, given maps of sets $f: X \rightarrow X'$ and $g: Y \rightarrow Y'$, the diagram

$$\begin{array}{ccc} \mathcal{P}(X) \times \mathcal{P}(Y) & \xrightarrow{f_* \times g_*} & \mathcal{P}(X') \times \mathcal{P}(Y') \\ \downarrow \wr & & \downarrow \wr \\ \mathcal{P}(X \coprod Y) & \xrightarrow{(f \coprod g)_*} & \mathcal{P}(X' \coprod Y') \end{array}$$

commutes, which is clear, as it acts on elements as

$$\begin{array}{ccc} (U, V) & \longmapsto & (f_*(U), g_*(V)) \\ \downarrow & & \downarrow \\ U \coprod V & \mapsto & (f \coprod g)_*(U \coprod V) = f_*(U) \coprod g_*(V), \end{array}$$

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

$$\begin{array}{ccc} (U, V) & \longmapsto & (f_*(U), g_*(V)) \\ \downarrow & & \downarrow \\ U \times V & \mapsto & (f \times g)_*(U \times V) = f_*(U) \times g_*(V), \end{array}$$

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

Proposition 2.4.3.1.6. Let X be a set.

1. *Powersets as Sets of Functions I.* The assignment $U \mapsto \chi_U$ defines a bijection

$$\chi_{(-)}: \mathcal{P}(X) \xrightarrow{\cong} \text{Sets}(X, \{\text{t}, \text{f}\}),$$

for each $X \in \text{Obj}(\text{Sets})$.

2. *Powersets as Sets of Functions II.* The bijection

$$\mathcal{P}(X) \cong \text{Sets}(X, \{\text{t}, \text{f}\})$$

of [Item 1](#) is natural in $X \in \text{Obj}(\text{Sets})$, refining to a natural isomorphism of functors

$$\mathcal{P}^{-1} \cong \text{Sets}(-, \{\text{t}, \text{f}\}).$$

3. *Powersets as Sets of Relations.* We have bijections

$$\begin{aligned} \mathcal{P}(X) &\cong \text{Rel}(\text{pt}, X), \\ \mathcal{P}(X) &\cong \text{Rel}(X, \text{pt}), \end{aligned}$$

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

$$\begin{array}{ccc} \mathcal{P}(Y) & \xrightarrow{f^{-1}} & \mathcal{P}(X) \\ \chi_{(-)} \downarrow & & \downarrow \chi_{(-)} \\ \text{Sets}(Y, \{\text{t}, \text{f}\}) & \xrightarrow{f^*} & \text{Sets}(X, \{\text{t}, \text{f}\}) \end{array}$$

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](#). \square

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 $A: X_{\text{disc}} \rightarrow \text{Sets}$.

Proposition 2.4.3.1.8. Let X be a set.

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

$$\begin{array}{ccc} & \mathcal{P}(X) & \\ \chi_X \nearrow & \downarrow \exists! & \\ X & \xrightarrow{f} & Y \end{array}$$

commute.

2. *Adjointness.* We have an adjunction³⁴

$$(\mathcal{P} \dashv \overline{\mathfrak{F}}): \text{Sets} \begin{array}{c} \xrightarrow{\mathcal{P}} \\ \perp \\ \xleftarrow{\mathfrak{F}} \end{array} \text{Pos}^{\text{cocomp}},$$

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

³⁴In this sense, $\mathcal{P}(A)$ is the free cocompletion of A . (Note that, despite its name,

- 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

$$X \xrightarrow{\chi_X} \mathcal{P}(X) \xrightarrow{f} Y.$$

- 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 ,

$$\begin{array}{ccc} & & \mathcal{P}(X) \\ \text{Lan}_{\chi_X}(f): \mathcal{P}(X) & \xrightarrow{\chi_X} & Y \\ & \parallel & \downarrow \text{Lan}_{\chi_X}(f) \\ X & \xrightarrow{f} & Y. \end{array}$$

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**.

however, this is not an idempotent operation, as we have $\mathcal{P}(\mathcal{P}(A)) \neq \mathcal{P}(A)$.)

Item 2, Adjointness: We claim we have adjunction $\mathcal{P} \dashv \text{忘}$, witnessed by a bijection

$$\text{Pos}^{\text{cocomp}\cdot}((\mathcal{P}(X), \subset), (Y, \preceq)) \cong \text{Sets}(X, Y),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $(Y, \preceq) \in \text{Obj}(\text{Pos}^{\text{cocomp}\cdot})$.

- *Map I.* We define a map

$$\Phi_{X,Y}: \text{Pos}^{\text{cocomp}\cdot}((\mathcal{P}(X), \subset), (Y, \preceq)) \rightarrow \text{Sets}(X, Y)$$

as in the statement, by

$$\Phi_{X,Y}(f) \stackrel{\text{def}}{=} f \circ \chi_X$$

for each $f \in \text{Pos}^{\text{cocomp}\cdot}((\mathcal{P}(X), \subset), (Y, \preceq))$.

- *Map II.* We define a map

$$\Psi_{X,Y}: \text{Sets}(X, Y) \rightarrow \text{Pos}^{\text{cocomp}\cdot}((\mathcal{P}(X), \subset), (Y, \preceq))$$

as in the statement, by

$$\begin{aligned} \Psi_{X,Y}(f) &\stackrel{\text{def}}{=} \text{Lan}_{\chi_X}(f), \\ & \quad \begin{array}{ccc} & \mathcal{P}(X) & \\ \nearrow \chi_X & \swarrow & \downarrow \\ X & \xrightarrow[f]{} & Y, \end{array} \\ & \quad \text{Lan}_{\chi_X}(f) \end{aligned}$$

for each $f \in \text{Sets}(X, Y)$.

- *Invertibility I.* We claim that

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \text{id}_{\text{Pos}^{\text{cocomp}\cdot}((\mathcal{P}(X), \subset), (Y, \preceq))}.$$

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

$$\Phi_{X,Y} \circ \Psi_{X,Y} = \text{id}_{\mathbf{Sets}(X,Y)}.$$

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

2.4.4 Direct Images

Let A and B be sets and let $f: A \rightarrow B$ be a function.

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 $U \in \mathcal{P}(A)$.

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 $b \in \exists_f(U)$.

³⁵Further Terminology: The set $f(U)$ is called the **direct image of U by f** .

³⁶We also have

$$f_*(U) = B \setminus f_!(A \setminus U);$$

- There exists some $a \in U$ such that $f(a) = b$.

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

$$f_*: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by

$$\begin{aligned} f_*(\chi_U) &\stackrel{\text{def}}{=} \text{Lan}_f(\chi_U) \\ &= \text{colim} \left(\left(f \xrightarrow{\rightarrow} \underline{(-1)} \right) \xrightarrow{\text{pr}} A \xrightarrow{\chi_U} \{\text{t}, \text{f}\} \right) \\ &= \underset{\substack{a \in A \\ f(a) = -1}}{\text{colim}} (\chi_U(a)) \\ &= \bigvee_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)), \end{aligned}$$

where we have used ?? for the second equality. In other words, we have

$$\begin{aligned} [f_*(\chi_U)](b) &= \bigvee_{\substack{a \in A \\ f(a) = b}} (\chi_U(a)) \\ &= \begin{cases} \text{true} & \text{if there exists some } a \in A \text{ such} \\ & \quad \text{that } f(a) = b \text{ and } a \in U, \\ \text{false} & \text{otherwise} \end{cases} \\ &= \begin{cases} \text{true} & \text{if there exists some } a \in U \\ & \quad \text{such that } f(a) = b, \\ \text{false} & \text{otherwise} \end{cases} \end{aligned}$$

for each $b \in B$.

Proposition 2.4.4.1.4. Let $f: A \rightarrow B$ be a function.

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) If $U \subset V$, then $f_*(U) \subset f_*(V)$.

2. *Triple Adjunctions.* We have a triple adjunction

$$(f_* \dashv f^{-1} \dashv f_!): \quad \mathcal{P}(A) \begin{array}{c} \xleftarrow{\quad \perp \quad} \\[-1ex] \xleftarrow{\quad f^{-1} \quad} \\[-1ex] \xleftarrow{\quad \perp \quad} \\[-1ex] \xleftarrow{\quad f_! \quad} \end{array} \mathcal{P}(B),$$

witnessed by bijections of sets

$$\text{Hom}_{\mathcal{P}(B)}(f_*(U), V) \cong \text{Hom}_{\mathcal{P}(A)}(U, f^{-1}(V)),$$

$$\text{Hom}_{\mathcal{P}(A)}(f^{-1}(U), V) \cong \text{Hom}_{\mathcal{P}(A)}(U, f_!(V)),$$

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 $U \subset f_!(V)$.

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 $U, V \in \mathcal{P}(A)$.

4. *Oplax Preservation of Limits.* We have an inclusion of sets

$$f_* \left(\bigcap_{i \in I} U_i \right) \subset \bigcap_{i \in I} f_*(U_i),$$

see Item 9 of Proposition 2.4.4.1.4.

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 $U, V \in \mathcal{P}(A)$.

5. *Symmetric Strict Monoidality With Respect to Unions.* The direct image function of [Item 1](#) has a symmetric strict monoidal structure

$$(f_*, f_*^\otimes, f_{*|1}^\otimes) : (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} f_{*|U,V}^\otimes : f_*(U) \cup f_*(V) &\xrightarrow{\sim} f_*(U \cup V), \\ f_{*|1}^\otimes : \emptyset &\xrightarrow{\sim} \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

6. *Symmetric Oplax Monoidality With Respect to Intersections.* The direct image function of [Item 1](#) has a symmetric oplax monoidal structure

$$(f_*, f_*^\otimes, f_{*|1}^\otimes) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} f_{*|U,V}^\otimes : f_*(U \cap V) &\hookrightarrow f_*(U) \cap f_*(V), \\ f_{*|1}^\otimes : f_*(A) &\hookrightarrow B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

7. *Interaction With Coproducts.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \coprod g)_*(U \coprod V) = f_*(U) \coprod g_*(V)$$

for each $U \in \mathcal{P}(A)$ and each $V \in \mathcal{P}(B)$.

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 $V \in \mathcal{P}(B)$.

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

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

$$\begin{aligned} f_*(U) &= B \setminus (B \setminus f_*(U)), \\ &= B \setminus f_!(A \setminus U), \end{aligned}$$

which finishes the proof. \square

Proposition 2.4.4.1.5. Let $f: A \rightarrow B$ be a function.

1. *Functionality I.* The assignment $f \mapsto f_*$ defines a function

$$(-)_{*|A,B}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

2. *Functionality II.* The assignment $f \mapsto f_!$ defines a function

$$(-)_{*|A,B}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

3. *Interaction With Identities.* For each $A \in \mathbf{Obj}(\mathbf{Sets})$, we have

$$(\mathrm{id}_A)_* = \mathrm{id}_{\mathcal{P}(A)}.$$

³⁷See also [Pro24t].

4. *Interaction With Composition.* For each pair of composable functions $f: A \rightarrow B$ and $g: B \rightarrow C$, we have

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{f_*} & \mathcal{P}(B) \\ (g \circ f)_* = g_* \circ f_*, & \searrow & \downarrow g_* \\ & (g \circ f)_* & \mathcal{P}(C). \end{array}$$

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 ??.

□

2.4.5 Inverse Images

Let A and B be sets and let $f: A \rightarrow B$ be a function.

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 $V \in \mathcal{P}(B)$.

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.

³⁸Further Notation: Also written $f^*: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$.

³⁹Further Terminology: The set $f^{-1}(V)$ is called the **inverse image of V by f** .

Proposition 2.4.5.1.3. Let $f: A \rightarrow B$ be a function.

1. *Functoriality.* The assignment $V \mapsto f^{-1}(V)$ defines a functor

$$f^{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

where

- *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 $U, V \in \mathcal{P}(B)$:

$$(\star) \text{ If } U \subset V, \text{ then } f^{-1}(U) \subset f^{-1}(V).$$

2. *Triple Adjointness.* We have a triple adjunction

$$(f_* \dashv f^{-1} \dashv f_!): \quad \mathcal{P}(A) \begin{array}{c} \xleftarrow{f_*} \\[-1ex] \perp \\[-1ex] \xleftarrow{f^{-1}} \end{array} \mathcal{P}(B), \quad \mathcal{P}(B) \begin{array}{c} \xrightarrow{f^{-1}} \\[-1ex] \perp \\[-1ex] \xrightarrow{f_!} \end{array} \mathcal{P}(A),$$

witnessed by bijections of sets

$$\text{Hom}_{\mathcal{P}(B)}(f_*(U), V) \cong \text{Hom}_{\mathcal{P}(A)}(U, f^{-1}(V)),$$

$$\text{Hom}_{\mathcal{P}(A)}(f^{-1}(U), V) \cong \text{Hom}_{\mathcal{P}(B)}(U, f_!(V)),$$

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 $U \subset f_!(V)$.

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 $U, V \in \mathcal{P}(B)$.

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 $U, V \in \mathcal{P}(B)$.

5. *Symmetric Strict Monoidality With Respect to Unions.* The inverse image function of [Item 1](#) has a symmetric strict monoidal structure

$$(f^{-1}, f^{-1,\otimes}, f_{\mathbb{1}}^{-1,\otimes}) : (\mathcal{P}(B), \cup, \emptyset) \rightarrow (\mathcal{P}(A), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} f_{U,V}^{-1,\otimes} : f^{-1}(U) \cup f^{-1}(V) &\xrightarrow{\equiv} f^{-1}(U \cup V), \\ f_{\mathbb{1}}^{-1,\otimes} : \emptyset &\xrightarrow{\equiv} f^{-1}(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

6. *Symmetric Strict Monoidality With Respect to Intersections.* The inverse image function of [Item 1](#) has a symmetric strict monoidal structure

$$(f^{-1}, f^{-1,\otimes}, f_{\mathbb{1}}^{-1,\otimes}) : (\mathcal{P}(B), \cap, B) \rightarrow (\mathcal{P}(A), \cap, A),$$

being equipped with equalities

$$\begin{aligned} f_{U,V}^{-1,\otimes} : f^{-1}(U) \cap f^{-1}(V) &\xrightarrow{\equiv} f^{-1}(U \cap V), \\ f_{\mathbb{1}}^{-1,\otimes} : A &\xrightarrow{\equiv} f^{-1}(B), \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

7. *Interaction With Coproducts.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \coprod g)^{-1}(U' \coprod V') = f^{-1}(U') \coprod g^{-1}(V')$$

for each $U' \in \mathcal{P}(A')$ and each $V' \in \mathcal{P}(B')$.

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. \square

Proposition 2.4.5.1.4. Let $f: A \rightarrow B$ be a function.

1. *Functionality I.* The assignment $f \mapsto f^{-1}$ defines a function

$$(-)_{A,B}^{-1}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Sets}(\mathcal{P}(B), \mathcal{P}(A)).$$

2. *Functionality II.* The assignment $f \mapsto f^{-1}$ defines a function

$$(-)_{A,B}^{-1}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Pos}((\mathcal{P}(B), \subset), (\mathcal{P}(A), \subset)).$$

3. *Interaction With Identities.* For each $A \in \mathbf{Obj}(\mathbf{Sets})$, we have

$$\text{id}_A^{-1} = \text{id}_{\mathcal{P}(A)}.$$

4. *Interaction With Composition.* For each pair of composable functions $f: A \rightarrow B$ and $g: B \rightarrow C$, we have

$$\begin{array}{ccc} \mathcal{P}(C) & \xrightarrow{g^{-1}} & \mathcal{P}(B) \\ (g \circ f)^{-1} = f^{-1} \circ g^{-1}, & \searrow^{(g \circ f)^{-1}} & \downarrow f^{-1} \\ & & \mathcal{P}(A). \end{array}$$

Proof. **Item 1, Functionality I:** Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: This follows from 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

⁴⁰See also [Pro24ac].

⁴¹See also [Pro24ab].

2.4.6 Direct Images With Compact Support

Let A and B be sets and let $f: A \rightarrow B$ be a function.

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}

$$\begin{aligned} f_!(U) &\stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ if we have} \\ f(a) = b, \text{ then } a \in U \end{array} \right\} \\ &= \left\{ b \in B \mid \text{we have } f^{-1}(b) \subset U \right\} \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

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 $a \in U$.

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

$$f_!: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

defined by

$$\begin{aligned} f_!(\chi_U) &\stackrel{\text{def}}{=} \text{Ran}_f(\chi_U) \\ &= \lim \left(\left(\underline{(-1)} \xrightarrow{\rightarrow} f \right) \xrightarrow{\text{pr}} A \xrightarrow{\chi_U} \{\text{true}, \text{false}\} \right) \\ &= \lim_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)) \\ &= \bigwedge_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)). \end{aligned}$$

⁴²Further Terminology: The set $f_!(U)$ is called the **direct image with compact support of U by f** .

⁴³We also have

$$f_!(U) = B \setminus f_*(A \setminus U);$$

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 $b \in B$.

Definition 2.4.6.1.4. Let U be a subset of A .^{44,45}

1. The **image part of the direct image with compact support** $f_!(U)$ of U is the set $f_{!,\text{im}}(U)$ defined by

$$\begin{aligned} f_{!,\text{im}}(U) &\stackrel{\text{def}}{=} f_!(U) \cap \text{Im}(f) \\ &= \left\{ b \in B \mid \begin{array}{l} \text{we have } f^{-1}(b) \subset \\ U \text{ and } f^{-1}(b) \neq \emptyset \end{array} \right\}. \end{aligned}$$

2. The **complement part of the direct image with compact**

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.

support $f_!(U)$ of U is the set $f_{!,cp}(U)$ defined by

$$\begin{aligned} f_{!,cp}(U) &\stackrel{\text{def}}{=} f_!(U) \cap (B \setminus \text{Im}(f)) \\ &= B \setminus \text{Im}(f) \\ &= \left\{ b \in B \mid \begin{array}{l} \text{we have } f^{-1}(b) \subset \\ U \text{ and } f^{-1}(b) = \emptyset \end{array} \right\} \\ &= \left\{ b \in B \mid f^{-1}(b) = \emptyset \right\}. \end{aligned}$$

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

$$\begin{aligned} f_{!,im}(U) &= f_*(U) \\ f_{!,cp}(U) &= \{\text{odd natural numbers}\} \end{aligned}$$

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

$$f_{!,cp}(U) = \mathbb{R}_{<0}$$

for any $U \subset \mathbb{R}$. Moreover, since $f^{-1}(x) = \{-\sqrt{x}, \sqrt{x}\}$, we have e.g.:

$$\begin{aligned} f_{!,im}([0, 1]) &= \{0\}, \\ f_{!,im}([-1, 1]) &= [0, 1], \\ f_{!,im}([1, 2]) &= \emptyset, \\ f_{!,im}([-2, -1] \cup [1, 2]) &= [1, 4]. \end{aligned}$$

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

$$f_{!,cp}(U) = \mathbb{R}_{<0}$$

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.:

$$\begin{aligned} f_{!,\text{im}}([-1, 1] \times [-1, 1]) &= [0, 1], \\ f_{!,\text{im}}(([[-1, 1] \times [-1, 1]] \setminus [-1, 1] \times \{0\})) &= \emptyset. \end{aligned}$$

Proposition 2.4.6.1.6. Let $f: A \rightarrow B$ be a function.

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) If $U \subset V$, then $f_!(U) \subset f_!(V)$.

2. *Triple Adjointness.* We have a triple adjunction

$$(f_* \dashv f^{-1} \dashv f_!): \quad \mathcal{P}(A) \begin{array}{c} \xleftarrow{f_*} \\[-1ex] \perp \\[-1ex] \xrightarrow{f^{-1}} \\[-1ex] \perp \\[-1ex] \xrightarrow{f_!} \end{array} \mathcal{P}(B),$$

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 $U \subset f_!(V)$.
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 $U, V \in \mathcal{P}(A)$.

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 $U, V \in \mathcal{P}(A)$.

5. *Symmetric Lax Monoidality With Respect to Unions.* The direct image with compact support function of [Item 1](#) has a symmetric lax monoidal structure

$$(f_!, f_!^\otimes, f_{!|1}^\otimes): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with inclusions

$$\begin{aligned} f_{!|U,V}^\otimes: f_!(U) \cup f_!(V) &\hookrightarrow f_!(U \cup V), \\ f_{!|1}^\otimes: \emptyset &\hookrightarrow f_!(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

6. *Symmetric Strict Monoidality With Respect to Intersections.* The direct image function of [Item 1](#) has a symmetric strict monoidal structure

$$(f_!, f_!^\otimes, f_{!|1}^\otimes): (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

$$\begin{aligned} f_{!|U,V}^{\otimes}: f_!(U \cap V) &\xrightarrow{\cong} f_!(U) \cap f_!(V), \\ f_{!|\mathbb{1}}^{\otimes}: f_!(A) &\xrightarrow{\cong} B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

7. *Interaction With Coproducts.* Let $f: A \rightarrow A'$ and $g: B \rightarrow B'$ be maps of sets. We have

$$(f \coprod g)_!(U \coprod V) = f_!(U) \coprod g_!(V)$$

for each $U \in \mathcal{P}(A)$ and each $V \in \mathcal{P}(B)$.

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 $V \in \mathcal{P}(B)$.

9. *Relation to Direct Images.* We have

$$f_!(U) = B \setminus f_*(A \setminus U)$$

for each $U \in \mathcal{P}(A)$.

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 $U \in \mathcal{P}(A)$.

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, Re-

mark 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. \square

Proposition 2.4.6.1.7. Let $f: A \rightarrow B$ be a function.

1. *Functionality I.* The assignment $f \mapsto f_!$ defines a function

$$(-)_{!|A,B}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

2. *Functionality II.* The assignment $f \mapsto f_!$ defines a function

$$(-)_{!|A,B}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

3. *Interaction With Identities.* For each $A \in \text{Obj}(\mathbf{Sets})$, we have

$$(\text{id}_A)_! = \text{id}_{\mathcal{P}(A)}.$$

4. *Interaction With Composition.* For each pair of composable functions $f: A \rightarrow B$ and $g: B \rightarrow C$, we have

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{f_!} & \mathcal{P}(B) \\ (g \circ f)_! = g_! \circ f_!, & \searrow & \downarrow g_! \\ & & \mathcal{P}(C). \end{array}$$

Proof. **Item 1, Functionality I:** Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: This follows from Remark 2.4.6.1.3 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

Relations

- 5. Relations

Constructions With Relations

- 6. Equivalence Relations and Apartness Relations

Category Theory

- 7. Categories

Bicategories

- 8. Types of Morphisms in Bicategories

Chapter 3

Pointed Sets

This chapter contains some foundational material on pointed sets.

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3.1 Pointed Sets

3.1.1 Foundations

Definition 3.1.1.1. A **pointed set**¹ is equivalently:

- An \mathbb{E}_0 -monoid in $(N_\bullet(\text{Sets}), \text{pt})$.
- A pointed object in (Sets, pt) .

Remark 3.1.1.2. 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 Sets , determining an element $x_0 \in X$, called the **basepoint of** X .

Example 3.1.1.3. 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 .

Example 3.1.1.4. 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 .

Example 3.1.1.5. The **underlying pointed set** of a semimodule (M, α_M) is the pointed set $(M, 0_M)$.

Example 3.1.1.6. The **underlying pointed set** of a module (M, α_M) is the pointed set $(M, 0_M)$.

¹Further Terminology: In the context of monoids with zero as models for \mathbb{F}_1 -algebras, pointed sets are viewed as **\mathbb{F}_1 -modules**.

²Further 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**.

³Further Notation: In the context of monoids with zero as models for \mathbb{F}_1 -algebras,

3.1.2 Morphisms of Pointed Sets

Definition 3.1.2.1.1. A **morphism of pointed sets**^{4,5} is equivalently:

- A morphism of \mathbb{E}_0 -monoids in $(N_\bullet(\text{Sets}), \text{pt})$.
- A morphism of pointed objects in (Sets, pt) .

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

$$f(x_0) = y_0.$$

3.1.3 The Category of Pointed Sets

Definition 3.1.3.1.1. The **category of pointed sets** is the category Sets_* defined equivalently as

- The homotopy category of the ∞ -category $\text{Mon}_{\mathbb{E}_0}(N_\bullet(\text{Sets}), \text{pt})$ of ??;
- The category Sets_* of ??.

Remark 3.1.3.1.2. In detail, the **category of pointed sets** is the category Sets_* where

- *Objects.* The objects of Sets_* are pointed sets;
- *Morphisms.* The morphisms of Sets_* are morphisms of pointed sets;
- *Identities.* For each $(X, x_0) \in \text{Obj}(\text{Sets}_*)$, the unit map

$$\mathbb{1}_{(X, x_0)}^{\text{Sets}_*}: \text{pt} \rightarrow \text{Sets}_*((X, x_0), (X, x_0))$$

of Sets_* at (X, x_0) is defined by⁶

$$\text{id}_{(X, x_0)}^{\text{Sets}_*} \stackrel{\text{def}}{=} \text{id}_X;$$

⁴*S⁰* is also denoted $(\mathbb{F}_1, 0)$.

⁵Further Terminology: Also called a **pointed function**.

⁵Further 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 $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$, the composition map

$$\circ^{\mathbf{Sets}_*}_{(X, x_0), (Y, y_0), (Z, z_0)} : \mathbf{Sets}_*((Y, y_0), (Z, z_0)) \times \mathbf{Sets}_*((X, x_0), (Y, y_0)) \rightarrow \mathbf{Sets}_*((X, x_0), (Z, z_0))$$

of \mathbf{Sets}_* at $((X, x_0), (Y, y_0), (Z, z_0))$ is defined by⁷

$$g \circ^{\mathbf{Sets}_*}_{(X, x_0), (Y, y_0), (Z, z_0)} f \stackrel{\text{def}}{=} g \circ f.$$

3.1.4 Elementary Properties of Pointed Sets

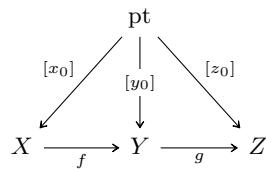
Proposition 3.1.4.1.1. Let (X, x_0) be a pointed set.

1. *Completeness.* The category \mathbf{Sets}_* of pointed sets and morphisms between them is complete, having in particular:
 - Products, described as in [Definition 3.2.3.1.1](#);
 - Pullbacks, described as in [Definition 3.2.4.1.1](#);
 - Equalisers, described as in [Definition 3.2.5.1.1](#).
2. *Cocompleteness.* The category \mathbf{Sets}_* of pointed sets and morphisms between them is cocomplete, having in particular:
 - Coproducts, described as in [Definition 3.3.3.1.1](#);
 - Pushouts, described as in [Definition 3.3.4.1.1](#);
 - Coequalisers, described as in [Definition 3.3.5.1.1](#).
3. *Failure To Be Cartesian Closed.* The category \mathbf{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 \mathbf{Sets}_* does admit monoidal closed structures however; see [Tensor Products of Pointed Sets](#).

4. *Morphisms From the Monoidal Unit.* We have a bijection of sets⁹

$$\mathbf{Sets}_*(S^0, X) \cong X,$$

natural in $(X, x_0) \in \text{Obj}(\mathbf{Sets}_*)$, internalising also to an isomorphism of pointed sets

$$\mathbf{Sets}_*(S^0, X) \cong (X, x_0),$$

again natural in $(X, x_0) \in \text{Obj}(\mathbf{Sets}_*)$.

5. *Relation to Partial Functions.* We have an equivalence of categories¹⁰

$$\mathbf{Sets}_* \xrightarrow{\text{eq.}} \mathbf{Sets}^{\text{part.}}$$

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

$$\text{忘}: \mathbf{Sets}_* \rightarrow \mathbf{Sets}$$

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.
END TEXTDBEND

(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]. □

3.2 Limits of Pointed Sets

3.2.1 The Terminal Pointed Set

Definition 3.2.1.1.1. The **terminal pointed set** is the pair $((\text{pt}, \star), \{\mathbf{!}_X\}_{(X, x_0) \in \text{Obj}(\text{Sets}_*)})$ consisting of:

- *The Limit.* The pointed set (pt, \star) .
- *The Cone.* The collection of morphisms of pointed sets

$$\{\mathbf{!}_X : (X, x_0) \rightarrow (\text{pt}, \star)\}_{(X, x_0) \in \text{Obj}(\text{Sets}_*)}$$

defined by

$$\mathbf{!}_X(x) \stackrel{\text{def}}{=} \star$$

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 $\mathbf{!}_X$. \square

3.2.2 Products of Families of Pointed Sets

Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

Definition 3.2.2.1.1. The **product of** $\{(X_i, x_0^i)\}_{i \in I}$ is the pair $((\prod_{i \in I} X_i, (x_0^i)_{i \in I}), \{\text{pr}_i\}_{i \in I})$ consisting of:

- *The Limit.* The pointed set $(\prod_{i \in I} X_i, (x_0^i)_{i \in I})$.
- *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

$$\text{pr}_i((x_j)_{j \in I}) \stackrel{\text{def}}{=} x_i$$

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 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 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

$$\begin{array}{ccc} (P, *) & & \\ \downarrow \phi \quad \exists! & \searrow^{p_i} & \\ (\prod_{i \in I} X_i, (x_0^i)_{i \in I}) & \xrightarrow{\text{pr}_i} & (X_i, x_0^i) \end{array}$$

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

Proposition 3.2.2.1.2. Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

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

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

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

\square

3.2.3 Products

Let (X, x_0) and (Y, y_0) be pointed sets.

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

$$\begin{array}{ccccc} & & (P, *) & & \\ & \swarrow p_1 & & \searrow p_2 & \\ (X, x_0) & \xleftarrow{\text{pr}_1} & (X \times Y, (x_0, y_0)) & \xrightarrow{\text{pr}_2} & (Y, y_0) \end{array}$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (P, *) \rightarrow (X \times Y, (x_0, y_0))$$

making the diagram

$$\begin{array}{ccccc} & & (P, *) & & \\ & \swarrow p_1 & \downarrow \phi \exists! & \searrow p_2 & \\ (X, x_0) & \xleftarrow{\text{pr}_1} & (X \times Y, (x_0, y_0)) & \xrightarrow{\text{pr}_2} & (Y, y_0) \end{array}$$

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

Proposition 3.2.3.1.2. Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

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](#).

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 $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

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

$$\begin{aligned}(\text{pt}, \star) \times (X, x_0) &\cong (X, x_0), \\ (X, x_0) \times (\text{pt}, \star) &\cong (X, x_0),\end{aligned}$$

natural in $(X, x_0) \in \text{Obj}(\mathbf{Sets}_*)$.

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 $(X, x_0), (Y, y_0) \in \text{Obj}(\mathbf{Sets}_*)$.

5. *Symmetric Monoidality.* The triple $(\mathbf{Sets}_*, \times, (\text{pt}, \star))$ 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](#). \square

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.

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

$$\begin{aligned} \text{pr}_1: (X \times_Z Y, (x_0, y_0)) &\rightarrow (X, x_0), \\ \text{pr}_2: (X \times_Z Y, (x_0, y_0)) &\rightarrow (Y, y_0) \end{aligned}$$

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 $(x, y) \in X \times_Z Y$.

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

$$\begin{array}{ccc} (X \times_Z Y, (x_0, y_0)) & \xrightarrow{\text{pr}_2} & (Y, y_0) \\ f \circ \text{pr}_1 = g \circ \text{pr}_2, & \text{pr}_1 \downarrow & \downarrow g \\ (X, x_0) & \xrightarrow{f} & (Z, z_0). \end{array}$$

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

$$\begin{array}{ccccc}
 & & p_2 & & \\
 (P, *) & \swarrow & & \searrow & \\
 & & (X \times_Z Y, (x_0, y_0)) - \text{pr}_2 \rightarrow (Y, y_0) & & \\
 p_1 \curvearrowleft & & \downarrow \text{pr}_1 & \lrcorner & \downarrow g \\
 & & (X, x_0) & \xrightarrow{f} & (Z, z_0)
 \end{array}$$

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

$$\begin{array}{ccccc}
 & & p_2 & & \\
 (P, *) & \swarrow \phi & & \searrow & \\
 & \exists! & & & \\
 & & (X \times_Z Y, (x_0, y_0)) - \text{pr}_2 \rightarrow (Y, y_0) & & \\
 p_1 \curvearrowleft & & \downarrow \text{pr}_1 & \lrcorner & \downarrow g \\
 & & (X, x_0) & \xrightarrow{f} & (Z, z_0)
 \end{array}$$

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 $x \in P$, 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

Proposition 3.2.4.1.2. Let (X, x_0) , (Y, y_0) , (Z, z_0) , and (A, a_0) be pointed sets.

1. *Functoriality.* The assignment $(X, Y, Z, f, g) \mapsto X \times_{f, Z, g} Y$ defines a functor

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

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

$$\begin{array}{ccccc} X \times_Z Y & \longrightarrow & Y & & \\ \downarrow & \lrcorner & \downarrow g & \searrow \psi & \\ X' \times_{Z'} Y' & \longrightarrow & Y' & & \\ \downarrow & \lrcorner & \downarrow & & \\ X & \xrightarrow{f} & Z & \xrightarrow{g'} & \\ \phi \searrow & & \downarrow & \swarrow \chi & \downarrow \\ X' & \xrightarrow{f'} & Z' & & \end{array}$$

in $\mathbf{Fun}(\mathcal{P}, \mathbf{Sets}_*)$ 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

$$\begin{array}{ccccc} X \times_Z Y & \longrightarrow & Y & & \\ \searrow \lrcorner & & \downarrow g & \searrow \psi & \\ X' \times_{Z'} Y' & \longrightarrow & Y' & & \\ \downarrow & \lrcorner & \downarrow & & \\ X & \xrightarrow{f} & Z & \xrightarrow{g'} & \\ \phi \searrow & & \downarrow & \swarrow \chi & \downarrow \\ X' & \xrightarrow{f'} & Z' & & \end{array}$$

commute.

2. *Associativity.* Given a diagram

$$\begin{array}{ccccc} X & & Y & & Z \\ \searrow f & & \swarrow g & \searrow h & \swarrow k \\ W & & V & & \end{array}$$

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

$$\begin{array}{ccc} \begin{array}{c} (X \times_W Y) \times_Y Z \\ \downarrow \quad \swarrow \\ X \times_W Y \end{array} & \begin{array}{c} (X \times_W Y) \times_Y (Y \times_V Z) \\ \downarrow \quad \swarrow \quad \searrow \\ X \times_W Y \end{array} & \begin{array}{c} X \times_W (Y \times_V Z) \\ \downarrow \quad \swarrow \\ Y \times_V Z \end{array} \\ \begin{array}{ccccc} X & \xrightarrow{\quad} & Y & \xrightarrow{\quad} & Z \\ \downarrow \quad \swarrow & & \downarrow \quad \searrow & & \downarrow \\ X & \xrightarrow{\quad} & Y & \xrightarrow{\quad} & Z \\ \downarrow f & \quad g & \quad h & \quad k & \\ W & & V & & \end{array} & \begin{array}{ccccc} X & \xrightarrow{\quad} & Y & \xrightarrow{\quad} & Z \\ \downarrow \quad \swarrow & & \downarrow \quad \searrow & & \downarrow \\ X & \xrightarrow{\quad} & Y & \xrightarrow{\quad} & Z \\ \downarrow f & \quad g & \quad h & \quad k & \\ W & & V & & \end{array} & \begin{array}{ccccc} X & \xrightarrow{\quad} & Y & \xrightarrow{\quad} & Z \\ \downarrow \quad \swarrow & & \downarrow \quad \searrow & & \downarrow \\ X & \xrightarrow{\quad} & Y & \xrightarrow{\quad} & Z \\ \downarrow f & \quad g & \quad h & \quad k & \\ W & & V & & \end{array} \end{array}$$

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

$$\begin{array}{ccc} A \xlongequal{\quad} A & & A \xrightarrow{f} X \\ \downarrow \lrcorner \quad \downarrow f & & \parallel \lrcorner \quad \parallel \\ X \xlongequal{\quad} X & & X \xrightarrow{f} X. \end{array} \quad \begin{array}{c} X \times_X A \cong A, \\ A \times_X X \cong A, \end{array}$$

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

$$\begin{array}{ccc} A \times_X B \longrightarrow B & & B \times_X A \longrightarrow A \\ \downarrow \lrcorner \quad \downarrow g & & \downarrow \lrcorner \quad \downarrow f \\ A \xrightarrow{f} X, & & B \xrightarrow{g} X. \end{array} \quad A \times_X B \cong B \times_X A$$

5. *Interaction With Products.* We have an isomorphism of pointed sets

$$\begin{array}{ccc} X \times Y \longrightarrow Y & & \\ \downarrow \lrcorner \quad \downarrow !_Y & & \\ X \xrightarrow{!_X} \text{pt.} & & \end{array} \quad X \times_{\text{pt}} Y \cong X \times Y,$$

6. *Symmetric Monoidality.* The triple $(\mathbf{Sets}_*, \times_X, X)$ 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](#). \square

3.2.5 Equalisers

Let $f, g: (X, x_0) \rightrightarrows (Y, y_0)$ be morphisms of pointed sets.

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

$$\begin{array}{ccc} (\text{Eq}(f, g), x_0) & \xrightarrow{\text{eq}(f, g)} & (X, x_0) \\ & \nearrow e & \xrightarrow{f} \\ & (E, *) & \xrightarrow{g} (Y, y_0) \end{array}$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (E, *) \rightarrow (\text{Eq}(f, g), x_0)$$

making the diagram

$$\begin{array}{ccc}
 (\text{Eq}(f, g), x_0) & \xrightarrow{\text{eq}(f, g)} & (X, x_0) \xrightarrow[g]{f} (Y, y_0) \\
 \phi \dashv \exists! \quad e \swarrow & & \\
 (E, *) & &
 \end{array}$$

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

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.

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

$$(X, x_0) \xrightarrow[g]{f} (Y, y_0)$$

in Sets_* , being explicitly given by

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

2. *Unitality.* We have an isomorphism of pointed sets

$$\mathrm{Eq}(f, f) \cong X.$$

3. *Commutativity.* We have an isomorphism of pointed sets

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

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

3.3 Colimits of Pointed Sets

3.3.1 The Initial Pointed Set

Definition 3.3.1.1.1. The **initial pointed set** is the pair $((\mathrm{pt}, \star), \{\iota_X\}_{(X, x_0) \in \mathrm{Obj}(\mathrm{Sets}_*)})$ consisting of:

- *The Limit.* The pointed set (pt, \star) .
- *The Cone.* The collection of morphisms of pointed sets

$$\{\iota_X : (\mathrm{pt}, \star) \rightarrow (X, x_0)\}_{(X, x_0) \in \mathrm{Obj}(\mathrm{Sets})}$$

defined by

$$\iota_X(\star) \stackrel{\mathrm{def}}{=} x_0.$$

Proof. We claim that (pt, \star) is the initial object of Sets_* . Indeed, suppose we have a diagram of the form

$$(\mathrm{pt}, \star) \quad (X, x_0)$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi : (\mathrm{pt}, \star) \rightarrow (X, x_0)$$

making the diagram

$$(\mathrm{pt}, \star) \xrightarrow{\phi} (X, x_0)$$

commute, namely ι_X . \square

3.3.2 Coproducts of Families of Pointed Sets

Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

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

$$\begin{array}{ccc} & (C, *) & \\ \iota_i \nearrow & \uparrow \phi \exists! & \\ (X_i, x_0^i) & \xrightarrow{\text{inj}_i} & \left(\bigvee_{i \in I} X_i, p_0 \right) \end{array}$$

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

$$\begin{aligned} \phi(p_0) &= \iota_i \left([(i, x_0^i)] \right) \\ &= *, \end{aligned}$$

as ι_i is a morphism of pointed sets. \square

Proposition 3.3.2.1.2. Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

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 ??.

\square

3.3.3 Coproducts

Let (X, x_0) and (Y, y_0) be pointed sets.

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

$$(X \vee Y, p_0) \stackrel{\text{def}}{=} (X, x_0) \coprod (Y, y_0) \cong (X \coprod_{\text{pt}} Y, p_0) \cong (X \coprod Y / \sim, p_0),$$

$$\begin{array}{ccc} X \vee Y & \xleftarrow{\lrcorner} & Y \\ \uparrow & & \uparrow [y_0] \\ X & \xleftarrow[\lrcorner_{x_0}]{} & \text{pt}, \end{array}$$

where \sim is the equivalence relation on $X \coprod Y$ 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

$$\begin{array}{ccccc} & & (C, *) & & \\ \iota_X \nearrow & & \downarrow & & \iota_Y \searrow \\ (X, x_0) & \xrightarrow{\text{inj}_X} & (X \vee Y, p_0) & \xleftarrow{\text{inj}_Y} & (Y, y_0) \end{array}$$

in Sets . Then there exists a unique morphism of pointed sets

$$\phi: (X \vee Y, p_0) \rightarrow (C, *)$$

making the diagram

$$\begin{array}{ccccc} & & (C, *) & & \\ \iota_X \nearrow & & \uparrow \phi \exists! & & \iota_Y \searrow \\ (X, x_0) & \xrightarrow{\text{inj}_X} & (X \vee Y, p_0) & \xleftarrow{\text{inj}_Y} & (Y, y_0) \end{array}$$

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

Proposition 3.3.3.1.2. Let (X, x_0) and (Y, y_0) be pointed sets.

1. *Functoriality.* The assignments

$$(X, x_0), (Y, y_0), ((X, x_0), (Y, y_0)) \mapsto (X \vee Y, p_0)$$

define functors

$$\begin{aligned}X \vee - &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ - \vee Y &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ -_1 \vee -_2 &: \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*.\end{aligned}$$

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

$$(X \vee Y) \vee Z \cong X \vee (Y \vee Z),$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \mathbf{Sets}_*$.

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 $(X, x_0) \in \mathbf{Sets}_*$.

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

$$X \vee Y \cong Y \vee X,$$

natural in $(X, x_0), (Y, y_0) \in \mathbf{Sets}_*$.

5. *Symmetric Monoidality.* The triple $(\text{Sets}_*, \vee, \text{pt})$ is a symmetric monoidal category.

6. *The Fold Map.* We have a natural transformation

$$\nabla: \vee \circ \Delta_{\text{Sets}_*}^{\text{Cats}} \Rightarrow \text{id}_{\text{Sets}_*},$$

$$\begin{array}{ccc} & \text{Sets}_* \times \text{Sets}_* & \\ \Delta_{\text{Sets}_*}^{\text{Cats}} & \nearrow \quad \parallel \quad \searrow & \\ \text{Sets}_* & \downarrow \nabla & \text{Sets}_*, \\ & \searrow \quad \downarrow \quad \nearrow & \\ & \text{id}_{\text{Sets}_*} & \end{array}$$

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

$$\begin{array}{ccc} X \vee X & \xrightarrow{\nabla_X} & X \\ \nabla_Y \circ (f \vee f) = f \circ \nabla_X, & \downarrow f \vee f & \downarrow f \\ Y \vee Y & \xrightarrow{\nabla_Y} & Y. \end{array}$$

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

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.

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

$$\begin{array}{ccc} (X \coprod_Z Y, p_0) & \xleftarrow{\text{inj}_2} & (Y, y_0) \\ \text{inj}_1 \circ f = \text{inj}_2 \circ g, & \uparrow \text{inj}_1 & \uparrow g \\ (X, x_0) & \xleftarrow[f]{ } & (Z, z_0). \end{array}$$

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 $X \coprod Y$ (the coproduct of unpointed sets of X and Y). Next, we prove that $X \coprod_Z Y$ satisfies the universal property of the pushout. Suppose we have a diagram of the form

$$\begin{array}{ccccc}
& & (P, *) & & \\
& \swarrow \iota_1 & & \searrow \iota_2 & \\
(X \coprod_Z Y, p_0) & & & \leftarrow \text{inj}_2 - (Y, y_0) & \\
\uparrow \text{inj}_1 & & \lrcorner & & \uparrow g \\
(X, x_0) & \xleftarrow{f} & (Z, z_0) & &
\end{array}$$

in Sets_* . Then there exists a unique morphism of pointed sets

$$\phi: (X \coprod_Z Y, p_0) \rightarrow (P, *)$$

making the diagram

$$\begin{array}{ccccc}
& & (P, *) & & \\
& \swarrow \iota_1 & & \searrow \iota_2 & \\
(X \coprod_Z Y, p_0) & & \xleftarrow{\exists! \phi} & & (Y, y_0) \\
\uparrow \text{inj}_1 & & \lrcorner & & \uparrow g \\
(X, x_0) & \xleftarrow{f} & (Z, z_0) & &
\end{array}$$

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 $p \in X \coprod_Z Y$, 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

$$\begin{aligned}\phi(p_0) &= \phi([(1, y_0)]) \\ &= \iota_2(y_0) \\ &= *\end{aligned}$$

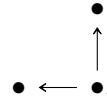
where we use that ι_1 (resp. ι_2) is a morphism of pointed sets. \square

Proposition 3.3.4.1.2. Let (X, x_0) , (Y, y_0) , (Z, z_0) , and (A, a_0) be pointed sets.

1. *Functoriality.* The assignment $(X, Y, Z, f, g) \mapsto X \coprod_{f, Z, g} Y$ defines a functor

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

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

$$\begin{array}{ccccc}
X \coprod_Z Y & \xleftarrow{\quad} & Y & \xrightarrow{\quad} & \psi \\
\uparrow & \lrcorner & \uparrow & \lrcorner & \searrow \\
X' \coprod_{Z'} Y' & \xleftarrow{\quad} & Y' & \xleftarrow{\quad} & \\
\uparrow & \lrcorner & \uparrow & \lrcorner & \\
X & \xleftarrow{\quad} & Z & \xleftarrow{\quad} & \\
\downarrow \phi & \searrow & \downarrow f & \swarrow & \downarrow g \\
X' & \xleftarrow{\quad} & Z' & \xleftarrow{\quad} & \\
& & \downarrow f' & & \downarrow g'
\end{array}$$

in $\mathbf{Fun}(\mathcal{P}, \mathbf{Sets}_*)$ to the morphism of pointed sets

$$\xi : (X \coprod_Z Y, p_0) \xrightarrow{\exists!} (X' \coprod_{Z'} Y', p'_0)$$

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 $p \in X \coprod_Z Y$, which is the unique morphism of pointed

sets making the diagram

$$\begin{array}{ccccc}
 X \coprod_Z Y & \xleftarrow{\quad} & Y & & \\
 \uparrow & \lrcorner & \uparrow \psi & & \\
 X' \coprod_{Z'} Y' & \xleftarrow{\quad} & Y' & & \\
 \uparrow & \lrcorner & \uparrow g & & \\
 X & \xleftarrow{\quad} & Z & \xrightarrow{\quad} & \\
 \downarrow \phi & & \downarrow f & & \downarrow g' \\
 X' & \xleftarrow{\quad} & Z' & \xrightarrow{\quad} &
 \end{array}$$

commute.

2. *Associativity.* Given a diagram

$$\begin{array}{ccccc}
 X & & Y & & Z \\
 & \swarrow f & \nearrow g & \swarrow h & \nearrow k \\
 W & & V & &
 \end{array}$$

in Sets , we have isomorphisms of pointed sets

$$(X \coprod_W Y) \coprod_V Z \cong (X \coprod_W Y) \coprod_Y (Y \coprod_V Z) \cong X \coprod_W (Y \coprod_V Z),$$

where these pullbacks are built as in the diagrams

$$\begin{array}{ccc}
 \begin{array}{c} (X \coprod_W Y) \coprod_V Z \\ \uparrow \wedge \uparrow \wedge \\ X \coprod_W Y \quad Y \coprod_V Z \\ \uparrow \wedge \uparrow \wedge \quad \uparrow \wedge \uparrow \\ X \quad Y \quad Z \\ \swarrow f \quad \nearrow g \quad \swarrow h \quad \nearrow k \\ W \quad V \quad Z \end{array} & \begin{array}{c} (X \coprod_W Y) \coprod_Y (Y \coprod_V Z) \\ \uparrow \wedge \uparrow \wedge \uparrow \wedge \\ X \coprod_W Y \quad Y \coprod_V Z \\ \uparrow \wedge \uparrow \quad \uparrow \wedge \uparrow \quad \uparrow \wedge \uparrow \\ X \quad Y \quad Z \\ \swarrow f \quad \nearrow g \quad \swarrow h \quad \nearrow k \\ W \quad V \quad Z \end{array} & \begin{array}{c} X \coprod_W (Y \coprod_V Z) \\ \uparrow \wedge \uparrow \wedge \uparrow \wedge \\ X \quad Y \quad Z \\ \swarrow f \quad \nearrow g \quad \swarrow h \quad \nearrow k \\ W \quad V \quad Z \end{array} \\
 X \coprod_W Y & & X \coprod_W Y \quad Y \coprod_V Z & & X \coprod_W (Y \coprod_V Z) \\
 \uparrow \wedge \uparrow & & \uparrow \wedge \uparrow \quad \uparrow \wedge \uparrow & & \uparrow \wedge \uparrow \quad \uparrow \wedge \uparrow \\
 X & & X \quad Y & & X \\
 \swarrow f \quad \nearrow g & & \swarrow f \quad \nearrow g \quad \swarrow h \quad \nearrow k & & \swarrow f \quad \nearrow g \quad \swarrow h \quad \nearrow k \\
 W & & V & & Z \\
 \end{array}$$

3. *Unitality.* We have isomorphisms of sets

$$\begin{array}{ccc}
 A & \xlongequal{\quad} & A \\
 \uparrow \lrcorner & & \uparrow f \\
 X & \xlongequal{\quad} & X
 \end{array}
 \quad
 \begin{array}{c}
 X \coprod_X A \cong A, \\
 A \coprod_X X \cong A,
 \end{array}
 \quad
 \begin{array}{c}
 A \xleftarrow{f} X \\
 \parallel \lrcorner \parallel \\
 X \xleftarrow{f} X.
 \end{array}$$

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

$$\begin{array}{ccc}
 X \coprod_Z Y & \xleftarrow{\quad} & Y \\
 \uparrow \lrcorner & & \uparrow g \\
 X & \xleftarrow{f} & Z
 \end{array}
 \quad
 X \coprod_Z Y \cong Y \coprod_Z X
 \quad
 \begin{array}{c}
 Y \coprod_Z X \xleftarrow{\quad} X \\
 \uparrow \lrcorner & & \uparrow f \\
 Y & \xleftarrow{g} & Z
 \end{array}$$

5. *Interaction With Coproducts.* We have

$$\begin{array}{ccc} X \vee Y & \longleftarrow & Y \\ \uparrow & \lrcorner & \uparrow [y_0] \\ X \coprod_{\text{pt}} Y \cong X \vee Y, & & \\ \uparrow & & \downarrow \\ X & \xleftarrow{[x_0]} & \text{pt.} \end{array}$$

6. *Symmetric Monoidality.* The triple $(\text{Sets}_*, \coprod_X, (X, x_0))$ 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

3.3.5 Coequalisers

Let $f, g: (X, x_0) \rightrightarrows (Y, y_0)$ be morphisms of pointed sets.

Definition 3.3.5.1.1. The **coequaliser of** (f, g) is the pointed set $(\text{CoEq}(f, g), [y_0])$.

Proof. We claim that $(\text{CoEq}(f, g), [y_0])$ 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

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

for each $x \in X$. Next, we prove that $\text{CoEq}(f, g)$ satisfies the universal

property of the coequaliser. Suppose we have a diagram of the form

$$(X, x_0) \xrightarrow{\begin{matrix} f \\ g \end{matrix}} (Y, y_0) \xrightarrow{\text{coeq}(f, g)} (\text{CoEq}(f, g), [y_0])$$

c

\searrow

$(C, *)$

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 $\phi: \text{CoEq}(f, g) \xrightarrow{\exists!} C$ making the diagram

$$(X, x_0) \xrightarrow{\begin{matrix} f \\ g \end{matrix}} (Y, y_0) \xrightarrow{\text{coeq}(f, g)} (\text{CoEq}(f, g), [y_0])$$

c

\searrow

$\phi \downarrow \exists!$

$(C, *)$

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

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.

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

$$(X, x_0) \xrightarrow{\begin{matrix} f \\ -g \\ h \end{matrix}} (Y, y_0)$$

in Sets_* .

2. *Unitality.* We have an isomorphism of pointed sets

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

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.

□

3.4 Constructions With Pointed Sets

3.4.1 Free Pointed Sets

Let X be a set.

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

$$\begin{aligned} X^+ &\stackrel{\text{def}}{=} X \coprod \text{pt} \\ &\stackrel{\text{def}}{=} X \coprod \{\star\}. \end{aligned}$$

- *The Basepoint.* The element \star of X^+ .

Proposition 3.4.1.1.2. Let X be a set.

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

$$f^+(x) \stackrel{\text{def}}{=} \begin{cases} f(x) & \text{if } x \in X, \\ \star_Y & \text{if } x = \star_X. \end{cases}$$

¹¹Further Notation: We sometimes write \star_X for the basepoint of X^+ for clarity

2. *Adjointness.* We have an adjunction

$$\left((-)^+ \dashv \text{忘} \right) : \text{Sets} \begin{array}{c} \xrightarrow{(-)^+} \\ \perp \\ \xleftarrow{\text{忘}} \end{array} \text{Sets}_*,$$

witnessed by a bijection of sets

$$\text{Sets}_* \left((X^+, \star_X), (Y, y_0) \right) \cong \text{Sets}(X, Y),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $(Y, y_0) \in \text{Obj}(\text{Sets}_*)$.

3. *Symmetric Strong Monoidality With Respect to Wedge Sums.* The free pointed set functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left((-)^+, (-)^+, \coprod, (-)_1^+ \coprod \right) : (\text{Sets}, \coprod, \emptyset) \rightarrow (\text{Sets}_*, \vee, \text{pt}),$$

being equipped with isomorphisms of pointed sets

$$\begin{aligned} (-)_{X,Y}^{+, \coprod} : X^+ \vee Y^+ &\xrightarrow{\cong} (X \coprod Y)^+, \\ (-)_1^+ \coprod : \text{pt} &\xrightarrow{\cong} \emptyset^+, \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

4. *Symmetric Strong Monoidality With Respect to Smash Products.*

The free pointed set functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left((-)^+, (-)^{+, \times}, (-)_1^{+, \times} \right) : (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Sets}_*, \wedge, S^0),$$

being equipped with isomorphisms of pointed sets

$$\begin{aligned} (-)_{X,Y}^{+, \times} : X^+ \wedge Y^+ &\xrightarrow{\cong} (X \times Y)^+, \\ (-)_1^{+, \times} : S^0 &\xrightarrow{\cong} \text{pt}^+, \end{aligned}$$

natural in $X, Y \in \text{Obj}(\text{Sets})$.

Proof. [Item 1](#), *Functionality:* Clear.

[Item 2](#), *Adjointness:* We claim there's an adjunction $(-)^+ \dashv \text{忘}$, witnessed by a bijection of sets

$$\text{Sets}_* \left((X^+, \star_X), (Y, y_0) \right) \cong \text{Sets}(X, Y),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $(Y, y_0) \in \text{Obj}(\text{Sets}_*)$.

- *Map I.* We define a map

$$\Phi_{X,Y}: \mathbf{Sets}_* \left((X^+, \star_X), (Y, y_0) \right) \rightarrow \mathbf{Sets}(X, Y)$$

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

$$\Psi_{X,Y}: \mathbf{Sets}(X, Y) \rightarrow \mathbf{Sets}_* \left((X^+, \star_X), (Y, y_0) \right)$$

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

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \text{id}_{\mathbf{Sets}_* \left((X^+, \star_X), (Y, y_0) \right)},$$

which is clear.

- *Invertibility II.* We claim that

$$\Phi_{X,Y} \circ \Psi_{X,Y} = \text{id}_{\mathbf{Sets}(X, Y)},$$

which is clear.

- *Naturality for Φ , Part I.* We need to show that, given a pointed

when there are multiple free pointed sets involved in the current discussion.

function $g: (Y, y_0) \rightarrow (Y', y'_0)$, the diagram

$$\begin{array}{ccc} \mathbf{Sets}_*((X^+, \star_X), (Y, y_0)) & \xrightarrow{\Phi_{X,Y}} & \mathbf{Sets}(X, Y) \\ g_* \downarrow & & \downarrow g_* \\ \mathbf{Sets}_*((X^+, \star_X), (Y', y'_0)) & \xrightarrow{\Phi_{X,Y'}} & \mathbf{Sets}(X, Y') \end{array}$$

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

$$\begin{array}{ccc} \mathbf{Sets}_*\left((X'^+, \star_X), (Y, y_0)\right) & \xrightarrow{\Phi_{X',Y}} & \mathbf{Sets}(X', Y) \\ f^* \downarrow & & \downarrow f^* \\ \mathbf{Sets}_*((X^+, \star_X), (Y, y_0)) & \xrightarrow{\Phi_{X,Y}} & \mathbf{Sets}(X, Y) \end{array}$$

commutes. Indeed, given a function

$$\xi: X' \rightarrow Y,$$

we have

$$\begin{aligned} [\Phi_{X,Y} \circ f^*](\xi) &= \Phi_{X,Y}(f^*(\xi)) \\ &= \Phi_{X,Y}(\xi \circ f) \\ &= \xi \circ f \\ &= \Phi_{X',Y}(\xi) \circ f \\ &= f^*(\Phi_{X',Y}(\xi)) \\ &= f^*(\Phi_{X',Y}(\xi)) \\ &= [f^* \circ \Phi_{X',Y}](\xi). \end{aligned}$$

- *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

$$\phi: X^+ \vee Y^+ \xrightarrow{\cong} (X \coprod Y)^+$$

is given by

$$\phi(z) = \begin{cases} x & \text{if } z = [(0, x)] \text{ with } x \in X, \\ y & \text{if } z = [(1, y)] \text{ with } y \in Y, \\ \star_{X \coprod Y} & \text{if } z = [(0, \star_X)], \\ \star_{X \coprod Y} & \text{if } z = [(1, \star_Y)] \end{cases}$$

for each $z \in X^+ \vee Y^+$, with inverse

$$\phi^{-1}: (X \coprod Y)^+ \xrightarrow{\cong} X^+ \vee Y^+$$

given by

$$\phi^{-1}(z) \stackrel{\text{def}}{=} \begin{cases} [(0, x)] & \text{if } z = [(0, x)], \\ [(1, y)] & \text{if } z = [(1, y)], \\ p_0 & \text{if } z = \star_{X \coprod Y} \end{cases}$$

for each $z \in (X \coprod Y)^+$.

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 $z \in (X \coprod Y)^+$.

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. \square

Appendices

3.A Other Chapters

Sets

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

Relations

- 5. Relations

Constructions With Relations

- 6. Equivalence Relations and Apartness Relations

Category Theory

- 7. Categories

Bicategories

- 8. Types of Morphisms in Bicategories

Chapter 4

Tensor Products of Pointed Sets

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*

$$\wedge: \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*,$$

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,

$$\begin{aligned} \lhd: \mathbf{Sets}_* \times \mathbf{Sets}_* &\rightarrow \mathbf{Sets}_*, \\ \rhd: \mathbf{Sets}_* \times \mathbf{Sets}_* &\rightarrow \mathbf{Sets}_*, \end{aligned}$$

called the *left* and *right tensor products of pointed sets*. In contrast to \wedge , which turns out to endow \mathbf{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

$$\odot: \text{Sets} \times \text{Sets}_* \rightarrow \text{Sets}_*,$$

called the *tensor* of sets with pointed sets. All in all, these tensor products assemble into a family of functors of the form

$$\begin{aligned}\otimes_{k,\ell}: \text{Mon}_{\mathbb{E}_k}(\text{Sets}) \times \text{Mon}_{\mathbb{E}_\ell}(\text{Sets}) &\rightarrow \text{Mon}_{\mathbb{E}_{k+\ell}}(\text{Sets}), \\ \triangleleft_{i,k}: \text{Mon}_{\mathbb{E}_k}(\text{Sets}) \times \text{Mon}_{\mathbb{E}_k}(\text{Sets}) &\rightarrow \text{Mon}_{\mathbb{E}_k}(\text{Sets}), \\ \triangleright_{i,k}: \text{Mon}_{\mathbb{E}_k}(\text{Sets}) \times \text{Mon}_{\mathbb{E}_k}(\text{Sets}) &\rightarrow \text{Mon}_{\mathbb{E}_k}(\text{Sets}),\end{aligned}$$

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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4.1 Bilinear Morphisms of Pointed Sets

4.1.1 Left Bilinear Morphisms of Pointed Sets

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

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}

(\star) *Left Unital Bilinearity.* The diagram

$$\begin{array}{ccc} & \text{pt} \times \text{pt} & \\ \text{id}_{\text{pt}} \times \epsilon_Y \nearrow & \curvearrowright & \\ \text{pt} \times Y & & \text{pt} \\ [x_0] \times \text{id}_Y \searrow & & \swarrow [z_0] \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commutes, i.e. for each $y \in Y$, we have

$$f(x_0, y) = z_0.$$

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

$$\text{Hom}_{\text{Sets}_*}^{\otimes, L}(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Hom}_{\text{Sets}}(X \times Y, Z) \mid f \text{ is left bilinear}\}.$$

¹*Slogan:* The map f is left bilinear if it preserves basepoints in its first argument.

²Succinctly, f is bilinear if we have

$$f(x_0, y) = z_0$$

4.1.2 Right Bilinear Morphisms of Pointed Sets

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

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}

(\star) *Right Unital Bilinearity.* The diagram

$$\begin{array}{ccc} & \text{pt} \times \text{pt} & \\ \epsilon_X \times \text{id}_{\text{pt}} \nearrow & \curvearrowright & \\ X \times \text{pt} & & \text{pt} \\ \downarrow \text{id}_X \times [y_0] & & \downarrow [z_0] \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commutes, i.e. for each $x \in X$, we have

$$f(x, y_0) = z_0.$$

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 $\text{Hom}_{\text{Sets}_*}^{\otimes, R}(X \times Y, Z)$ defined by

$$\text{Hom}_{\text{Sets}_*}^{\otimes, R}(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Hom}_{\text{Sets}}(X \times Y, Z) \mid f \text{ is right bilinear}\}.$$

4.1.3 Bilinear Morphisms of Pointed Sets

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

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

$$f(x, y_0) = z_0$$

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

$$\begin{array}{ccc} & \text{pt} \times \text{pt} & \\ \text{id}_{\text{pt}} \times \epsilon_Y \nearrow & \curvearrowright & \\ \text{pt} \times Y & & \text{pt} \\ \downarrow [x_0] \times \text{id}_Y & & \downarrow [z_0] \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commutes, i.e. for each $y \in Y$, we have

$$f(x_0, y) = z_0.$$

2. *Right Unital Bilinearity.* The diagram

$$\begin{array}{ccc} & \text{pt} \times \text{pt} & \\ \epsilon_X \times \text{id}_{\text{pt}} \nearrow & \curvearrowright & \\ X \times \text{pt} & & \text{pt} \\ \downarrow \text{id}_X \times [y_0] & & \downarrow [z_0] \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commutes, i.e. for each $x \in X$, we have

$$f(x, y_0) = z_0.$$

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.

⁶ Succinctly, f is bilinear if we have

$$\begin{aligned} f(x_0, y) &= z_0, \\ f(x, y_0) &= z_0 \end{aligned}$$

4.2 Tensors and Cotensors of Pointed Sets by Sets

4.2.1 Tensors of Pointed Sets by Sets

Let (X, x_0) be a pointed set and let A be a set.

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 $(K, k_0) \in \text{Obj}(\text{Sets}_*)$.

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

$$\text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times X, K) \stackrel{\text{def}}{=} \left\{ f \in \text{Sets}(A \times X, K) \mid \begin{array}{l} \text{for each } a \in A, \text{ we} \\ \text{have } f(a, x_0) = k_0 \end{array} \right\}.$$

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

$$\xi: A \rightarrow \text{Sets}_*(X, K),$$

$$a \mapsto (\xi_a: X \rightarrow K),$$

for each $x \in X$ and each $y \in Y$.

⁷Further Terminology: Also called the **copower of** (X, x_0) **by** A .

⁸Further 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

$$\begin{aligned} \xi^\dagger: A &\longrightarrow \text{Sets}_*(X, K), \\ a &\mapsto (\xi_a^\dagger: X \rightarrow K), \end{aligned}$$

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. □

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.) \square

Notation 4.2.1.1.4. We write $a \odot x$ for the element $[(a, x)]$ of

$$\begin{aligned} A \odot X &\cong \bigvee_{a \in A} (X, x_0) \\ &\stackrel{\text{def}}{=} \left(\coprod_{i \in I} X_i \right) / \sim. \end{aligned}$$

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

$$\bigvee_{a \in A} (X, x_0) \stackrel{\text{def}}{=} \coprod_{a \in A} X / \sim$$

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

$$\mathbf{Sets}_*(A \odot X, K) \cong \mathbf{Sets}(A, \mathbf{Sets}_*(X, K))$$

natural in $(K, k_0) \in \mathbf{Obj}(\mathbf{Sets}_*)$.

- *Map I.* We define a map

$$\Phi_K : \mathbf{Sets}_*(A \odot X, K) \rightarrow \mathbf{Sets}(A, \mathbf{Sets}_*(X, K))$$

by sending a morphism of pointed sets

$$\xi : (A \odot X, a \odot x_0) \rightarrow (K, k_0)$$

to the map of sets

$$\begin{aligned} \xi^\dagger : A &\longrightarrow \mathbf{Sets}_*(X, K), \\ a &\mapsto (\xi_a : X \rightarrow K), \end{aligned}$$

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

$$\Psi_K: \mathbf{Sets}(A, \mathbf{Sets}_*(X, K)) \rightarrow \mathbf{Sets}_*(A \odot X, K)$$

given by sending a map

$$\begin{aligned}\xi: A &\longrightarrow \mathbf{Sets}_*(X, K), \\ a &\mapsto (\xi_a: X \rightarrow K),\end{aligned}$$

to the morphism of pointed sets

$$\xi^\dagger: (A \odot X, a \odot x_0) \rightarrow (K, k_0)$$

defined by

$$\xi^\dagger(a \odot x) \stackrel{\text{def}}{=} \xi_a(x)$$

for each $a \odot x \in A \odot X$. Note that ξ^\dagger is indeed a morphism of pointed sets, as we have

$$\begin{aligned}\xi^\dagger(a \odot x_0) &\stackrel{\text{def}}{=} \xi_a(x_0) \\ &= k_0,\end{aligned}$$

where we have used that $\xi(a) \in \mathbf{Sets}_*(X, K)$ is a morphism of pointed sets.

- *Invertibility I.* We claim that

$$\Psi_K \circ \Phi_K = \text{id}_{\mathbf{Sets}_*(A \odot X, K)}.$$

Indeed, given a morphism of pointed sets

$$\xi: (A \odot X, a \odot x_0) \rightarrow (K, k_0),$$

we have

$$\begin{aligned}[\Psi_K \circ \Phi_K](\xi) &= \Psi_K(\Phi_K(\xi)) \\ &= \Psi_K([\![a \mapsto [x \mapsto \xi(a \odot x)]]\!]) \\ &= \Psi_K([\![a' \mapsto [x' \mapsto \xi(a' \odot x')]]\!]) \\ &= [\![a \odot x \mapsto \text{ev}_x(\text{ev}_a([\![a' \mapsto [x' \mapsto \xi(a' \odot x')]]\!]))]\!] \\ &= [\![a \odot x \mapsto \text{ev}_x([\![x' \mapsto \xi(a \odot x')]\!])]\!] \\ &= [\![a \odot x \mapsto \xi(a \odot x)]\!] \\ &= \xi.\end{aligned}$$

- *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

$$\begin{aligned} [\Phi_K \circ \Psi_K](\xi) &= \Phi_K(\Psi_K(\xi)) \\ &= \Phi_K([\![a \odot x \mapsto \xi_a(x)]\!]) \\ &= [\![a \mapsto [\![x \mapsto \xi_a(x)]]\!]] \\ &= [\![a \mapsto \xi(a)]\!] \\ &= \xi. \end{aligned}$$

- *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

$$\begin{aligned} [\Phi_{K'} \circ \phi_*](\xi) &= \Phi_{K'}(\phi_*(\xi)) \\ &= \Phi_{K'}(\phi \circ \xi) \\ &= (\phi \circ \xi)^\dagger \\ &= [\![a \mapsto \phi \circ \xi(a \odot -)]\!] \\ &= [\![a \mapsto \phi_*(\xi(a \odot -))]\!] \\ &= (\phi_*)_*(\![[a \mapsto \xi(a \odot -)]]\!) \\ &= (\phi_*)_*(\Phi_K(\xi)) \\ &= [(\phi_*)_* \circ \Phi_K](\xi). \end{aligned}$$

- *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

Proposition 4.2.1.1.6. Let (X, x_0) be a pointed set and let A be a set.

1. *Functionality.* The assignments $A, (X, x_0), (A, (X, x_0))$ define functions

$$\begin{aligned} A \odot - &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ - \odot X &: \mathbf{Sets} \rightarrow \mathbf{Sets}_*, \\ -_1 \odot -_2 &: \mathbf{Sets} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*. \end{aligned}$$

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 $a \odot x \in A \odot X$.

2. *Adjointness I.* We have an adjunction

$$(- \odot X \dashv \mathbf{Sets}_*(X, -)): \quad \mathbf{Sets} \begin{array}{c} \xrightarrow{- \odot X} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*,$$

witnessed by a bijection

$$\mathbf{Sets}_*(A \odot X, K) \cong \mathbf{Sets}(A, \mathbf{Sets}_*(X, K)),$$

natural in $A \in \text{Obj}(\mathbf{Sets})$ and $X, Y \in \text{Obj}(\mathbf{Sets}_*)$.

3. *Adjointness II.* We have an adjunctions

$$(A \odot - \dashv A \pitchfork -): \quad \mathbf{Sets}_* \begin{array}{c} \xrightarrow{A \odot -} \\ \perp \\ \xleftarrow{A \pitchfork -} \end{array} \mathbf{Sets}_*,$$

witnessed by a bijection

$$\text{Hom}_{\mathbf{Sets}_*}(A \odot X, Y) \cong \text{Hom}_{\mathbf{Sets}_*}(X, A \pitchfork Y),$$

natural in $A \in \text{Obj}(\mathbf{Sets})$ and $X, Y \in \text{Obj}(\mathbf{Sets}_*)$.

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 $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

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 $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

6. *Interaction With Homs.* We have a natural isomorphism

$$\text{Sets}_*(A \odot X, -) \cong A \pitchfork \text{Sets}_*(X, -).$$

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 $f \odot x \in \text{Sets}_*(X, Y) \odot X$.

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

$$\text{coev}_{A,X}^\odot: A \rightarrow \text{Sets}_*(X, A \odot X),$$

natural in $A \in \text{Obj}(\text{Sets})$ and $X \in \text{Obj}(\text{Sets}_*)$, and given by

$$\text{coev}_{A,X}^\odot(a) \stackrel{\text{def}}{=} [x \mapsto a \odot x]$$

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 Hom: 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

4.2.2 Cotensors of Pointed Sets by Sets

Let (X, x_0) be a pointed set and let A be a set.

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 $(K, k_0) \in \text{Obj}(\text{Sets}_*)$.

Remark 4.2.2.1.2. The universal property of Definition 4.2.2.1.1 is equivalent to the following one:

(UP) We have a bijection

$$\text{Sets}_*(K, A \pitchfork X) \cong \text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X),$$

natural in $(K, k_0) \in \text{Obj}(\text{Sets}_*)$, where $\text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X)$ is the set defined by

$$\text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X) \stackrel{\text{def}}{=} \left\{ f \in \text{Sets}(A \times K, X) \mid \begin{array}{l} \text{for each } a \in A, \text{ we} \\ \text{have } f(a, k_0) = x_0 \end{array} \right\}.$$

Proof. This follows from the bijection

$$\text{Sets}(A, \text{Sets}_*(K, X)) \cong \text{Sets}_{\mathbb{E}_0}^{\otimes}(A \times K, X),$$

natural in $(K, k_0) \in \text{Obj}(\text{Sets}_*)$ constructed in the proof of Remark 4.2.1.1.2. \square

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:

⁹Further Terminology: Also called the **power of** (X, x_0) **by** A .

¹⁰Further Notation: Often written $A \pitchfork X$ for simplicity.

- *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 $(K, k_0) \in \text{Obj}(\mathbf{Sets}_*)$.

- *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

$$\begin{aligned} \xi^\dagger: A &\longrightarrow \mathbf{Sets}_*(K, X), \\ a &\mapsto (\xi_a: K \rightarrow X), \end{aligned}$$

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 $\xi(k) = \left[(x_a^k)_{a \in A} \right]$.

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

$$\begin{aligned} \left[\left(x_a^k \right)_{a \in A} \right] &= [(x_0)_{a \in A}], \\ \left[\left(y_a^k \right)_{a \in A} \right] &= [(x_0)_{a \in A}], \end{aligned}$$

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

$$\Psi_K: \mathbf{Sets}(A, \mathbf{Sets}_*(K, X)) \rightarrow \mathbf{Sets}_*(K, A \pitchfork X),$$

given by sending a map

$$\begin{aligned} \xi: A &\longrightarrow \mathbf{Sets}_*(K, X), \\ a &\mapsto (\xi_a: K \rightarrow X), \end{aligned}$$

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 $\xi_a \in \mathbf{Sets}_*(K, X)$ 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

$$\begin{aligned} \xi: A &\longrightarrow \text{Sets}_*(K', X), \\ a &\mapsto (\xi_a: K' \rightarrow X), \end{aligned}$$

we have

$$\begin{aligned} [\Psi_K \circ (\phi^*)_*](\xi) &= \Psi_K((\phi^*)_*(\xi)) \\ &= \Psi_K((\phi^)_*(\llbracket a \mapsto \xi_a \rrbracket)) \\ &= \Psi_K(\llbracket a \mapsto \phi^*(\xi_a) \rrbracket) \\ &= \Psi_K(\llbracket a \mapsto \llbracket k \mapsto \xi_a(\phi(k)) \rrbracket \rrbracket) \\ &= \llbracket k \mapsto \llbracket (\xi_a(\phi(k)))_{a \in A} \rrbracket \rrbracket \\ &= \phi^*\left(\llbracket k' \mapsto \llbracket (\xi_a(k'))_{a \in A} \rrbracket \rrbracket\right) \\ &= \phi^*(\Psi_{K'}(\xi)) \\ &= [\phi^* \circ \Psi_{K'}](\xi). \end{aligned}$$

- *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

$$\begin{aligned} [\Psi_K \circ \Phi_K](\xi) &= \Psi_K(\Phi_K(\xi)) \\ &= \Psi_K(\llbracket a \mapsto \xi_a \rrbracket) \\ &= \Psi_K(\llbracket a' \mapsto \xi_{a'} \rrbracket) \\ &= \llbracket k \mapsto \llbracket (\text{ev}_a(\llbracket a' \mapsto \xi_{a'}(k) \rrbracket))_{a \in A} \rrbracket \rrbracket \\ &= \llbracket k \mapsto \llbracket (\xi_a(k))_{a \in A} \rrbracket \rrbracket. \end{aligned}$$

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 $\xi(k) = \left[\left(x_a^k \right)_{a \in A} \right]$ instead, we have

$$\begin{aligned} [\Psi_K \circ \Phi_K](\xi) &= \dots \\ &= \llbracket k \mapsto [(\xi_a(k))_{a \in A}] \rrbracket \\ &= \llbracket k \mapsto \left[\left(x_a^k \right)_{a \in A} \right] \rrbracket \\ &= \llbracket k \mapsto \xi(k) \rrbracket \\ &= \xi. \end{aligned}$$

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

Proposition 4.2.2.1.4. Let (X, x_0) be a pointed set and let A be a set.

1. *Functionality.* 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

$$[f \odot \phi]([(x_a)_{a \in A}]) \stackrel{\text{def}}{=} \left[\left(\phi(x_{f(a)}) \right)_{a \in A} \right]$$

for each $[(x_a)_{a \in A}] \in A \pitchfork X$.

2. *Adjointness I.* We have an adjunction

$$(- \pitchfork X \dashv \mathbf{Sets}_*(-, X)): \quad \mathbf{Sets}^{\text{op}} \begin{array}{c} \xrightarrow{- \pitchfork X} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(-, X)} \end{array} \mathbf{Sets}_*,$$

witnessed by a bijection

$$\mathbf{Sets}_*^{\text{op}}(A \pitchfork X, K) \cong \mathbf{Sets}(A, \mathbf{Sets}_*(K, X)),$$

i.e. by a bijection

$$\mathbf{Sets}_*(K, A \pitchfork X) \cong \mathbf{Sets}(A, \mathbf{Sets}_*(K, X)),$$

natural in $A \in \text{Obj}(\mathbf{Sets})$ and $X, Y \in \text{Obj}(\mathbf{Sets}_*)$.

3. *Adjointness II.* We have an adjunctions

$$(A \odot - \dashv A \pitchfork -): \quad \mathbf{Sets}_* \begin{array}{c} \xrightarrow{A \odot -} \\ \perp \\ \xleftarrow{A \pitchfork -} \end{array} \mathbf{Sets}_*,$$

witnessed by a bijection

$$\text{Hom}_{\mathbf{Sets}_*}(A \odot X, Y) \cong \text{Hom}_{\mathbf{Sets}_*}(X, A \pitchfork Y),$$

natural in $A \in \text{Obj}(\mathbf{Sets})$ and $X, Y \in \text{Obj}(\mathbf{Sets}_*)$.

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 $A: \text{pt} \rightarrow \mathbf{Sets}$ picking $A \in \text{Obj}(\mathbf{Sets})$;

- X for the functor $X: \text{pt} \rightarrow \text{Sets}_*$ picking $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

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 $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

6. *Commutativity With Homs.* We have natural isomorphisms

$$\begin{aligned} A \pitchfork \text{Sets}_*(X, -) &\cong \text{Sets}_*(A \odot X, -), \\ A \pitchfork \text{Sets}_*(-, Y) &\cong \text{Sets}_*(-, A \pitchfork Y). \end{aligned}$$

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 $x \in X$.

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

4.3 The Left Tensor Product of Pointed Sets

4.3.1 Foundations

Let (X, x_0) and (Y, y_0) be pointed sets.

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

$$\text{Sets}_* \times \text{Sets}_* \xrightarrow{\text{id} \times \text{忘}} \text{Sets}_* \times \text{Sets} \xrightarrow{\beta_{\text{Sets}_*, \text{Sets}}^{\text{Cats}_2}} \text{Sets} \times \text{Sets}_* \xrightarrow{\odot} \text{Sets}_*,$$

where:

- 忘: $\text{Sets}_* \rightarrow \text{Sets}$ is the forgetful functor from pointed sets to 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.

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 $y \in Y$.

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 $\iota: (X \times Y, (x_0, y_0)) \rightarrow X \triangleleft Y$;

¹¹Further Notation: Also written $\triangleleft_{\text{Sets}_*}$.

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

$$\begin{array}{ccc} & X \triangleleft Y & \\ \iota \nearrow & \downarrow & \exists! \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commute.

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 $y \in Y$.

Notation 4.3.1.1.5. We write¹² $x \triangleleft y$ for the element $[(y, x)]$ of

$$X \triangleleft Y \cong |Y| \odot X.$$

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 $y, y' \in Y$.

Proposition 4.3.1.1.7. Let (X, x_0) and (Y, y_0) be pointed sets.

¹²Further Notation: Also written $x \triangleleft_{\text{Sets}_*} y$.

1. *Functionality.* 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 $x \triangleleft y \in X \triangleleft Y$.

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](#).

3. *Adjointness II.* The functor

$$X \triangleleft -: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

does not admit a right adjoint.

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](#), *Functionality:* 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

$$\begin{aligned} X \triangleleft \text{pt} &\stackrel{\text{def}}{=} |\text{pt}| \odot X \\ &\cong X \\ &\not\cong \text{pt}, \end{aligned}$$

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

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

$$\text{Hom}_{\mathbf{Sets}_*}(X \triangleleft Y, Z) \cong \text{Hom}_{\mathbf{Sets}}(|Y|, \mathbf{Sets}_*(X, Z)),$$

so it would be reasonable to wonder whether a natural bijection of the form

$$\text{Hom}_{\mathbf{Sets}_*}(X \triangleleft Y, Z) \cong \text{Hom}_{\mathbf{Sets}_*}(Y, \mathbf{Sets}_*(X, Z)),$$

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

4.3.2 The Left Internal Hom of Pointed Sets

Let (X, x_0) and (Y, y_0) be pointed sets.

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

$$\mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \xrightarrow{\text{忘} \times \text{id}} \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \xrightarrow{\text{!`}} \mathbf{Sets}_*,$$

where:

¹³The functor $\mathbf{Sets}_*(X, -)$ is instead right adjoint to $X \wedge -$, the smash product of

- 忘: $\text{Sets}_* \rightarrow \text{Sets}$ is the forgetful functor from pointed sets to sets.
- $\pitchfork: \text{Sets}^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*$ is the cotensor functor of [Item 1](#) of [Proposition 4.2.2.1.4](#).

Proof. For a proof that $[-, -]_{\text{Sets}_*}^{\triangleleft}$ is indeed the left internal Hom of Sets_* with respect to the left tensor product of pointed sets, see [Item 2](#) of [Proposition 4.3.1.1.7](#). \square

Remark 4.3.2.1.2. The left internal Hom of pointed sets satisfies the following universal property:

$$\text{Sets}_*(X \triangleleft Y, Z) \cong \text{Sets}_*\left(X, [Y, Z]_{\text{Sets}_*}^{\triangleleft}\right)$$

That is to say, the following data are in bijection:

1. Pointed maps $f: X \triangleleft Y \rightarrow Z$.
2. Pointed maps $f: X \rightarrow [Y, Z]_{\text{Sets}_*}^{\triangleleft}$.

Remark 4.3.2.1.3. In detail, the **left internal Hom of (X, x_0) and (Y, y_0)** is the pointed set $([X, Y]_{\text{Sets}_*}^{\triangleleft}, [(y_0)_{x \in X}])$ consisting of

- *The Underlying Set.* The set $[X, Y]_{\text{Sets}_*}^{\triangleleft}$ defined by

$$\begin{aligned} [X, Y]_{\text{Sets}_*}^{\triangleleft} &\stackrel{\text{def}}{=} |X| \pitchfork Y \\ &\cong \bigwedge_{x \in X} (Y, y_0), \end{aligned}$$

where $|X|$ denotes the underlying set of (X, x_0) ;

- *The Underlying Basepoint.* The point $[(y_0)_{x \in X}]$ of $\bigwedge_{x \in X} (Y, y_0)$.

Proposition 4.3.2.1.4. Let (X, x_0) and (Y, y_0) be pointed sets.

1. *Functionality.* 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

$$[f, g]_{\mathbf{Sets}_*}^\triangleleft : [A, Y]_{\mathbf{Sets}_*}^\triangleleft \rightarrow [X, B]_{\mathbf{Sets}_*}^\triangleleft$$

is given by

$$[f, g]_{\mathbf{Sets}_*}^\triangleleft([(y_a)_{a \in A}]) \stackrel{\text{def}}{=} \left[\left(g(y_{f(x)}) \right)_{x \in X} \right]$$

for each $[(y_a)_{a \in A}] \in [A, Y]_{\mathbf{Sets}_*}^\triangleleft$.

2. *Adjointness I.* We have an adjunction

$$\left(- \triangleleft Y \dashv [Y, -]_{\mathbf{Sets}_*}^\triangleleft \right) : \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \triangleleft Y} \\[-1ex] \perp \\[-1ex] \xleftarrow{[Y, -]_{\mathbf{Sets}_*}^\triangleleft} \end{array} \mathbf{Sets}_*,$$

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 $(X, x_0), (Y, y_0), (Z, z_0) \in \mathrm{Obj}(\mathbf{Sets}_*)$

3. *Adjointness II.* The functor

$$X \triangleleft - : \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

does not admit a right adjoint.

Proof. **Item 1, Functoriality:** Clear.

Item 2, Adjointness I: This is a repetition of **Item 2** of [Proposition 4.3.1.1.7](#), 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

4.3.3 The Left Skew Unit

Definition 4.3.3.1.1. The **left skew unit of the left tensor product of pointed sets** is the functor

$$\mathbb{1}_{\mathbf{Sets}_*}^{\triangleleft} : \mathrm{pt} \rightarrow \mathbf{Sets}_*$$

defined by

$$\mathbb{1}_{\mathbf{Sets}_*}^{\triangleleft} \stackrel{\text{def}}{=} S^0.$$

4.3.4 The Left Skew Associator

Definition 4.3.4.1.1. The **skew associator of the left tensor product of pointed sets** is the natural transformation

$$\alpha^{\text{Sets}_*, \triangleleft} : \triangleleft \circ (\triangleleft \times \text{id}_{\text{Sets}_*}) \Rightarrow \triangleleft \circ (\text{id}_{\text{Sets}_*} \times \triangleleft) \circ \alpha^{\text{Cats}}_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}$$

as in the diagram

$$\begin{array}{ccc}
 & \text{Sets}_* \times (\text{Sets}_* \times \text{Sets}_*) & \\
 & \swarrow \alpha^{\text{Cats}}_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*} \quad \searrow \text{id} \times \triangleleft & \\
 (\text{Sets}_* \times \text{Sets}_*) \times \text{Sets}_* & \xrightarrow{\quad \quad \quad} & \text{Sets}_* \times \text{Sets}_* \\
 \downarrow \triangleleft \times \text{id} & \parallel \alpha^{\text{Sets}_*, \triangleleft} & \downarrow \triangleleft \\
 \text{Sets}_* \times \text{Sets}_* & \xrightarrow{\quad \quad \quad} & \text{Sets}_*,
 \end{array}$$

whose component

$$\alpha^{\text{Sets}_*, \triangleleft}_{X, Y, Z} : (X \triangleleft Y) \triangleleft Z \rightarrow X \triangleleft (Y \triangleleft Z)$$

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.) \square

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 $(x \triangleleft y) \triangleleft z \in (X \triangleleft Y) \triangleleft Z$.

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

$$\begin{aligned} f: (X, x_0) &\rightarrow (X', x'_0), \\ g: (Y, y_0) &\rightarrow (Y', y'_0), \\ h: (Z, z_0) &\rightarrow (Z', z'_0) \end{aligned}$$

pointed sets of Definition 4.5.1.1.1. See Item 2 of Proposition 4.5.1.9.

the diagram

$$\begin{array}{ccc} (X \triangleleft Y) \triangleleft Z & \xrightarrow{(f \triangleleft g) \triangleleft h} & (X' \triangleleft Y') \triangleleft Z' \\ \downarrow \alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft} & & \downarrow \alpha_{X',Y',Z'}^{\text{Sets}_*, \triangleleft} \\ X \triangleleft (Y \triangleleft Z) & \xrightarrow{f \triangleleft (g \triangleleft h)} & X' \triangleleft (Y' \triangleleft Z') \end{array}$$

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

4.3.5 The Left Skew Left Unit

Definition 4.3.5.1.1. The **skew left unit of the left tensor product of pointed sets** is the natural transformation

$$\begin{array}{ccc} \text{pt} \times \text{Sets}_* & \xrightarrow{1^{\text{Sets}_*} \times \text{id}} & \text{Sets}_* \times \text{Sets}_* \\ \lambda^{\text{Sets}_*, \triangleleft}: \triangleleft \circ (1^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \lambda^{\text{Cats}_2}_{\text{Sets}_*} & \swarrow \quad \searrow & \downarrow \triangleleft \\ & \lambda^{\text{Cats}_2}_{\text{Sets}_*} & \end{array}$$

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

$$\begin{aligned} S^0 \triangleleft X &\cong |X| \odot S^0 \\ &\cong \bigvee_{x \in X} S^0 \\ &\rightarrow X, \end{aligned}$$

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.) □

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 $1 \triangleleft x \in S^0 \triangleleft X$.

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

$$\begin{aligned}[\lambda_X^{\text{Sets}_*, \triangleleft} \circ \phi](x) &= \lambda_X^{\text{Sets}_*, \triangleleft}(\phi(x)) \\ &= \lambda_X^{\text{Sets}_*, \triangleleft}(1 \triangleleft x) \\ &= x \\ &= [\text{id}_X](x)\end{aligned}$$

so that

$$\lambda_X^{\text{Sets}_*, \triangleleft} \circ \phi = \text{id}_X$$

and

$$\begin{aligned}[\phi \circ \lambda_X^{\text{Sets}_*, \triangleleft}](1 \triangleleft x) &= \phi(\lambda_X^{\text{Sets}_*, \triangleleft}(1 \triangleleft x)) \\ &= \phi(x) \\ &= 1 \triangleleft x \\ &= [\text{id}_{S^0 \triangleleft X}](1 \triangleleft x),\end{aligned}$$

but

$$\begin{aligned}[\phi \circ \lambda_X^{\text{Sets}_*, \triangleleft}](0 \triangleleft x) &= \phi(\lambda_X^{\text{Sets}_*, \triangleleft}(0 \triangleleft x)) \\ &= \phi(x_0) \\ &= 1 \triangleleft x_0,\end{aligned}$$

where $0 \triangleleft x \neq 1 \triangleleft x_0$. Thus

$$\phi \circ \lambda_X^{\text{Sets}_*, \triangleleft} \stackrel{?}{=} \text{id}_{S^0 \triangleleft X}$$

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

$$\begin{array}{ccc} S^0 \triangleleft X & \xrightarrow{\text{id}_{S^0} \triangleleft f} & S^0 \triangleleft Y \\ \lambda_X^{\mathbf{Sets}_*, \triangleleft} \downarrow & & \downarrow \lambda_Y^{\mathbf{Sets}_*, \triangleleft} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} 0 \triangleleft x & & 0 \triangleleft x \longmapsto 0 \triangleleft f(x) \\ \downarrow & & \downarrow \\ x_0 \longmapsto f(x_0) & & y_0 \end{array}$$

and

$$\begin{array}{ccc} 1 \triangleleft x \longmapsto 1 \triangleleft f(x) & & \\ \downarrow & & \downarrow \\ x \longmapsto f(x) & & \end{array}$$

and hence indeed commutes, showing $\lambda^{\mathbf{Sets}_*, \triangleleft}$ to be a natural transformation. This finishes the proof. \square

4.3.6 The Left Skew Right Unitor

Definition 4.3.6.1.1. The **skew right unitor of the left tensor product of pointed sets** is the natural transformation

$$\begin{array}{ccc}
 \text{Sets}_* \times \text{pt} & \xrightarrow{\text{id} \times 1^{\text{Sets}_*}} & \text{Sets}_* \times \text{Sets}_* \\
 \downarrow & & \downarrow \lhd \\
 \rho_{\text{Sets}_*}^{\text{Sets}_*, \lhd} : \rho_{\text{Sets}_*}^{\text{Cats}_2} \xrightarrow{\sim} \lhd \circ (\text{id} \times 1^{\text{Sets}_*}), & \lhd \circ & \lhd \\
 & \lhd \lhd \lhd & \lhd \lhd \lhd & \lhd \lhd \lhd \\
 & & \rho_{\text{Sets}_*}^{\text{Sets}_*, \lhd} & \\
 & & \searrow & \downarrow \\
 & & & \text{Sets}_*,
 \end{array}$$

whose component

$$\rho_X^{\text{Sets}_*, \lhd} : X \rightarrow X \lhd S^0$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by the composition

$$\begin{aligned}
 X &\rightarrow X \vee X \\
 &\cong |S^0| \odot X \\
 &\cong X \lhd S^0,
 \end{aligned}$$

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.) □

Remark 4.3.6.1.2. In other words, $\rho_X^{\text{Sets}_*, \lhd}$ acts on elements as

$$\rho_X^{\text{Sets}_*, \lhd}(x) \stackrel{\text{def}}{=} [(1, x)]$$

i.e. by

$$\rho_X^{\text{Sets}_*, \lhd}(x) \stackrel{\text{def}}{=} x \lhd 1$$

for each $x \in X$.

Remark 4.3.6.1.3. The morphism $\rho_X^{\text{Sets}_*, \lhd}$ is non-invertible, as it is non-surjective when viewed as a map of sets, since the elements $x \lhd 0$ of $X \lhd S^0$ with $x \neq x_0$ are outside the image of $\rho_X^{\text{Sets}_*, \lhd}$, which sends x to $x \lhd 1$.

Proof. Firstly, note that, given $(X, x_0) \in \text{Obj}(\text{Sets}_*)$, the map

$$\rho_X^{\text{Sets}_*, \lhd} : X \rightarrow X \lhd S^0$$

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

$$x \longmapsto f(x)$$

and hence indeed commutes, showing $\rho^{\text{Sets}_*, \triangleleft}$ to be a natural transformation. This finishes the proof. \square

4.3.7 The Diagonal

Definition 4.3.7.1.1. The diagonal of the left tensor product of pointed sets is the natural transformation

$$\Delta^\lhd : \text{id}_{\text{Sets}_*} \implies \lhd \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2},$$

whose component

$$\Delta_X^\lhd: (X, x_0) \rightarrow (X \lhd X, x_0 \lhd x_0)$$

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

$$\begin{array}{ccc} x & \longmapsto & f(x) \\ \downarrow & & \downarrow \\ x \triangleleft x & \longmapsto & f(x) \triangleleft f(x) \end{array}$$

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

Proposition 4.3.8.1.1. The category Sets_* admits a left-closed left skew monoidal category structure consisting of

- *The Underlying Category.* The category Sets_* of pointed sets;
- *The Left Skew Monoidal Product.* The left tensor product functor

$$\triangleleft: \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

of Definition 4.3.1.1.1;

- *The Left Internal Skew Hom.* The left internal Hom functor

$$[-, -]_{\text{Sets}_*}^\triangleleft: \text{Sets}_*^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*$$

of Definition 4.3.2.1.1;

- *The Left Skew Monoidal Unit.* The functor

$$1^{\text{Sets}_*, \triangleleft}: \text{pt} \rightarrow \text{Sets}_*$$

of Definition 4.3.3.1.1;

- *The Left Skew Associators.* The natural transformation

$$\alpha^{\text{Sets}_*, \triangleleft}: \triangleleft \circ (\triangleleft \times \text{id}_{\text{Sets}_*}) \Rightarrow \triangleleft \circ (\text{id}_{\text{Sets}_*} \times \triangleleft) \circ \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}}$$

of Definition 4.3.4.1.1;

- *The Left Skew Left Unitors.* The natural transformation

$$\lambda^{\text{Sets}_*, \triangleleft}: \triangleleft \circ (\mathbb{1}^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \lambda_{\text{Sets}_*}^{\text{Cats}_2}$$

of Definition 4.3.5.1.1;

- *The Left Skew Right Unitors.* The natural transformation

$$\rho^{\text{Sets}_*, \triangleleft}: \rho_{\text{Sets}_*}^{\text{Cats}_2} \Rightarrow \triangleleft \circ (\text{id} \times \mathbb{1}^{\text{Sets}_*})$$

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

$$\begin{array}{ccc}
 & (W \triangleleft (X \triangleleft Y)) \triangleleft Z & \\
 \swarrow \alpha_{W,X,Y}^{\text{Sets}_*, \triangleleft} \text{id}_Z & & \searrow \alpha_{W,X \triangleleft Y,Z}^{\text{Sets}_*, \triangleleft} \\
 ((W \triangleleft X) \triangleleft Y) \triangleleft Z & & W \triangleleft ((X \triangleleft Y) \triangleleft Z) \\
 \downarrow \alpha_{W \triangleleft X, Y, Z}^{\text{Sets}_*, \triangleleft} & & \downarrow \text{id}_W \triangleleft \alpha_{X, Y, Z}^{\text{Sets}_*, \triangleleft} \\
 (W \triangleleft X) \triangleleft (Y \triangleleft Z) & \xrightarrow{\alpha_{W, X, Y \triangleleft Z}^{\text{Sets}_*, \triangleleft}} & W \triangleleft (X \triangleleft (Y \triangleleft Z))
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc}
 & & (w \triangleleft (x \triangleleft y)) \triangleleft z & & \\
 & \nearrow & & \searrow & \\
 ((w \triangleleft x) \triangleleft y) \triangleleft z & & & & w \triangleleft ((x \triangleleft y) \triangleleft z) \\
 \downarrow & & & & \downarrow \\
 (w \triangleleft x) \triangleleft (y \triangleleft z) & \longmapsto & w \triangleleft (x \triangleleft (y \triangleleft z))
 \end{array}$$

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

$$\begin{array}{ccc}
 (S^0 \triangleleft X) \triangleleft Y & \xrightarrow{\alpha_{S^0, X, Y}^{\text{Sets}_*, \triangleleft}} & S^0 \triangleleft (X \triangleleft Y) \\
 \downarrow \lambda_X^{\text{Sets}_*, \triangleleft} \quad \swarrow \text{id}_Y & & \downarrow \lambda_{X \triangleleft Y}^{\text{Sets}_*, \triangleleft} \\
 X \triangleleft Y & &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 (0 \triangleleft x) \triangleleft y & \longmapsto & 0 \triangleleft (x \triangleleft y) \\
 \downarrow & & \downarrow \\
 x_0 \triangleleft y = x_0 \triangleleft y_0 & &
 \end{array}$$

and

$$\begin{array}{ccc}
 (1 \triangleleft x) \triangleleft y & \longmapsto & 1 \triangleleft (x \triangleleft y) \\
 \downarrow & & \downarrow \\
 x \triangleleft y & &
 \end{array}$$

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

$$\begin{array}{ccc}
 x \triangleleft y & & \\
 \downarrow & \swarrow & \\
 (x \triangleleft y) \triangleleft 1 & \mapsto & x \triangleleft (y \triangleleft 1)
 \end{array}$$

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

$$\begin{array}{ccc}
 X \triangleleft Y & \xlongequal{\quad} & X \triangleleft Y \\
 \downarrow \rho_X^{\text{Sets}_*, \triangleleft} \triangleleft \text{id}_Y & & \uparrow \text{id}_A \triangleleft \lambda_Y^{\text{Sets}_*, \triangleleft} \\
 (X \triangleleft S^0) \triangleleft Y & \xrightarrow{\alpha_{X, S^0, Y}^{\text{Sets}_*, \triangleleft}} & X \triangleleft (S^0 \triangleleft Y)
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 x \triangleleft y & \xlongequal{\quad} & x \triangleleft y \\
 \downarrow & & \uparrow \\
 (x \triangleleft 1) \triangleleft y & \mapsto & x \triangleleft (1 \triangleleft y)
 \end{array}$$

and hence indeed commutes. Thus the right skew triangle identity is satisfied.

The Zig-Zag Identity: We have to show that the diagram

$$\begin{array}{ccc}
 S^0 & \xrightarrow{\rho_{S^0}^{\text{Sets}_*, \triangleleft}} & S^0 \triangleleft S^0 \\
 & \searrow \parallel & \downarrow \lambda_{S^0}^{\text{Sets}_*, \triangleleft} \\
 & & S^0
 \end{array}$$

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. \square

4.3.9 Monoids With Respect to the Left Tensor Product of Pointed Sets

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 .

¹⁴A monoid with left zero is defined similarly as the monoids with zero of ??.

satisfying the following conditions:

1. *Associativity.* The diagram

$$\begin{array}{ccc}
 & A \triangleleft (A \triangleleft A) & \\
 \alpha_{A,A,A}^{\text{Sets}_*, \triangleleft} \nearrow & & \searrow \text{id}_A \triangleleft \mu_A \\
 (A \triangleleft A) \triangleleft A & & A \triangleleft A \\
 \downarrow \mu_A \triangleleft \text{id}_A & & \downarrow \mu_A \\
 A \triangleleft A & \xrightarrow{\mu_A} & A
 \end{array}$$

2. *Left Unitality.* The diagram

$$\begin{array}{ccc}
 S^0 \triangleleft A & \xrightarrow{\eta_A \times \text{id}_A} & A \triangleleft A \\
 & \searrow \lambda_A^{\text{Sets}_*, \triangleleft} & \downarrow \mu_A \\
 & & A
 \end{array}$$

commutes.

3. *Right Unitality.* The diagram

$$\begin{array}{ccc}
 A & \xrightarrow{\rho_A^{\text{Sets}_*, \triangleleft}} & A \triangleleft S^0 \\
 \parallel & & \downarrow \text{id}_A \times \eta_A \\
 A & \xleftarrow{\mu_A} & A \triangleleft A
 \end{array}$$

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:

Succinctly, they are monoids (A, μ_A, η_A) with a special element 0_A satisfying

$$0_A a = 0_A$$

for each $a \in A$.

1. *Associativity.* The associativity condition acts as

$$\begin{array}{ccc}
 & a \triangleleft (b \triangleleft c) & \\
 & \swarrow \quad \searrow & \\
 (a \triangleleft b) \triangleleft c & (a \triangleleft b) \triangleleft c & a \triangleleft bc \\
 \downarrow \quad \uparrow & \downarrow & \downarrow \\
 ab \triangleleft c \xrightarrow{\quad} (ab)c & & a(bc)
 \end{array}$$

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

$$\begin{array}{ccc}
 0 \triangleleft a & & 0 \triangleleft a \mapsto 0_A \triangleleft a \\
 \swarrow \quad \searrow & & \downarrow \\
 0_A & & 0_A a.
 \end{array}$$

(b) On $1 \triangleleft a$ as

$$\begin{array}{ccc}
 1 \triangleleft a & & 1 \triangleleft a \mapsto 1_A \triangleleft a \\
 \swarrow \quad \searrow & & \downarrow \\
 a & & 1_A a.
 \end{array}$$

This gives

$$1_A a = a,$$

$$0_A a = 0_A$$

for each $a \in A$.

3. *Right Unitality.* The right unitality condition acts as

$$\begin{array}{ccc}
 a & a \xrightarrow{\quad} a \triangleleft 1 & \\
 \downarrow & & \downarrow \\
 a & a 1_A \longleftrightarrow a \triangleleft 1_A &
 \end{array}$$

This gives

$$a1_A = a$$

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

$$\begin{array}{ccc} a \triangleleft b & & a \triangleleft b \mapsto f(a) \triangleleft f(b) \\ \downarrow & & \downarrow \\ ab & \longmapsto & f(ab) & f(a)f(b) \end{array}$$

and

$$\begin{array}{ccc} 0 & \nwarrow & 0 \mapsto 0_A \\ & 0_B & \downarrow \\ & & f(0_A) \end{array}$$

and

$$\begin{array}{ccc} 1 & \xrightarrow{\quad} & 1_A \\ \searrow & & \downarrow \\ & 1_B & f(1_A) \end{array}$$

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

4.4 The Right Tensor Product of Pointed Sets

4.4.1 Foundations

Let (X, x_0) and (Y, y_0) be pointed sets.

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

$$\text{Sets}_* \times \text{Sets}_* \xrightarrow{\text{忘} \times \text{id}} \text{Sets} \times \text{Sets}_* \xrightarrow{\odot} \text{Sets}_*,$$

where:

- 忘: $\text{Sets}_* \rightarrow \text{Sets}$ 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](#).

Remark 4.4.1.1.2. The right tensor product of pointed sets satisfies the following natural bijection:

$$\text{Sets}_*(X \triangleright Y, Z) \cong \text{Hom}_{\text{Sets}_*}^{\otimes, R}(X \times Y, Z).$$

That is to say, the following data are in natural bijection:

¹⁵Further Notation: Also written $\triangleright_{\text{Sets}_*}$.

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 $x \in X$.

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 $(X \triangleright Y, x_0 \triangleright y_0)$;
 - 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

$$\begin{array}{ccc} & X \triangleright Y & \\ \iota \nearrow & \downarrow \exists! & \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commute.

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 $x \in X$.

Notation 4.4.1.1.5. We write¹⁶ $x \triangleright y$ for the element $[(x, y)]$ of

$$X \triangleright Y \cong |X| \odot Y.$$

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 $x, x' \in X$.

Proposition 4.4.1.1.7. Let (X, x_0) and (Y, y_0) be pointed sets.

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 $x \triangleright y \in X \triangleright Y$.

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

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleright Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}_*}\left(Y, [X, Z]_{\mathbf{Sets}_*}^{\triangleright}\right)$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \mathrm{Obj}(\mathbf{Sets}_*)$, where $[X, Y]_{\mathbf{Sets}_*}^{\triangleright}$ is the pointed set of [Definition 4.4.2.1.1](#).

¹⁶Further Notation: Also written $x \triangleright_{\mathbf{Sets}_*} y$.

3. *Adjointness II.* The functor

$$- \triangleright Y : \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

does not admit a right adjoint.

4. *Adjointness III.* We have a bijection of sets

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleright Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}}(|X|, \mathbf{Sets}_*(Y, Z))$$

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 $- \triangleright Y$ to admit a right adjoint would require it to preserve colimits by ?? of ?. However, we have

$$\begin{aligned} \mathrm{pt} \triangleright X &\stackrel{\mathrm{def}}{=} |\mathrm{pt}| \odot X \\ &\cong X \\ &\not\cong \mathrm{pt}, \end{aligned}$$

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

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

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleright Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}}(|X|, \mathbf{Sets}_*(Y, Z)),$$

so it would be reasonable to wonder whether a natural bijection of the form

$$\mathrm{Hom}_{\mathbf{Sets}_*}(X \triangleright Y, Z) \cong \mathrm{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(Y, Z)),$$

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

¹⁷The functor $\mathbf{Sets}_*(Y, -)$ is instead right adjoint to $- \wedge Y$, the smash product of

4.4.2 The Right Internal Hom of Pointed Sets

Let (X, x_0) and (Y, y_0) be pointed sets.

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

$$\text{Sets}_*^{\text{op}} \times \text{Sets}_* \xrightarrow{\text{忘} \times \text{id}} \text{Sets}_*^{\text{op}} \times \text{Sets}_* \xrightarrow{\pitchfork} \text{Sets}_*,$$

where:

- 忘: $\text{Sets}_* \rightarrow \text{Sets}$ is the forgetful functor from pointed sets to sets.
- $\pitchfork: \text{Sets}_*^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*$ is the cotensor functor of [Item 1](#) of [Proposition 4.2.2.1.4](#).

Proof. For a proof that $[-, -]_{\text{Sets}_*}^\triangleright$ is indeed the right internal Hom of Sets_* with respect to the right tensor product of pointed sets, see [Item 2](#) of [Proposition 4.4.1.1.7](#). \square

Remark 4.4.2.1.2. We have

$$[-, -]_{\text{Sets}_*}^\triangleleft = [-, -]_{\text{Sets}_*}^\triangleright.$$

Remark 4.4.2.1.3. The right internal Hom of pointed sets satisfies the following universal property:

$$\text{Sets}_*(X \triangleright Y, Z) \cong \text{Sets}_*\left(Y, [X, Z]_{\text{Sets}_*}^\triangleright\right)$$

That is to say, the following data are in bijection:

1. Pointed maps $f: X \triangleright Y \rightarrow Z$.
2. Pointed maps $f: Y \rightarrow [X, Z]_{\text{Sets}_*}^\triangleright$.

Remark 4.4.2.1.4. In detail, the **right internal Hom of (X, x_0) and (Y, y_0)** is the pointed set $([X, Y]_{\text{Sets}_*}^\triangleright, [(y_0)_{x \in X}])$ consisting of

- *The Underlying Set.* The set $[X, Y]_{\text{Sets}_*}^\triangleright$ defined by

$$\begin{aligned} [X, Y]_{\text{Sets}_*}^\triangleright &\stackrel{\text{def}}{=} |X| \pitchfork Y \\ &\cong \bigwedge_{x \in X} (Y, y_0), \end{aligned}$$

where $|X|$ denotes the underlying set of (X, x_0) ;

- *The Underlying Basepoint.* The point $[(y_0)_{x \in X}]$ of $\Lambda_{x \in X}(Y, y_0)$.

Proposition 4.4.2.1.5. Let (X, x_0) and (Y, y_0) be pointed sets.

1. *Functoriality.* The assignments $X, Y, (X, Y) \mapsto [X, Y]_{\text{Sets}_*}^\triangleright$ define functors

$$\begin{aligned}[X, -]_{\text{Sets}_*}^\triangleright &: \text{Sets}_* \rightarrow \text{Sets}_*, \\ [-, Y]_{\text{Sets}_*}^\triangleright &: \text{Sets}_*^{\text{op}} \rightarrow \text{Sets}_*, \\ [-_1, -_2]_{\text{Sets}_*}^\triangleright &: \text{Sets}_*^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*. \end{aligned}$$

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

$$[f, g]_{\text{Sets}_*}^\triangleright : [A, Y]_{\text{Sets}_*}^\triangleright \rightarrow [X, B]_{\text{Sets}_*}^\triangleright$$

is given by

$$[f, g]_{\text{Sets}_*}^\triangleright([(y_a)_{a \in A}]) \stackrel{\text{def}}{=} \left[\left(g(y_{f(x)}) \right)_{x \in X} \right]$$

for each $[(y_a)_{a \in A}] \in [A, Y]_{\text{Sets}_*}^\triangleright$.

2. *Adjointness I.* We have an adjunction

$$\left(X \triangleright - \dashv [X, -]_{\text{Sets}_*}^\triangleright \right) : \text{Sets}_* \begin{array}{c} \xrightarrow{X \triangleright -} \\ \perp \\ \xleftarrow{[X, -]_{\text{Sets}_*}^\triangleright} \end{array} \text{Sets}_*,$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Sets}_*}(X \triangleright Y, Z) \cong \text{Hom}_{\text{Sets}_*}(Y, [X, Z]_{\text{Sets}_*}^\triangleright)$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$, where $[X, Y]_{\text{Sets}_*}^\triangleright$ is the pointed set of [Definition 4.4.2.1.1](#).

3. *Adjointness II.* The functor

$$- \triangleright Y : \text{Sets}_* \rightarrow \text{Sets}_*$$

does not admit a right adjoint.

Proof. [Item 1, Functoriality:](#) Clear.

[Item 2, Adjointness I:](#) This is a repetition of [Item 2](#) of [Proposition 4.4.1.1.7](#), 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

4.4.3 The Right Skew Unit

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

$$\mathbb{1}_{\text{Sets}_*}^{\triangleright} \stackrel{\text{def}}{=} S^0.$$

4.4.4 The Right Skew Associator

Definition 4.4.4.1.1. The **skew associator of the right tensor product of pointed sets** is the natural transformation

$$\alpha^{\text{Sets}_*, \triangleright} : \triangleright \circ (\text{id}_{\text{Sets}_*} \times \triangleright) \Rightarrow \triangleright \circ (\triangleright \times \text{id}_{\text{Sets}_*}) \circ \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}, -1}$$

as in the diagram

$$\begin{array}{ccc}
 & (\text{Sets}_* \times \text{Sets}_*) \times \text{Sets}_* & \\
 \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}, -1} \swarrow & \nearrow \triangleright \times \text{id} & \\
 \text{Sets}_* \times (\text{Sets}_* \times \text{Sets}_*) & & \text{Sets}_* \times \text{Sets}_* \\
 \downarrow \text{id} \times \triangleright & \alpha^{\text{Sets}_*, \triangleright} \parallel & \downarrow \triangleright \\
 \text{Sets}_* \times \text{Sets}_* & \xrightarrow[\triangleright]{} & \text{Sets}_*,
 \end{array}$$

whose component

$$\alpha_{X, Y, Z}^{\text{Sets}_*, \triangleright} : X \triangleright (Y \triangleright Z) \rightarrow (X \triangleright Y) \triangleright Z$$

pointed sets of [Definition 4.5.1.1.1](#). See [Item 2 of Proposition 4.5.1.1.9](#).

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.) \square

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 $x \triangleright (y \triangleright z) \in X \triangleright (Y \triangleright Z)$.

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

4.4.5 The Right Skew Left Unit

Definition 4.4.5.1.1. The **skew left unit of the right tensor product of pointed sets** is the natural transformation

$$\begin{array}{ccc} \text{pt} \times \text{Sets}_* & \xrightarrow{\mathbb{1}^{\text{Sets}_*} \times \text{id}} & \text{Sets}_* \times \text{Sets}_* \\ \lambda_{\text{Sets}_*}^{\text{Sets}_*, \triangleright} : \lambda_{\text{Sets}_*}^{\text{Cats}_2} \xrightarrow{\sim} \triangleright \circ (\mathbb{1}^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) & \swarrow \quad \searrow & \downarrow \triangleright \\ & \lambda_{\text{Sets}_*}^{\text{Sets}_*, \triangleright} & \text{Sets}_*, \\ & \lambda_{\text{Sets}_*}^{\text{Cats}_2} & \end{array}$$

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.) □

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 $x \in X$.

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

$$\begin{array}{ccc} x & \xrightarrow{\quad} & f(x) \\ \downarrow & & \downarrow \\ 1 \triangleright x & \xrightarrow{\quad} & 1 \triangleright f(x) \end{array}$$

and hence indeed commutes, showing $\lambda^{\text{Sets}_*, \triangleright}$ to be a natural transformation. This finishes the proof. \square

4.4.6 The Right Skew Right Unitor

Definition 4.4.6.1.1. The **skew right unitor of the right tensor product of pointed sets** is the natural transformation

$$\begin{array}{ccc} \text{Sets}_* \times \text{pt} & \xrightarrow{\text{id} \times 1^{\text{Sets}_*}} & \text{Sets}_* \times \text{Sets}_* \\ \rho^{\text{Sets}_*, \triangleright} : \triangleright \circ (\text{id} \times 1^{\text{Sets}_*}) \xrightarrow{\sim} \rho_{\text{Sets}_*}^{\text{Cats}_2}, & \swarrow \rho^{\text{Sets}_*, \triangleright} & \downarrow \triangleright \\ & \rho_{\text{Sets}_*}^{\text{Cats}_2} & \end{array}$$

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.) \square

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 $x \triangleright 1 \in X \triangleright S^0$.

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

$$\begin{aligned} [\rho_X^{\text{Sets}_*, \triangleright} \circ \phi](x) &= \rho_X^{\text{Sets}_*, \triangleright}(\phi(x)) \\ &= \rho_X^{\text{Sets}_*, \triangleright}(x \triangleright 1) \\ &= x \\ &= [\text{id}_X](x) \end{aligned}$$

so that

$$\rho_X^{\text{Sets}_*, \triangleright} \circ \phi = \text{id}_X$$

and

$$\begin{aligned} [\phi \circ \rho_X^{\text{Sets}_*, \triangleright}](x \triangleright 1) &= \phi\left(\rho_X^{\text{Sets}_*, \triangleright}(x \triangleright 1)\right) \\ &= \phi(x) \\ &= x \triangleright 1 \\ &= [\text{id}_{X \triangleright S^0}](x \triangleright 1), \end{aligned}$$

but

$$\begin{aligned} [\phi \circ \rho_X^{\text{Sets}_*, \triangleright}](x \triangleright 0) &= \phi\left(\rho_X^{\text{Sets}_*, \triangleright}(x \triangleright 0)\right) \\ &= \phi(x_0) \\ &= 1 \triangleright x_0, \end{aligned}$$

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

$$\begin{array}{ccc} x \triangleright 0 & & x \triangleright 0 \mapsto f(x) \triangleright 0 \\ \downarrow & & \downarrow \\ x_0 \mapsto f(x_0) & & y_0 \end{array}$$

and

$$\begin{array}{ccc} x \triangleright 1 \mapsto f(x) \triangleright 1 & & \\ \downarrow & & \downarrow \\ x \mapsto f(x) & & \end{array}$$

and hence indeed commutes, showing $\rho^{\text{Sets}_*, \triangleright}$ to be a natural transformation. This finishes the proof. \square

4.4.7 The Diagonal

Definition 4.4.7.1.1. The **diagonal of the right tensor product of pointed sets** is the natural transformation

$$\begin{array}{c} \Delta^\triangleright : \text{id}_{\text{Sets}_*} \Rightarrow \triangleright \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2}, \\ \Delta_{\text{Sets}_*}^{\text{Cats}_2} \quad \text{id}_{\text{Sets}_*} \quad \Delta^\triangleright \quad \triangleright \\ \Downarrow \qquad \qquad \qquad \Downarrow \qquad \qquad \Downarrow \\ \text{Sets}_* \times \text{Sets}_*, \end{array}$$

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. \square

4.4.8 The Right Skew Monoidal Structure on Pointed Sets Associated to \triangleright

Proposition 4.4.8.1.1. The category Sets_* admits a right-closed right skew monoidal category structure consisting of

- *The Underlying Category.* The category Sets_* of pointed sets;
- *The Right Skew Monoidal Product.* The right tensor product functor

$$\triangleright: \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

of Definition 4.4.1.1;

- *The Right Internal Skew Hom.* The right internal Hom functor

$$[-, -]_{\text{Sets}_*}^\triangleright: \text{Sets}_*^{\text{op}} \times \text{Sets}_* \rightarrow \text{Sets}_*$$

of Definition 4.4.2.1.1;

- *The Right Skew Monoidal Unit.* The functor

$$\mathbb{1}_{\text{Sets}_*, \triangleright}: \text{pt} \rightarrow \text{Sets}_*$$

of Definition 4.4.3.1.1;

- *The Right Skew Associators.* The natural transformation

$$\alpha^{\text{Sets}_*, \triangleright} : \triangleright \circ (\text{id}_{\text{Sets}_*} \times \triangleright) \Rightarrow \triangleright \circ (\triangleright \times \text{id}_{\text{Sets}_*}) \circ \alpha^{\text{Cats}, -1}_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}$$

of Definition 4.4.4.1.1;

- *The Right Skew Left Unitors.* The natural transformation

$$\lambda^{\text{Sets}_*, \triangleright} : \lambda^{\text{Cats}_2}_{\text{Sets}_*} \Rightarrow \triangleright \circ (\mathbb{1}^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*})$$

of Definition 4.4.5.1.1;

- *The Right Skew Right Unitors.* The natural transformation

$$\rho^{\text{Sets}_*, \triangleright} : \triangleright \circ (\text{id} \times \mathbb{1}^{\text{Sets}_*}) \Rightarrow \rho^{\text{Cats}_2}_{\text{Sets}_*}$$

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

$$\begin{array}{ccc}
 & W \triangleright ((X \triangleright Y) \triangleright Z) & \\
 & \nearrow \alpha_{W, X, Y}^{\text{Sets}_*, \triangleright} \text{id}_Z & \searrow \alpha_{W, X \triangleright Y, Z}^{\text{Sets}_*, \triangleright} \\
 W \triangleright (X \triangleright (Y \triangleright Z)) & & (W \triangleright (X \triangleright Y)) \triangleright Z \\
 & \swarrow \alpha_{W \triangleright X, Y, Z}^{\text{Sets}_*, \triangleright} & \searrow \text{id}_W \triangleright \alpha_{X, Y, Z}^{\text{Sets}_*, \triangleright} \\
 & (W \triangleright X) \triangleright (Y \triangleright Z) & \xrightarrow{\alpha_{W, X, Y \triangleright Z}^{\text{Sets}_*, \triangleright}} ((W \triangleright X) \triangleright Y) \triangleright Z
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc}
 & & w \triangleright ((x \triangleright y) \triangleright z) & & \\
 & \nearrow & & \searrow & \\
 w \triangleright (x \triangleright (y \triangleright z)) & & & & (w \triangleright (x \triangleright y)) \triangleright z \\
 \downarrow & & & & \downarrow \\
 (w \triangleright x) \triangleright (y \triangleright z) & \longmapsto & & & ((w \triangleright x) \triangleright y) \triangleright z
 \end{array}$$

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

$$\begin{array}{ccc}
 X \triangleright Y & & \\
 \downarrow \lambda_{X \triangleright Y}^{\text{Sets}_*, \triangleright} & \searrow \lambda_X^{\text{Sets}_*, \triangleright} \triangleright \text{id}_Y & \\
 S^0 \triangleright (X \triangleright Y) & \xrightarrow{\alpha_{S^0, X, Y}^{\text{Sets}_*, \triangleright}} & (S^0 \triangleright X) \triangleright Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 x \triangleright y & & \\
 \downarrow & \swarrow & \\
 1 \triangleright (x \triangleright y) & \longmapsto & (1 \triangleright x) \triangleright y
 \end{array}$$

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

$$\begin{array}{ccc}
 X \triangleright (Y \triangleright S^0) & \xrightarrow{\text{id}_X \triangleright \rho_Y^{\text{Sets}_*, \triangleright}} & (X \triangleright Y) \triangleright S^0 \\
 \downarrow \alpha_{S^0, X, Y}^{\text{Sets}_*, \triangleright} & \searrow & \downarrow \rho_{X \triangleright Y}^{\text{Sets}_*, \triangleright} \\
 & & X \triangleright Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x \triangleright (y \triangleright 0) & \longmapsto & (x \triangleright y) \triangleright 0 \\ \swarrow & & \downarrow \\ x \triangleright y_0 = x_0 \triangleright y_0 & & \end{array}$$

and

$$\begin{array}{ccc} x \triangleright (y \triangleright 1) & \longmapsto & (x \triangleright y) \triangleright 1 \\ \swarrow & & \downarrow \\ x \triangleright y & & \end{array}$$

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

$$\begin{array}{ccc} x \triangleright y & \longrightarrow & x \triangleright y \\ \downarrow & & \uparrow \\ x \triangleright (1 \triangleright y) & \longmapsto & (x \triangleright 1) \triangleright y \end{array}$$

and hence indeed commutes. Thus the right skew triangle identity is satisfied.

The Zig-Zag Identity: We have to show that the diagram

$$\begin{array}{ccc} S^0 & \xrightarrow{\lambda_{S^0}^{\text{Sets}_*, \triangleright}} & S^0 \triangleright S^0 \\ & \searrow & \downarrow \rho_{S^0}^{\text{Sets}_*, \triangleright} \\ & & S^0 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} 0 & \xrightarrow{\quad} & 1 \triangleright 0 \\ & \searrow & \downarrow \\ & & 0 \end{array}$$

and

$$\begin{array}{ccc} 1 & \xrightarrow{\quad} & 1 \triangleright 1 \\ & \searrow & \downarrow \\ & & 1 \end{array}$$

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. \square

4.4.9 Monoids With Respect to the Right Tensor Product of Pointed Sets

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 .

¹⁸A monoid with right zero is defined similarly as the monoids with zero of ??.

satisfying the following conditions:

1. *Associativity.* The diagram

$$\begin{array}{ccc}
 & A \triangleright (A \triangleright A) & \\
 \alpha_{A,A,A}^{\text{Sets}_*, \triangleright} \nearrow & & \searrow \text{id}_{A \triangleright \mu_A} \\
 (A \triangleright A) \triangleright A & & A \triangleright A \\
 \downarrow \mu_{A \triangleright \text{id}_A} & & \downarrow \mu_A \\
 A \triangleright A & \xrightarrow{\mu_A} & A
 \end{array}$$

2. *Left Unitality.* The diagram

$$\begin{array}{ccc}
 A & \xrightarrow{\lambda_A^{\text{Sets}_*, \triangleright}} & S^0 \triangleright A \\
 \parallel & & \downarrow \eta_A \times \text{id}_A \\
 A & \xleftarrow{\mu_A} & A \triangleright A
 \end{array}$$

commutes.

3. *Right Unitality.* The diagram

$$\begin{array}{ccc}
 A \triangleright S^0 & \xrightarrow{\text{id}_A \times \eta_A} & A \triangleright A \\
 & \searrow \rho_A^{\text{Sets}_*, \triangleright} & \downarrow \mu_A \\
 & & A
 \end{array}$$

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:

Succinctly, they are monoids (A, μ_A, η_A) with a special element 0_A satisfying

$$0_A a = 0_A$$

for each $a \in A$.

1. *Associativity.* The associativity condition acts as

$$\begin{array}{ccc}
 & a \triangleright (b \triangleright c) & \\
 & \swarrow \quad \searrow & \\
 (a \triangleright b) \triangleright c & (a \triangleright b) \triangleright c & a \triangleright bc \\
 \downarrow & \downarrow & \downarrow \\
 ab \triangleright c \longmapsto (ab)c & a(bc) &
 \end{array}$$

This gives

$$(ab)c = a(bc)$$

for each $a, b, c \in A$.

2. *Left Unitality.* The left unitality condition acts as

$$\begin{array}{ccc}
 a & a \longmapsto 1 \triangleright a & \\
 \downarrow & & \downarrow \\
 a & 1_A a \longleftrightarrow 1_A \triangleright a &
 \end{array}$$

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

$$\begin{array}{ccc}
 1 \triangleright 0 & a \triangleright 0 \longmapsto a \triangleright 0_A & \\
 \swarrow \quad \searrow & \downarrow & \\
 0_A & a0_A. &
 \end{array}$$

(b) On $a \triangleright 1$ as

$$\begin{array}{ccc}
 a \triangleright 1 & a \triangleright 1 \longmapsto a \triangleright 1_A & \\
 \swarrow \quad \searrow & \downarrow & \\
 a & a1_A. &
 \end{array}$$

This gives

$$\begin{aligned} a1_A &= a, \\ a0_A &= 0_A \end{aligned}$$

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 $(A, \mu_A, 0_A)$ to $(B, \mu_B, 0_B)$ 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

$$\begin{array}{ccc} A \triangleright A & \xrightarrow{f \triangleright f} & B \triangleright B \\ \mu_A \downarrow & & \downarrow \mu_B \\ A & \xrightarrow{f} & B \end{array}$$

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

$$\begin{array}{ccc} a \triangleright b & & a \triangleright b \mapsto f(a) \triangleright f(b) \\ \downarrow & & \downarrow \\ ab & \longmapsto & f(ab) \\ & & f(a)f(b) \end{array}$$

and

$$\begin{array}{ccc} 0 & \nwarrow & 0 \mapsto 0_A \\ & 0_B & \downarrow \\ & & f(0_A) \end{array}$$

and

$$\begin{array}{ccc} 1 & \xrightarrow{\quad} & 1_A \\ \searrow & & \downarrow \\ & 1_B & f(1_A) \end{array}$$

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 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

4.5 The Smash Product of Pointed Sets

4.5.1 Foundations

Let (X, x_0) and (Y, y_0) be pointed sets.

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 $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$.

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

$$\begin{aligned} f(x_0, y) &= z_0, \\ f(x, y_0) &= z_0 \end{aligned}$$

for each $x \in X$ and each $y \in Y$.

¹⁹Further 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** .

²⁰Further Notation: In the context of monoids with zero as models for \mathbb{F}_1 -algebras,

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 $f: (X \times Y, (x_0, y_0)) \rightarrow X \wedge Y$;

there exists a unique morphism of pointed sets $X \wedge Y \xrightarrow{\exists!} Z$ making the diagram

$$\begin{array}{ccc} & X \wedge Y & \\ \iota \nearrow & \downarrow \exists! & \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commute.

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

$$\mathbf{Sets}_*(X \wedge Y, Z) \cong \text{Hom}_{\mathbf{Sets}}^R(X \times Y, Z).$$

Now, by definition, $\text{Hom}_{\mathbf{Sets}}^R(X \times Y, Z)$ is the set

$$\text{Hom}_{\mathbf{Sets}}^R(X \times Y, Z) \stackrel{\text{def}}{=} \left\{ f \in \text{Hom}_{\mathbf{Sets}}(X \times Y, Z) \mid \begin{array}{l} \text{for each } x, y \in X, \text{ if} \\ (x, y) \sim_R (x', y'), \text{ then} \\ f(x, y) = f(x', y') \end{array} \right\}.$$

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:
 - (a) We have $x = x_0$ or $y = y_0$.
 - (b) We have $x' = x_0$ or $y' = y_0$.

So, given $f \in \text{Hom}_{\mathbf{Sets}}(X \times Y, Z)$ 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 $\text{Hom}_{\mathbf{Sets}}(X \times Y, Z)$ 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

$$\text{Hom}_{\mathbf{Sets}}^R(X \times Y, Z) = \text{Hom}_{\mathbf{Sets}_*}^\otimes(X \times Y, Z)$$

of sets, which when composed with our earlier isomorphism

$$\mathbf{Sets}_*(X \wedge Y, Z) \cong \text{Hom}_{\mathbf{Sets}}^R(X \times Y, Z)$$

gives our desired natural bijection, finishing the proof. \square

the smash product $X \wedge Y$ is also denoted $X \otimes_{\mathbb{F}_1} Y$.

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 $(x, y), (x', y') \in X \vee Y$.

Notation 4.5.1.1.6. We write $x \wedge y$ for the element $[(x, y)]$ of

$$X \wedge Y \cong X \times Y / \sim.$$

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 $y, y' \in Y$.

Example 4.5.1.1.8. Here are some examples of smash products of pointed sets.

1. *Smashing With pt.* For any pointed set X , we have isomorphisms of pointed sets

$$\begin{aligned} \text{pt} \wedge X &\cong \text{pt}, \\ X \wedge \text{pt} &\cong \text{pt}. \end{aligned}$$

2. *Smashing With S^0 .* For any pointed set X , we have isomorphisms of pointed sets

$$\begin{aligned} S^0 \wedge X &\cong X, \\ X \wedge S^0 &\cong X. \end{aligned}$$

Proposition 4.5.1.1.9. Let (X, x_0) and (Y, y_0) be pointed sets.

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 $x \wedge y \in X \wedge Y$.

2. *Adjointness.* We have adjunctions

$$\begin{aligned} (X \wedge - \dashv \mathbf{Sets}_*(X, -)): \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*, \\ (- \wedge Y \dashv \mathbf{Sets}_*(Y, -)): \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*, \end{aligned}$$

witnessed by bijections

$$\begin{aligned} \mathrm{Hom}_{\mathbf{Sets}_*}(X \wedge Y, Z) &\cong \mathrm{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(Y, Z)), \\ \mathrm{Hom}_{\mathbf{Sets}_*}(X \wedge Y, Z) &\cong \mathrm{Hom}_{\mathbf{Sets}_*}(X, \mathbf{Sets}_*(A, Z)), \end{aligned}$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \mathrm{Obj}(\mathbf{Sets}_*)$.

3. *Enriched Adjointness.* We have \mathbf{Sets}_* -enriched adjunctions

$$\begin{aligned} (X \wedge - \dashv \mathbf{Sets}_*(X, -)): \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*, \\ (- \wedge Y \dashv \mathbf{Sets}_*(Y, -)): \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\ \perp \\ \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*, \end{aligned}$$

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 $(X, x_0), (Y, y_0), (Z, z_0) \in \mathrm{Obj}(\mathbf{Sets}_*)$.

4. *As a Pushout.* We have an isomorphism

$$\begin{array}{ccc} X \wedge Y & \leftarrow & X \times Y \\ \uparrow & \lrcorner & \uparrow \\ X \wedge Y & \cong \text{pt} \coprod_{X \vee Y} (X \times Y), & \\ \uparrow & & \downarrow \iota \\ \text{pt} & \xleftarrow{!} & X \vee Y, \end{array}$$

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.

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

$$\mathbf{Sets}(X \times Y, Z) \cong \mathbf{Sets}(X, \mathbf{Sets}(Y, Z))$$

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

$$\begin{aligned} \xi^\dagger(x, y_0) &\stackrel{\text{def}}{=} \xi_x(y_0) \\ &\stackrel{\text{def}}{=} z_0 \end{aligned}$$

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 Sets_* ([Definition 3.3.3.1.1](#)). \square

4.5.2 The Internal Hom of Pointed Sets

Let (X, x_0) and (Y, y_0) be pointed sets.

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 $\text{Sets}_*((X, x_0), (Y, y_0))$ ²² consisting of:

- *The Underlying Set.* The set $\text{Sets}_*((X, x_0), (Y, y_0))$ of morphisms of pointed sets from (X, x_0) to (Y, y_0) .
- *The Basepoint.* The element

$$\Delta_{y_0} : (X, x_0) \rightarrow (Y, y_0)$$

of $\text{Sets}_*((X, x_0), (Y, y_0))$ given by

$$\Delta_{y_0}(x) \stackrel{\text{def}}{=} y_0$$

for each $x \in X$.

Proof. For a proof that Sets_* is indeed the internal Hom of Sets_* with respect to the smash product of pointed sets, see [Item 2](#) of [Proposition 4.5.1.1.9](#). \square

²¹The pointed set $\text{Sets}_*(X, Y)$ is the internal Hom of Sets_* with respect to the smash product of [Definition 4.5.1.1.1](#); see [Item 2](#) of [Proposition 4.5.1.1.9](#).

²²Further Notation: Also written $\text{Hom}_{\text{Sets}_*}(X, Y)$.

Proposition 4.5.2.1.2. Let (X, x_0) and (Y, y_0) be pointed sets.

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

$$\begin{aligned}\mathbf{Sets}_*(X, -) &: \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*, \\ \mathbf{Sets}_*(-, Y) &: \mathbf{Sets}_*^{\text{op}} \rightarrow \mathbf{Sets}_*, \\ \mathbf{Sets}_*(-_1, -_2) &: \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*.\end{aligned}$$

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 $\phi \in \mathbf{Sets}_*(A, Y)$.

2. *Adjointness.* We have adjunctions

$$\begin{aligned}(X \wedge - \dashv \mathbf{Sets}_*(X, -)) : \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\[-1ex] \perp \\[-1ex] \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*, \\ (- \wedge Y \dashv \mathbf{Sets}_*(Y, -)) : \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\[-1ex] \perp \\[-1ex] \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*,\end{aligned}$$

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 $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

3. *Enriched Adjointness.* We have \mathbf{Sets}_* -enriched adjunctions

$$\begin{aligned}(X \wedge - \dashv \mathbf{Sets}_*(X, -)) : \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{X \wedge -} \\[-1ex] \perp \\[-1ex] \xleftarrow{\mathbf{Sets}_*(X, -)} \end{array} \mathbf{Sets}_*, \\ (- \wedge Y \dashv \mathbf{Sets}_*(Y, -)) : \quad & \mathbf{Sets}_* \begin{array}{c} \xrightarrow{- \wedge Y} \\[-1ex] \perp \\[-1ex] \xleftarrow{\mathbf{Sets}_*(Y, -)} \end{array} \mathbf{Sets}_*,\end{aligned}$$

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 $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$.

Proof. *Item 1, Functoriality:* This follows from *Item 1* of [Proposition 2.3.5.1.2](#) and from the equalities

$$\begin{aligned}g \circ \Delta_{y_0} &= \Delta_{z_0}, \\ \Delta_{y_0} \circ f &= \Delta_{y_0}\end{aligned}$$

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

4.5.3 The Monoidal Unit

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

$$\mathbb{1}_{\mathbf{Sets}_*} \stackrel{\text{def}}{=} S^0.$$

4.5.4 The Associator

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

$$\begin{array}{ccc} & \mathbf{Sets}_* \times (\mathbf{Sets}_* \times \mathbf{Sets}_*) & \\ \alpha_{\mathbf{Sets}_*, \mathbf{Sets}_*, \mathbf{Sets}_*}^{\text{Cats}} \swarrow & \nearrow \text{id} \times \wedge & \\ (\mathbf{Sets}_* \times \mathbf{Sets}_*) \times \mathbf{Sets}_* & & \mathbf{Sets}_* \times \mathbf{Sets}_* \\ \wedge \times \text{id} \searrow & \alpha_{\mathbf{Sets}_*} \swarrow & \downarrow \wedge \\ \mathbf{Sets}_* \times \mathbf{Sets}_* & \xrightarrow{\wedge} & \mathbf{Sets}_*, \end{array}$$

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

4.5.5 The Left Unitor

Definition 4.5.5.1.1. The **left unitor of the smash product of pointed sets** is the natural isomorphism

$$\begin{array}{ccc} \text{pt} \times \text{Sets}_* & \xrightarrow{\text{id}_{\text{Sets}_*} \times \text{id}} & \text{Sets}_* \times \text{Sets}_* \\ \lambda^{\text{Sets}_*} : \wedge \circ (\text{id}_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \lambda_{\text{Sets}_*}^{\text{Cats}_2} & \swarrow \lambda^{\text{Sets}_*} & \downarrow \wedge \\ & \searrow \lambda_{\text{Sets}_*}^{\text{Cats}_2} & \\ & \text{Sets}_*, & \end{array}$$

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

$$\begin{aligned} [\lambda_X^{\text{Sets}_*, -1} \circ \lambda_X^{\text{Sets}_*}](0 \wedge x) &= \lambda_X^{\text{Sets}_*, -1}(\lambda_X^{\text{Sets}_*}(0 \wedge x)) \\ &= \lambda_X^{\text{Sets}_*, -1}(x_0) \\ &= 1 \wedge x_0 \\ &= 0 \wedge x, \end{aligned}$$

and

$$\begin{aligned} [\lambda_X^{\text{Sets}_*, -1} \circ \lambda_X^{\text{Sets}_*}](1 \wedge x) &= \lambda_X^{\text{Sets}_*, -1}(\lambda_X^{\text{Sets}_*}(1 \wedge x)) \\ &= \lambda_X^{\text{Sets}_*, -1}(x) \\ &= 1 \wedge x \end{aligned}$$

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

$$\begin{aligned} [\lambda_X^{\text{Sets}_*} \circ \lambda_X^{\text{Sets}_*, -1}](x) &= \lambda_X^{\text{Sets}_*}(\lambda_X^{\text{Sets}_*, -1}(x)) \\ &= \lambda_X^{\text{Sets}_*, -1}(1 \wedge x) \\ &= x \end{aligned}$$

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

$$\begin{array}{ccc} S^0 \wedge X & \xrightarrow{\text{id}_{S^0} \wedge f} & S^0 \wedge Y \\ \downarrow \lambda_X^{\text{Sets}_*} & & \downarrow \lambda_Y^{\text{Sets}_*} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} 0 \wedge x & \longmapsto & 0 \wedge x \longmapsto 0 \wedge f(x) \\ \downarrow & & \downarrow \\ x_0 \longmapsto f(x_0) & & y_0 \end{array}$$

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 λ^{Sets_*} to be a natural transformation.

Being a Natural Isomorphism: Since λ^{Sets_*} is natural and $\lambda^{\text{Sets}_*, -1}$ is a componentwise inverse to λ^{Sets_*} , it follows from Item 2 of Proposition 8.8.6.1.2 that $\lambda^{\text{Sets}_*, -1}$ is also natural. Thus λ^{Sets_*} is a natural isomorphism. \square

4.5.6 The Right Unitor

Definition 4.5.6.1.1. The **right unitor of the smash product of pointed sets** is the natural isomorphism

$$\begin{array}{ccc} \text{Sets}_* \times \text{pt} & \xrightarrow{\text{id} \times 1^{\text{Sets}_*}} & \text{Sets}_* \times \text{Sets}_* \\ \rho^{\text{Sets}_*}: \wedge \circ (\text{id} \times 1^{\text{Sets}_*}) \xrightarrow{\sim} \rho_{\text{Sets}_*}^{\text{Cats}_2}, & \swarrow \quad \searrow & \downarrow \wedge \\ & \rho_{\text{Sets}_*}^{\text{Cats}_2} & \text{Sets}_*, \end{array}$$

whose component

$$\rho_X^{\text{Sets}_*} : X \wedge S^0 \xrightarrow{\cong} X$$

at $X \in \text{Obj}(\text{Sets}_*)$ 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

$$\begin{aligned} [\rho_X^{\text{Sets}_*, -1} \circ \rho_X^{\text{Sets}_*}](x \wedge 0) &= \rho_X^{\text{Sets}_*, -1}(\rho_X^{\text{Sets}_*}(x \wedge 0)) \\ &= \rho_X^{\text{Sets}_*, -1}(x_0) \\ &= x_0 \wedge 1 \\ &= x \wedge 0, \end{aligned}$$

and

$$\begin{aligned} [\rho_X^{\text{Sets}_*, -1} \circ \rho_X^{\text{Sets}_*}](x \wedge 1) &= \rho_X^{\text{Sets}_*, -1}(\rho_X^{\text{Sets}_*}(x \wedge 1)) \\ &= \rho_X^{\text{Sets}_*, -1}(x) \\ &= x \wedge 1 \end{aligned}$$

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

$$\begin{aligned} [\rho_X^{\text{Sets}_*} \circ \rho_X^{\text{Sets}_*, -1}](x) &= \rho_X^{\text{Sets}_*}(\rho_X^{\text{Sets}_*, -1}(x)) \\ &= \rho_X^{\text{Sets}_*, -1}(x \wedge 1) \\ &= x \end{aligned}$$

for each $x \in X$, and thus we have

$$\rho_X^{\text{Sets}_*} \circ \rho_X^{\text{Sets}_*, -1} = \text{id}_X.$$

This shows $\rho_X^{\text{Sets}_*}$ 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

$$\begin{array}{ccc} X \wedge S^0 & \xrightarrow{f \wedge \text{id}_{S^0}} & Y \wedge S^0 \\ \rho_X^{\text{Sets}_*} \downarrow & & \downarrow \rho_Y^{\text{Sets}_*} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x \wedge 0 & \xrightarrow{\quad} & x \wedge 0 \mapsto f(x) \wedge 0 \\ \downarrow & & \downarrow \\ x_0 \mapsto f(x_0) & & y_0 \end{array}$$

and

$$\begin{array}{ccc} x \wedge 1 & \xrightarrow{\quad} & x \wedge 1 \mapsto f(x) \wedge 1 \\ \downarrow & & \downarrow \\ x \mapsto f(x) & & \end{array}$$

and hence indeed commutes, showing ρ^{Sets_*} to be a natural transformation.

Being a Natural Isomorphism: Since ρ^{Sets_*} is natural and $\rho^{\text{Sets}_*, -1}$ is a componentwise inverse to ρ^{Sets_*} , it follows from Item 2 of Proposition 8.8.6.1.2 that $\rho^{\text{Sets}_*, -1}$ is also natural. Thus ρ^{Sets_*} is a natural isomorphism. \square

4.5.7 The Symmetry

Definition 4.5.7.1.1. The **symmetry of the smash product of pointed sets** is the natural isomorphism

$$\sigma^{\text{Sets}_*} : \wedge \xrightarrow{\sim} \wedge \circ \sigma_{\text{Sets}_*, \text{Sets}_*}^{\text{Cats}_2},$$

$$\begin{array}{ccc} \text{Sets}_* \times \text{Sets}_* & \xrightarrow{\wedge} & \text{Sets}_*, \\ \sigma_{\text{Sets}_*, \text{Sets}_*}^{\text{Cats}_2} \downarrow & \Downarrow \sigma^{\text{Sets}_*} & \downarrow \wedge \\ \text{Sets}_* \times \text{Sets}_* & & \end{array}$$

whose component

$$\sigma_{X,Y}^{\text{Sets}_*} : X \wedge Y \xrightarrow{\cong} Y \wedge X$$

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 σ^{Sets_*} to be a natural transformation.

Being a Natural Isomorphism: Since σ^{Sets_*} is natural and $\sigma^{\text{Sets}_*, -1}$ is a componentwise inverse to σ^{Sets_*} , it follows from Item 2 of Proposition 8.8.6.1.2 that $\sigma^{\text{Sets}_*, -1}$ is also natural. Thus σ^{Sets_*} is a natural isomorphism. \square

4.5.8 The Diagonal

Definition 4.5.8.1.1. The **diagonal of the smash product of pointed sets** is the natural transformation

$$\begin{array}{ccc} \Delta^\wedge: \text{id}_{\text{Sets}_*} & \Longrightarrow & \wedge \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2}, \\ & & \Delta_{\text{Sets}_*}^{\text{Cats}_2} \searrow \quad \Delta^\wedge \downarrow \quad \nearrow \wedge \\ & & \text{Sets}_* \wedge \text{Sets}_*, \end{array}$$

$\text{id}_{\text{Sets}_*} \quad \parallel \quad \Delta^\wedge \quad \wedge$

whose component

$$\Delta_X^\wedge: (X, x_0) \rightarrow (X \wedge X, x_0 \wedge x_0)$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ 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 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. \square

Proposition 4.5.8.1.2. Let $(X, x_0) \in \text{Obj}(\text{Sets}_*)$.

1. *Monoidality.* The diagonal

$$\Delta^\wedge: \text{id}_{\text{Sets}_*} \Rightarrow \wedge \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2},$$

of the smash product of pointed sets is a monoidal natural transformation:

- (a) *Compatibility With Strong Monoidality Constraints.* For each $(X, x_0), (Y, y_0) \in \text{Obj}(\text{Sets}_*)$, the diagram

$$\begin{array}{ccc} X \wedge Y & \xrightarrow{\Delta_X^\wedge \wedge \Delta_Y^\wedge} & (X \wedge X) \wedge (Y \wedge Y) \\ & \searrow \Delta_{X \wedge Y}^\wedge & \downarrow ? \\ & & (X \wedge Y) \wedge (X \wedge Y) \end{array}$$

commutes.

(b) *Compatibility With Strong Unitality Constraints.* The diagrams

$$\begin{array}{ccc} S^0 & \xrightarrow{\Delta_{S^0}^\wedge} & S^0 \wedge S^0 \\ \searrow & \downarrow \lambda_{S^0}^{\text{Sets}_*, -1} & \swarrow \\ & S^0 & \end{array} \quad \begin{array}{ccc} S^0 & \xrightarrow{\Delta_{S^0}^\wedge} & S^0 \wedge S^0 \\ \searrow & \downarrow \rho_{S^0}^{\text{Sets}_*, -1} & \swarrow \\ & S^0 & \end{array}$$

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 ??.

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

$$\begin{array}{ccc} X \wedge Y & \xrightarrow{\Delta_X^\wedge \wedge \Delta_Y^\wedge} & (X \wedge X) \wedge (Y \wedge Y) \\ & \searrow \Delta_{X \wedge Y}^\wedge & \downarrow \text{?} \\ & & (X \wedge Y) \wedge (X \wedge Y) \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x \wedge y & \longmapsto & (x \wedge x) \wedge (y \wedge y) \\ & \searrow & \downarrow \\ & & (x \wedge y) \wedge (x \wedge y) \end{array}$$

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 unit of \mathbf{Sets}_* with respect to the smash product of pointed sets at $(X, x_0) \in \text{Obj}(\mathbf{Sets}_*)$ is given by

$$\lambda_X^{\mathbf{Sets}_*, -1}(x) \stackrel{\text{def}}{=} 1 \wedge x$$

for each $x \in X$, so when $X = S^0$, we have

$$\begin{aligned}\lambda_{S^0}^{\mathbf{Sets}_*, -1}(0) &\stackrel{\text{def}}{=} 1 \wedge 0, \\ \lambda_{S^0}^{\mathbf{Sets}_*, -1}(1) &\stackrel{\text{def}}{=} 1 \wedge 1.\end{aligned}$$

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 $\Delta_{S^0}^\wedge = \lambda_{S^0}^{\mathbf{Sets}_*, -1}$.

This finishes the proof.

Item 2, The Diagonal of the Unit: This follows from [Item 1](#) and the invertibility of the left/right unit of \mathbf{Sets}_* with respect to \wedge , proved in the proof of [Definition 4.5.5.1.1](#) for the left unit or the proof of [Definition 4.5.6.1.1](#) for the right unit. \square

4.5.9 The Monoidal Structure on Pointed Sets Associated to \wedge

Proposition 4.5.9.1.1. The category \mathbf{Sets}_* admits a closed monoidal category with diagonals structure consisting of

- *The Underlying Category.* The category \mathbf{Sets}_* of pointed sets;
- *The Monoidal Product.* The smash product functor

$$\wedge: \mathbf{Sets}_* \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

of [Item 1](#) of [Proposition 4.5.1.1.9](#);

- *The Internal Hom.* The internal Hom functor

$$\mathbf{Sets}_*: \mathbf{Sets}_*^{\text{op}} \times \mathbf{Sets}_* \rightarrow \mathbf{Sets}_*$$

of [Item 1](#) of [Proposition 4.5.2.1.2](#);

- *The Monoidal Unit.* The functor

$$1^{\mathbf{Sets}_*}: \text{pt} \rightarrow \mathbf{Sets}_*$$

of [Definition 4.5.3.1.1](#);

- *The Associators.* The natural isomorphism

$$\alpha^{\text{Sets}_*} : \wedge \circ (\wedge \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \wedge \circ (\text{id}_{\text{Sets}_*} \times \wedge) \circ \alpha_{\text{Sets}_*, \text{Sets}_*, \text{Sets}_*}^{\text{Cats}_2}$$

of Definition 4.5.4.1.1;

- *The Left Unitors.* The natural isomorphism

$$\lambda^{\text{Sets}_*} : \wedge \circ (\mathbb{1}^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\sim} \lambda_{\text{Sets}_*}^{\text{Cats}_2}$$

of Definition 4.5.5.1.1;

- *The Right Unitors.* The natural isomorphism

$$\rho^{\text{Sets}_*} : \wedge \circ (\text{id} \times \mathbb{1}^{\text{Sets}_*}) \xrightarrow{\sim} \rho_{\text{Sets}_*}^{\text{Cats}_2}$$

of Definition 4.5.6.1.1;

- *The Symmetry.* The natural isomorphism

$$\sigma^{\text{Sets}_*} : \wedge \xrightarrow{\sim} \wedge \circ \sigma_{\text{Sets}_*, \text{Sets}_*}^{\text{Cats}_2}$$

of Definition 4.5.7.1.1;

- *The Diagonals.* The monoidal natural transformation

$$\Delta^\wedge : \text{id}_{\text{Sets}_*} \Longrightarrow \wedge \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2}$$

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

$$\begin{array}{ccc}
 & (W \wedge (X \wedge Y)) \wedge Z & \\
 \nearrow \alpha_{W, X, Y}^{\text{Sets}_*} \wedge \text{id}_Z & & \searrow \alpha_{W, X \wedge Y, Z}^{\text{Sets}_*} \\
 ((W \wedge X) \wedge Y) \wedge Z & & W \wedge ((X \wedge Y) \wedge Z) \\
 \downarrow \alpha_{W \wedge X, Y, Z}^{\text{Sets}_*} & & \downarrow \text{id}_W \wedge \alpha_{X, Y, Z}^{\text{Sets}_*} \\
 (W \wedge X) \wedge (Y \wedge Z) & \xrightarrow{\alpha_{W, X, Y \wedge Z}^{\text{Sets}_*}} & W \wedge (X \wedge (Y \wedge Z))
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc}
 & & (w \wedge (x \wedge y)) \wedge z & & \\
 & \nearrow & & \searrow & \\
 ((w \wedge x) \wedge y) \wedge z & & & & w \wedge ((x \wedge y) \wedge z) \\
 \downarrow & & & & \downarrow \\
 (w \wedge x) \wedge (y \wedge z) & \longmapsto & w \wedge (x \wedge (y \wedge z))
 \end{array}$$

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

$$\begin{array}{ccc}
 (X \wedge S^0) \wedge Y & \xrightarrow{\alpha_{X,S^0,Y}^{\text{Sets}_*}} & X \wedge (S^0 \wedge Y) \\
 \rho_X^{\text{Sets}_*} \wedge \text{id}_Y \quad & & \text{id}_X \wedge \lambda_Y^{\text{Sets}_*} \\
 \downarrow & & \downarrow \\
 X \wedge Y & &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 (x \wedge 0) \wedge y & & (x \wedge 0) \wedge y \longmapsto x \wedge (0 \wedge y) \\
 \swarrow & & \searrow \\
 x_0 \wedge y & & x \wedge y_0
 \end{array}$$

and

$$\begin{array}{ccc}
 (x \wedge 1) \wedge y \longmapsto x \wedge (1 \wedge y) & & \\
 \swarrow \quad \searrow & & \\
 x \wedge y, & &
 \end{array}$$

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

$$\begin{array}{ccc}
 & (X \wedge Y) \wedge Z & \\
 \alpha_{X,Y,Z}^{\text{Sets}*} \swarrow & & \searrow \beta_{X,Y}^{\text{Sets}*} \wedge \text{id}_Z \\
 X \wedge (Y \wedge Z) & & (Y \wedge X) \wedge Z \\
 \downarrow \beta_{X,Y \wedge Z}^{\text{Sets}*} & & \downarrow \alpha_{Y,X,Z}^{\text{Sets}*} \\
 (Y \wedge Z) \wedge X & & Y \wedge (X \wedge Z) \\
 \downarrow \alpha_{Y,Z,X}^{\text{Sets}*} & & \downarrow \text{id}_Y \wedge \beta_{X,Z}^{\text{Sets}*} \\
 & Y \wedge (Z \wedge X) &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 & (x \wedge y) \wedge z & \\
 \swarrow & & \searrow \\
 x \wedge (y \wedge z) & & (y \wedge x) \wedge z \\
 \downarrow & & \downarrow \\
 (y \wedge z) \wedge x & & y \wedge (x \wedge z) \\
 \swarrow & & \searrow \\
 & y \wedge (z \wedge x) &
 \end{array}$$

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

$$\begin{array}{ccc}
 & X \wedge (Y \wedge Z) & \\
 (\alpha_{X,Y,Z}^{\text{Sets}*})^{-1} \swarrow & & \searrow \text{id}_X \wedge \beta_{Y,Z}^{\text{Sets}*} \\
 (X \wedge Y) \wedge Z & & X \wedge (Z \wedge Y) \\
 \downarrow \beta_{X \wedge Y, Z}^{\text{Sets}*} & & \downarrow (\alpha_{X,Z,Y}^{\text{Sets}*})^{-1} \\
 Z \wedge (X \wedge Y) & & (X \wedge Z) \wedge Y \\
 \downarrow (\alpha_{Z,X,Y}^{\text{Sets}*})^{-1} & & \downarrow \beta_{X,Z}^{\text{Sets}*} \wedge \text{id}_Y \\
 (Z \wedge X) \wedge Y & &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc}
 & & x \wedge (y \wedge z) & & \\
 & \swarrow & & \searrow & \\
 (x \wedge y) \wedge z & & & & x \wedge (z \wedge y) \\
 \downarrow & & & & \downarrow \\
 z \wedge (x \wedge y) & & & & (x \wedge z) \wedge y \\
 \swarrow & & & \searrow & \\
 (z \wedge x) \wedge y & & & &
 \end{array}$$

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](#). \square

4.5.10 Universal Properties of the Smash Product of Pointed Sets I

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 $1_{\text{Sets}_*} = S^0$.

Proof. Omitted. \square

4.5.11 Universal Properties of the Smash Product of Pointed Sets II

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

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 ??.

□

4.5.13 Comonoids With Respect to the Smash Product of Pointed Sets

Proposition 4.5.13.1.1. The symmetric monoidal functor

$$\left((-)^+, (-)^{+,\times}, (-)_{\mathbb{1}}^{+,\times} \right): (\text{Sets}, \times, \text{pt}) \rightarrow \left(\text{Sets}_*, \wedge, S^0 \right),$$

of Item 4 of Proposition 3.4.1.1.2 lifts to an equivalence of categories

$$\begin{aligned} \text{CoMon}(\text{Sets}_*, \wedge, S^0) &\xrightarrow{\text{eq.}} \text{CoMon}(\text{Sets}, \times, \text{pt}) \\ &\cong \text{Sets}. \end{aligned}$$

Proof. See [PS19, Lemma 2.4].

□

4.6 Miscellany

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.

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

Constructions With 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

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 **Rel** and **Rel** ([Proposition 5.3.1.1.1](#)).
 - (b) Identifications of equivalences and isomorphisms in **Rel** with bijections ([Proposition 5.3.2.1.1](#)).
 - (c) Identifications of adjunctions in **Rel** with functions ([Proposition 5.3.3.1.1](#)).
 - (d) Identifications of monads in **Rel** with preorders ([Proposition 5.3.4.1.1](#)).
 - (e) Identifications of comonads in **Rel** with subsets ([Proposition 5.3.5.1.1](#)).
 - (f) A description of the monoids and comonoids in **Rel** with respect to the Cartesian product ([Remark 5.3.6.1.1](#)).
 - (g) Characterisations of monomorphisms in **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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5.1 Relations

5.1.1 Foundations

Let A and B be sets.

Definition 5.1.1.1.1. A relation $R: A \nrightarrow B$ from A to B ^{1,2} is a subset R of $A \times B$.

Notation 5.1.1.1.2. Let $R: A \nrightarrow B$ be a relation.

- Given elements $a \in A$ and $b \in B$ and a relation $R: A \nrightarrow B$, we write $a \sim_R b$ to mean $(a, b) \in R$.

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** .

2. Viewing R as a function

$$R: A \times B \rightarrow \{\text{t, f}\}$$

via Remark 5.1.1.1.4, we write R_a^b for the value of R at (a, b) .³

Definition 5.1.1.1.3. Let A and B be sets.

1. The **set of relations from A to B** is the set $\text{Rel}(A, B)$ defined by

$$\text{Rel}(A, B) \stackrel{\text{def}}{=} \{\text{Relations from } A \text{ to } B\}.$$

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

$$\subset: \text{Rel}(A, B) \times \text{Rel}(A, B) \rightarrow \{\text{true, false}\}$$

on $\text{Rel}(A, B)$ given by inclusion of relations.

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.

Remark 5.1.1.1.4. A relation from A to B is equivalently:⁵

1. A subset of $A \times B$.
2. A function from $A \times B$ to $\{\text{true, false}\}$.
3. A function from A to $\mathcal{P}(B)$.
4. A function from B to $\mathcal{P}(A)$.
5. A cocontinuous morphism of posets from $(\mathcal{P}(A), \subset)$ to $(\mathcal{P}(B), \subset)$.

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).

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

$$\begin{aligned}\text{Hom}_{\text{Sets}}(A \times B, \{\text{true}, \text{false}\}) &\cong \text{Hom}_{\text{Sets}}(B, \text{Hom}_{\text{Sets}}(B, \{\text{true}, \text{false}\})) \\ &\cong \text{Hom}_{\text{Sets}}(B, \mathcal{P}(A)),\end{aligned}$$

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 $R: A \nrightarrow B$, 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

Proposition 5.1.1.1.5. Let A and B be sets and let $R, S: A \nrightarrow B$ be relations.

1. *End Formula for the Set of Inclusions of Relations.* We have

$$\text{Hom}_{\mathbf{Rel}(A,B)}(R, S) \cong \int_{a \in A} \int_{b \in B} \text{Hom}_{\{\text{t,f}\}}(R_a^b, S_a^b).$$

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

$$\int_{a \in A} \int_{b \in B} \text{Hom}_{\{\text{t,f}\}}(R_a^b, S_a^b) \cong \begin{cases} \text{pt} & \text{if, for each } a \in A \text{ and each } b \in B, \\ & \text{we have } \text{Hom}_{\{\text{t,f}\}}(R_a^b, S_a^b) \cong \text{pt} \\ \emptyset & \text{otherwise.} \end{cases}$$

Since we have $\text{Hom}_{\{\text{t,f}\}}(R_a^b, S_a^b) = \{\text{true}\} \cong \text{pt}$ exactly when $R_a^b = \text{false}$ or $R_a^b = S_a^b = \text{true}$, we get

$$\int_{a \in A} \int_{b \in B} \text{Hom}_{\{\text{t,f}\}}(R_a^b, S_a^b) \cong \begin{cases} \text{pt} & \text{if, for each } a \in A \text{ and each } b \in B, \\ & \text{if } a \sim_R b, \text{ then } a \sim_S b, \\ \emptyset & \text{otherwise.} \end{cases}$$

On the left hand-side, we have

$$\text{Hom}_{\mathbf{Rel}(A,B)}(R, S) \cong \begin{cases} \text{pt} & \text{if } R \subset S, \\ \emptyset & \text{otherwise.} \end{cases}$$

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

5.1.2 Relations as Decategorifications of Profunctors

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 D is a functor

$$\mathfrak{p}: D^{\text{op}} \times C \rightarrow \text{Sets}.$$

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 $(-)^{\text{op}}: \mathbf{Cats} \rightarrow \mathbf{Cats}$ restricts to the identity endofunctor on \mathbf{Sets} .
- The values that profunctors and relations take are analogous:
 - A category is enriched over the category

$$\mathbf{Sets} \stackrel{\text{def}}{=} \mathbf{Cats}_0$$

of sets, with profunctors taking values on it.

- A set is enriched over the set

$$\{\text{true}, \text{false}\} \stackrel{\text{def}}{=} \mathbf{Cats}_{-1}$$

of classical truth values, with relations taking values on it.

Remark 5.1.2.1.2. Extending Remark 5.1.2.1.1, the equivalent definitions of relations in Remark 5.1.1.1.4 are also related to the corresponding ones for profunctors (??), which state that a profunctor $\mathbf{p}: \mathcal{C} \nrightarrow \mathcal{D}$ is equivalently:

1. A functor $\mathbf{p}: \mathcal{D}^{\text{op}} \times \mathcal{C} \rightarrow \mathbf{Sets}$.
2. A functor $\mathbf{p}: \mathcal{C} \rightarrow \mathbf{PSh}(\mathcal{D})$.
3. A functor $\mathbf{p}: \mathcal{D}^{\text{op}} \rightarrow \mathbf{Fun}(\mathcal{C}, \mathbf{Sets})$.
4. A colimit-preserving functor $\mathbf{p}: \mathbf{PSh}(\mathcal{C}) \rightarrow \mathbf{PSh}(\mathcal{D})$.

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

$$\begin{aligned} \mathbf{Sets}(A \times B, \{\text{true}, \text{false}\}) &\cong \mathbf{Sets}(A, \mathbf{Sets}(B, \{\text{true}, \text{false}\})) \\ &\cong \mathbf{Sets}(A, \mathcal{P}(B)), \\ \mathbf{Fun}(\mathcal{D}^{\text{op}} \times \mathcal{D}, \mathbf{Sets}) &\cong \mathbf{Fun}(\mathcal{C}, \mathbf{Fun}(\mathcal{D}^{\text{op}}, \mathbf{Sets})) \\ &\cong \mathbf{Fun}(\mathcal{C}, \mathbf{PSh}(\mathcal{D})). \end{aligned}$$

- 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

$$\mathfrak{Y}: C \hookrightarrow \text{PSh}(C)$$

of C into $\text{PSh}(C)$, as stated and proved in ?? of ??.

5.1.3 Examples of Relations

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 $b \in B$.

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

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.

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 $\sqrt{-}: \mathbb{Q} \rightarrow \mathcal{P}(\mathbb{Q})$ sends a rational number x (e.g. 2) to the empty set (since $\sqrt{2} \notin \mathbb{Q}$).

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

$$\log(a + bi) \stackrel{\text{def}}{=} \left\{ \log(\sqrt{a^2 + b^2}) + i \arg(a + bi) + (2\pi i)k \mid k \in \mathbb{Z} \right\}$$

for each $a + bi \in \mathbb{C}$.

Example 5.1.3.1.6. See [Wik24] for more examples of relations, such as antiderivation, inverse trigonometric functions, and inverse hyperbolic functions.

5.1.4 Functional Relations

Let A and B be sets.

Definition 5.1.4.1.1. A relation $R: A \nrightarrow B$ is **functional** if, for each $a \in A$, the set $R(a)$ is either empty or a singleton.

Proposition 5.1.4.1.2. Let $R: A \nrightarrow B$ be a relation.

1. *Characterisations.* The following conditions are equivalent:

- (a) The relation R is functional.
- (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

$$[R \diamond R^\dagger](b, b') \preceq_{\{\text{t,f}\}} \chi_B(b, b'),$$

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

$$[R \diamond R^\dagger](b, b') \preceq_{\{\text{t,f}\}} \chi_B(b, b'),$$

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. □

5.1.5 Total Relations

Let A and B be sets.

Definition 5.1.5.1.1. A relation $R: A \rightarrow B$ is **total** if, for each $a \in A$, we have $R(a) \neq \emptyset$.

Proposition 5.1.5.1.2. Let $R: A \rightarrow B$ be a relation.

1. *Characterisations.* The following conditions are equivalent:

- (a) The relation R is total.
- (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

$$\chi_A(a, a') \preceq_{\{\text{t}, \text{f}\}} [R^\dagger \diamond R](a, a'),$$

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. □

5.2 Categories of Relations

5.2.1 The Category of Relations

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](#).

5.2.2 The Closed Symmetric Monoidal Category of Relations

5.2.2.1 The Monoidal Product

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

$$\begin{aligned} R &: A \not\rightarrow B, \\ S &: C \not\rightarrow D \end{aligned}$$

to the relation

$$R \times S : A \times C \not\rightarrow B \times D$$

of [Definition 6.3.9.1.1](#).

5.2.2.2 The Monoidal Unit

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 .

5.2.2.3 The Associator

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

$$\begin{array}{ccc} & \text{Rel} \times (\text{Rel} \times \text{Rel}) & \\ \alpha_{\text{Rel}, \text{Rel}, \text{Rel}}^{\text{Cats}} & \swarrow \quad \searrow & \\ (\text{Rel} \times \text{Rel}) \times \text{Rel} & & \text{Rel} \times \text{Rel} \\ \downarrow \quad \uparrow & & \downarrow \quad \uparrow \\ (\times) \times \text{id} & \quad \quad \quad \alpha^{\text{Rel}} & \\ \downarrow \quad \uparrow & & \downarrow \quad \uparrow \\ \text{Rel} \times \text{Rel} & \xrightarrow{\quad \times \quad} & \text{Rel}, \end{array}$$

whose component

$$\alpha_{A, B, C}^{\text{Rel}} : (A \times B) \times C \nrightarrow A \times (B \times C)$$

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 $c = c'$.

5.2.2.4 The Left Unitor

Definition 5.2.2.4.1. The **left unitor** of Rel is the natural isomorphism

$$\begin{array}{ccc} \text{pt} \times \text{Rel} & \xrightarrow{\mathbb{1}^{\text{Rel}} \times \text{id}} & \text{Rel} \times \text{Rel}, \\ \lambda^{\text{Rel}} : \times \circ (\mathbb{1}^{\text{Rel}} \times \text{id}) \xrightarrow{\sim} \lambda_{\text{Rel}}^{\text{Cats}_2}, & \swarrow \quad \searrow & \downarrow \times \\ \lambda_{\text{Rel}}^{\text{Cats}_2} & & \text{Rel} \end{array}$$

whose component

$$\lambda_A^{\text{Rel}} : \mathbb{1}_{\text{Rel}} \times A \rightarrowtail A$$

at A is defined by declaring

$$(\star, a) \sim_{\lambda_A^{\text{Rel}}} b$$

iff $a = b$.

5.2.2.5 The Right Unitor

Definition 5.2.2.5.1. The **right unitor of Rel** is the natural isomorphism

$$\begin{array}{ccc} \text{Rel} \times \text{pt} & \xrightarrow{\text{id} \times \mathbb{1}^{\text{Rel}}} & \text{Rel} \times \text{Rel}, \\ \rho^{\text{Rel}} : \times \circ (\text{id} \times \mathbb{1}^{\text{Rel}}) \xrightarrow{\sim} \rho_{\text{Rel}}^{\text{Cats}_2}, & \swarrow \quad \searrow & \downarrow \times \\ & \rho_{\text{Rel}}^{\text{Cats}_2} & \text{Rel} \end{array}$$

whose component

$$\rho_A^{\text{Rel}} : A \times \mathbb{1}_{\text{Rel}} \rightarrowtail A$$

at A is defined by declaring

$$(a, \star) \sim_{\rho_A^{\text{Rel}}} b$$

iff $a = b$.

5.2.2.6 The Symmetry

Definition 5.2.2.6.1. The **symmetry of Rel** is the natural isomorphism

$$\begin{array}{ccc} \text{Rel} \times \text{Rel} & \xrightarrow{\times} & \text{Rel}, \\ \sigma^{\text{Rel}} : \times \Longrightarrow \times \circ \sigma_{\text{Rel}, \text{Rel}}^{\text{Cats}_2}, & \swarrow \quad \searrow & \downarrow \sigma^{\text{Rel}} \\ \sigma_{\text{Rel}, \text{Rel}}^{\text{Cats}_2} & & \text{Rel} \times \text{Rel} \end{array}$$

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 $b = b'$.

5.2.2.7 The Internal Hom

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.

Proposition 5.2.2.7.2. Let $A, B, C \in \text{Obj}(\text{Rel})$.

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

5.2.2.8 The Closed Symmetric Monoidal Category of Relations

Proposition 5.2.2.8.1. The category Rel admits a closed symmetric monoidal category structure consisting of⁶

⁶  *Warning:* This is not a Cartesian monoidal structure, as the product on Rel is in fact given by the disjoint union of sets; see ??.

- *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

$$\lambda^{\text{Rel}} : \times \circ (\mathbb{1}^{\text{Rel}} \times \text{id}_{\text{Rel}}) \xrightarrow{\sim} \lambda_{\text{Rel}}^{\text{Cats}_2}$$

of [Definition 5.2.2.4.1](#).

- *The Right Unitors.* The natural isomorphism

$$\rho^{\text{Rel}} : \times \circ (\text{id} \times \mathbb{1}^{\text{Rel}}) \xrightarrow{\sim} \rho_{\text{Rel}}^{\text{Cats}_2}$$

of [Definition 5.2.2.5.1](#).

- *The Symmetry.* The natural isomorphism

$$\sigma^{\text{Rel}} : \times \xrightarrow{\sim} \times \circ \sigma_{\text{Rel}, \text{Rel}}^{\text{Cats}_2}$$

of [Definition 5.2.2.6.1](#).

Proof. Omitted. □

END TEXTDBEND

5.2.3 The 2-Category of Relations

Definition 5.2.3.1.1. The **2-category of relations** is the locally posetal 2-category **Rel** where

- **Objects.** The objects of **Rel** are sets.
- **Hom-Objects.** For each $A, B \in \text{Obj}(\text{Sets})$, we have

$$\begin{aligned}\text{Hom}_{\mathbf{Rel}}(A, B) &\stackrel{\text{def}}{=} \mathbf{Rel}(A, B) \\ &\stackrel{\text{def}}{=} (\text{Rel}(A, B), \subset).\end{aligned}$$

- **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 **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](#).

- **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 **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](#).

5.2.4 The Double Category of Relations

5.2.4.1 The Double Category of Relations

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.

⁷Note that this is indeed a morphism of posets: given relations $R_1, R_2 \in \mathbf{Rel}(A, B)$ and $S_1, S_2 \in \mathbf{Rel}(B, C)$ such that

$$\begin{aligned}R_1 &\subset R_2, \\ S_1 &\subset S_2,\end{aligned}$$

- *Vertical Morphisms.* The vertical morphisms of Rel^{dbl} are maps of sets $f: A \rightarrow B$.
- *Horizontal Morphisms.* The horizontal morphisms of Rel^{dbl} are relations $R: A \nrightarrow X$.
- *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 Rel^{dbl} is either non-existent or an inclusion of relations of the form

$$\begin{array}{ccc} A \times B & \xrightarrow{R} & \{\text{true, false}\} \\ R \subset S \circ (f \times g), & f \times g \downarrow & \curvearrowleft \qquad \downarrow \text{id}_{\{\text{true, false}\}} \\ X \times Y & \xrightarrow[S]{} & \{\text{true, false}\}. \end{array}$$

- *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 $R: A \nrightarrow B$ of Rel^{dbl} , the identity 2-morphism

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ \text{id}_A \downarrow & \Downarrow \text{id}_R & \downarrow \text{id}_B \\ A & \xrightarrow[R]{} & B \end{array}$$

of R is the identity inclusion

$$\begin{array}{ccc} B \times A & \xrightarrow{R} & \{\text{true, false}\} \\ R \subset R, \quad \text{id}_B \times \text{id}_A \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} \\ B \times A & \xrightarrow[R]{} & \{\text{true, false}\}. \end{array}$$

- *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](#).

5.2.4.2 Horizontal Identities

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

$$\begin{array}{ccc} A & \xrightarrow{\mathbb{1}_A} & A \\ f \downarrow & \parallel & \downarrow f \\ B & \xrightarrow{\mathbb{1}_B} & B \end{array}$$

we have also $S_1 \diamond R_1 \subset S_2 \diamond R_2$.

of f is the inclusion

$$\begin{array}{ccc} A \times A & \xrightarrow{\chi_A(-_1, -_2)} & \{\text{true, false}\} \\ \chi_B \circ (f \times f) \subset \chi_A, \quad f \times f \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} \\ B \times B & \xrightarrow{\chi_B(-_1, -_2)} & \{\text{true, false}\} \end{array}$$

of Item 1 of Proposition 2.4.1.1.3.

5.2.4.3 Horizontal Composition

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

- *Action on Objects.* For each composable pair $A \xrightarrow{R} B \xrightarrow{S} C$ of horizontal morphisms of Rel^{dbl} , we have

$$S \odot R \stackrel{\text{def}}{=} S \diamond R,$$

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

$$\begin{array}{ccc} A & \xrightarrow{R} & B & \quad & B & \xrightarrow{S} & C \\ f \downarrow & \Downarrow \alpha & \downarrow g & \quad & g \downarrow & \Downarrow \beta & \downarrow h \\ X & \xrightarrow{T} & Y & \quad & Y & \xrightarrow{U} & Z \end{array}$$

of 2-morphisms of Rel^{dbl} , i.e. for each pair

$$\begin{array}{ccc} A \times B & \xrightarrow{R} & \{\text{true, false}\} & \quad & B \times C & \xrightarrow{S} & \{\text{true, false}\} \\ f \times g \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} & \quad & g \times h \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} \\ X \times Y & \xrightarrow{T} & \{\text{true, false}\} & \quad & Y \times Z & \xrightarrow{U} & \{\text{true, false}\} \end{array}$$

of inclusions of relations, the horizontal composition

$$\begin{array}{ccc} A & \xrightarrow{S \odot R} & C \\ f \downarrow & \Downarrow \beta \odot \alpha & \downarrow h \\ X & \xrightarrow{U \odot T} & Z \end{array}$$

of α and β is the inclusion of relations⁸

$$\begin{array}{ccc} A \times C & \xrightarrow{S \diamond R} & \{\text{true, false}\} \\ (U \diamond T) \circ (f \times h) \subset (S \diamond R) & f \times h \downarrow & \curvearrowleft \quad \downarrow \text{id}_{\{\text{true, false}\}} \\ X \times Z & \xrightarrow{U \diamond T} & \{\text{true, false}\}. \end{array}$$

5.2.4.4 Vertical Composition of 2-Morphisms

Definition 5.2.4.4.1. The **vertical composition** in Rel^{dbl} is defined as follows: for each vertically composable pair

$$\begin{array}{ccc} A & \xrightarrow{R} & X \\ f \downarrow & \Downarrow \alpha & \downarrow g \\ B & \xrightarrow[S]{ } & Y \\ h \downarrow & \Downarrow \beta & \downarrow k \\ C & \xrightarrow[T]{ } & Z \end{array}$$

of 2-morphisms of Rel^{dbl} , i.e. for each each pair

$$\begin{array}{ccc} A \times X & \xrightarrow{R} & \{\text{true, false}\} \\ f \times g \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} \\ B \times Y & \xrightarrow[S]{ } & \{\text{true, false}\} \end{array} \quad \begin{array}{ccc} B \times Y & \xrightarrow{S} & \{\text{true, false}\} \\ h \times k \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} \\ C \times Z & \xrightarrow[T]{ } & \{\text{true, false}\} \end{array}$$

of inclusions of relations, we define the vertical composition

$$\begin{array}{ccc} A & \xrightarrow{R} & X \\ h \circ f \downarrow & \Downarrow \beta \circ \alpha & \downarrow k \circ g \\ C & \xrightarrow[T]{ } & Z \end{array}$$

⁸This is justified by noting that, given $(a, c) \in A \times C$, the statement

- We have $a \sim_{(U \diamond T) \circ (f \times h)} c$, i.e. $f(a) \sim_{U \diamond T} h(c)$, i.e. there exists some $y \in Y$ such that:
 1. We have $f(a) \sim_T y$;
 2. We have $y \sim_U h(c)$;

is implied by the statement

- We have $a \sim_{S \diamond R} c$, i.e. there exists some $b \in B$ such that:
 1. We have $a \sim_R b$;

of α and β as the inclusion of relations

$$T \circ [(h \circ f) \times (k \circ g)] \subset R, \quad (h \circ f) \times (k \circ g) \hookrightarrow A \times X \xrightarrow{R} \{\text{true, false}\}$$

$$C \times Z \xrightarrow{T} \{\text{true, false}\} \quad \downarrow \text{id}_{\{\text{true, false}\}}$$

given by the pasting of inclusions⁹

$$A \times X \xrightarrow{R} \{\text{true, false}\}$$

$$f \times g \downarrow \quad \hookrightarrow \quad \downarrow \text{id}_{\{\text{true, false}\}}$$

$$B \times Y \xrightarrow{-S} \{\text{true, false}\}$$

$$h \times k \downarrow \quad \hookrightarrow \quad \downarrow \text{id}_{\{\text{true, false}\}}$$

$$C \times Z \xrightarrow{T} \{\text{true, false}\}.$$

5.2.4.5 The Associators

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

$$\alpha_{T,S,R}^{\text{Rel}^{\text{dbl}}} : (T \odot S) \odot R \xrightarrow{\sim} T \odot (S \odot R), \quad \begin{array}{c} A \xrightarrow{R} B \xrightarrow{S} C \xrightarrow{T} D \\ \downarrow \text{id}_A \quad \downarrow \alpha_{T,S,R}^{\text{Rel}^{\text{dbl}}} \quad \downarrow \text{id}_D \\ A \xrightarrow{R} B \xrightarrow{S} C \xrightarrow{T} D \end{array}$$

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 $U \circ (g \times h) \subset S$.

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

of the associator of Rel^{dbl} at (R, S, T) is the identity inclusion¹⁰

$$(T \diamond S) \diamond R = T \diamond (S \diamond R) \quad \begin{array}{ccc} A \times B & \xrightarrow{(T \diamond S) \diamond R} & \{\text{true, false}\} \\ \parallel & \equiv & \downarrow \text{id}_{\{\text{true, false}\}} \\ A \times B & \xrightarrow{T \diamond (S \diamond R)} & \{\text{true, false}\}. \end{array}$$

5.2.4.6 The Left Unitors

Definition 5.2.4.6.1. For each horizontal morphism $R: A \dashrightarrow B$ of Rel^{dbl} , the component

$$\lambda_R^{\text{Rel}^{\text{dbl}}}: \mathbb{1}_B \odot R \xrightarrow{\sim} R, \quad \begin{array}{ccccc} A & \xrightarrow{R} & B & \xrightarrow{\mathbb{1}_B} & B \\ \text{id}_A \downarrow & \lambda_R^{\text{Rel}^{\text{dbl}}} \Downarrow & \parallel & & \downarrow \text{id}_B \\ A & \xrightarrow{R} & B & & \end{array}$$

of the left unit of Rel^{dbl} at R is the identity inclusion¹¹

$$R = \chi_B \diamond R, \quad \begin{array}{ccc} A \times B & \xrightarrow{\chi_B \diamond R} & \{\text{true, false}\} \\ \parallel & \equiv & \downarrow \text{id}_{\{\text{true, false}\}} \\ A \times B & \xrightarrow{R} & \{\text{true, false}\}. \end{array}$$

5.2.4.7 The Right Unitors

Definition 5.2.4.7.1. For each horizontal morphism $R: A \dashrightarrow B$ of Rel^{dbl} , the component

$$\rho_R^{\text{Rel}^{\text{dbl}}}: R \odot \mathbb{1}_A \xrightarrow{\sim} R, \quad \begin{array}{ccccc} A & \xrightarrow{\mathbb{1}_A} & A & \xrightarrow{R} & B \\ \text{id}_A \downarrow & \rho_R^{\text{Rel}^{\text{dbl}}} \Downarrow & \parallel & & \downarrow \text{id}_B \\ A & \xrightarrow{R} & B & & \end{array}$$

- 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 $h(f(a)) \sim_T k(g(x))$.

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 unit of $\mathbf{Rel}^{\text{dbl}}$ at R is the identity inclusion¹²

$$\begin{array}{ccc} A \times B & \xrightarrow{R \diamond \chi_A} & \{\text{true}, \text{false}\} \\ R = R \diamond \chi_A, & \parallel & \cong \\ & & \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ A \times B & \xrightarrow{R} & \{\text{true}, \text{false}\}. \end{array}$$

5.3 Properties of the 2-Category of Relations

5.3.1 Self-Duality

Proposition 5.3.1.1.1. The (2-)category of relations is self-dual:

1. *Self-Duality I.* We have an isomorphism

$$\mathbf{Rel}^{\text{op}} \xrightarrow{\text{eq.}} \mathbf{Rel}$$

of categories.

2. *Self-Duality II.* We have a 2-isomorphism

$$\mathbf{Rel}^{\text{op}} \xrightarrow{\text{eq.}} \mathbf{Rel}$$

of 2-categories.

Proof. **Item 1, Self-Duality I:** We claim that the functor

$$F: \mathbf{Rel}^{\text{op}} \rightarrow \mathbf{Rel}$$

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

$$(-)^\dagger: \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(B, A)$$

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

$$F: \mathbf{Rel}^{\text{op}} \rightarrow \mathbf{Rel}$$

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

5.3.2 Isomorphisms and Equivalences in **Rel**

Let $R: A \nrightarrow B$ be a relation from A to B .

Proposition 5.3.2.1.1. The following conditions are equivalent:

1. The relation $R: A \nrightarrow B$ is an equivalence in **Rel**, i.e.:
 - (\star) There exists a relation $R^{-1}: B \nrightarrow A$ from B to A together with isomorphisms

$$\begin{aligned} R^{-1} \diamond R &\cong \chi_A, \\ R \diamond R^{-1} &\cong \chi_B. \end{aligned}$$

2. The relation $R: A \nrightarrow B$ is an isomorphism in **Rel**, i.e.:
 - (\star) There exists a relation $R^{-1}: B \nrightarrow A$ from B to A such that we have

$$\begin{aligned} R^{-1} \diamond R &= \chi_A, \\ R \diamond R^{-1} &= \chi_B. \end{aligned}$$

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 **Rel** is locally posetal, so that natural isomorphisms and equalities of 1-morphisms in **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. \square

5.3.3 Adjunctions in **Rel**

Let A and B be sets.

Proposition 5.3.3.1.1. We have a natural bijection

$$\left\{ \begin{array}{c} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\} \cong \left\{ \begin{array}{c} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\},$$

with every adjunction in **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

$$\begin{aligned}R: A &\nrightarrow B, \\ S: B &\nrightarrow A,\end{aligned}$$

together with inclusions

$$\begin{aligned}\chi_A &\subset S \diamond R, \\ R \diamond S &\subset \chi_B.\end{aligned}$$

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

$$\left\{ \begin{array}{l} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\}.$$

Moreover, by uniqueness of adjoints (?? of ??), this implies also that $S = f^{-1}$.

2. *From Functions to Adjunctions in \mathbf{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 \mathbf{Rel} , giving a map

$$\left\{ \begin{array}{l} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\}.$$

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 shown 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. □

5.3.4 Monads in **Rel**

Let A be a set.

Proposition 5.3.4.1.1. We have a natural identification¹³

$$\left\{ \begin{array}{l} \text{Monads in} \\ \text{\textbf{Rel} on } A \end{array} \right\} \cong \{\text{Preorders on } A\}.$$

Proof. A monad in **Rel** on A consists of a relation $R: A \nrightarrow A$ together with maps

$$\begin{aligned} \mu_R: R \diamond R &\subset R, \\ \eta_R: \chi_A &\subset R \end{aligned}$$

making the diagrams

$$\begin{array}{ccccc} \chi_A \diamond R & \xrightarrow{\eta_R \diamond \text{id}_R} & R \diamond R & \xrightarrow{\alpha_{R,R,R}^{\text{Rel}(A,B)}} & R \diamond (R \diamond R) \\ \lambda_R^{\text{Rel}(A,B)} \searrow & & \downarrow \mu_R & & \swarrow \text{id}_{R \diamond R} \circ \mu_R \\ & & R & & R \diamond R \\ & & \downarrow \mu_{R \diamond R} & & \downarrow \mu_R \\ & & R & & R \diamond R \\ & & \xrightarrow{\mu_R} & & \xrightarrow{\mu_R} \end{array} \quad \begin{array}{c} (R \diamond R) \diamond R \\ \swarrow \mu_{R \diamond R} \\ R \end{array} \quad \begin{array}{c} R \diamond R \\ \swarrow \mu_R \\ R \end{array} \quad \begin{array}{c} R \diamond \chi_A \\ \xrightarrow{\text{id}_R \diamond \eta_R} R \diamond R \\ \downarrow \mu_R \\ R \end{array} \quad \begin{array}{c} \rho_R^{\text{Rel}(A,B)} \\ \searrow & \\ & R \end{array}$$

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 . \square

5.3.5 Comonads in **Rel**

Let A be a set.

Proposition 5.3.5.1.1. We have a natural identification

$$\left\{ \begin{array}{l} \text{Comonads in} \\ \text{\textbf{Rel} on } A \end{array} \right\} \cong \{\text{Subsets of } A\}.$$

¹³See also ?? for an extension of this correspondence to “relative monads in **Rel**”.

Proof. A comonad in **Rel** on A consists of a relation $R: A \nrightarrow A$ together with maps

$$\begin{aligned}\Delta_R: R &\subset R \diamond R, \\ \epsilon_R: R &\subset \chi_A\end{aligned}$$

making the diagrams

$$\begin{array}{ccccc} & & R \diamond R & & \\ & \nearrow \Delta_R & \downarrow \text{id}_R \circ \Delta_R & \searrow & \\ R & \xrightarrow{\quad \Delta_R \quad} & R \diamond R & \xrightarrow{\quad \text{id}_R \circ \Delta_R \quad} & R \diamond (R \diamond R) \\ \lambda_R^{\text{Rel}(A, B), -1} \swarrow & \downarrow \epsilon_R \diamond \text{id}_R & \Delta_R \swarrow & \parallel & \rho_R^{\text{Rel}(A, B), -1} \\ \chi_A \diamond R & & R & & R \diamond (R \diamond R) \\ & \downarrow & \Delta_R \downarrow & \parallel & \downarrow \text{id}_R \diamond \epsilon_R \\ & & R \diamond R & \xrightarrow{\quad \Delta_R \quad} & R \diamond \chi_A \end{array}$$

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. \square

5.3.6 Co/Monoids in **Rel**

Remark 5.3.6.1.1. The monoids in **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 **Rel** are called *hypercomonoids*, and they are defined and studied in [??](#).

5.3.7 Monomorphisms in **Rel**

In this section we characterise the epimorphisms in the category **Rel**, following [??](#).

Proposition 5.3.7.1.1. Let $R: A \nrightarrow B$ be a relation. The following conditions are equivalent:

1. The relation R is a monomorphism in Rel .
2. The direct image function

$$R_*: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$$

associated to R is injective.

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

$$\text{pt} \xrightarrow[U]{\quad} A \xrightarrow[R]{\quad} B.$$

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 $R \diamond U = R \diamond V$, 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

$$X \xrightarrow[S]{\quad} A \xrightarrow[R]{\quad} B,$$

and suppose that $R \diamond S = R \diamond T$. Note that, since R_* is injective,

given a diagram of the form

$$\text{pt} \xrightarrow[U]{\quad} A \xrightarrow[R]{\quad} B,$$

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

$$\text{pt} \xrightarrow[x]{\quad} X \xrightarrow[S]{\quad} A \xrightarrow[R]{\quad} B,$$

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

$$\text{pt} \xrightarrow[a]{\quad} A \xrightarrow[R]{\quad} B,$$

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

$$\begin{aligned} a &\sim_R b, \\ a' &\sim_R b, \end{aligned}$$

then $a = a'$.

consider the diagram

$$X \xrightarrow[T]{\quad\quad\quad} A \xrightarrow{R} B,$$

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

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.

Proposition 5.3.8.1.1. Let $R: A \nrightarrow B$ be a relation.

1. *Representably Faithful Morphisms in **Rel**.* Every morphism of **Rel** is a representably faithful morphism.
2. *Representably Full Morphisms in **Rel**.* The following conditions are equivalent:
 - (a) The morphism $R: A \nrightarrow B$ is a representably full morphism.
 - (b) For each pair of relations $S, T: X \rightrightarrows A$, the following condition is satisfied:
 - (\star) If $R \diamond S \subset R \diamond T$, then $S \subset T$.
 - (c) The functor

$$R_*: (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

is full.

- (d) For each $U, V \in \mathcal{P}(A)$, if $R_*(U) \subset R_*(V)$, then $U \subset V$.
(e) The functor

$$R_! : (\mathcal{P}(A), \subset) \rightarrow (\mathcal{P}(B), \subset)$$

is full.

- (f) For each $U, V \in \mathcal{P}(A)$, if $R_!(U) \subset R_!(V)$, then $U \subset V$.

3. *Representably Fully Faithful Morphisms in **Rel***. Every representably full morphism in **Rel** is a representably fully faithful morphism.

Proof. **Item 1, Representably Faithful Morphisms in **Rel**:** The relation R is a representably faithful morphism in **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 **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 **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

$$R_{*|S,T} : \text{Hom}_{\mathbf{Rel}(X,A)}(S, T) \rightarrow \text{Hom}_{\mathbf{Rel}(X,B)}(R \diamond S, R \diamond T)$$

is surjective for each $S, T \in \text{Obj}(\mathbf{Rel}(X, A))$, 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

$$R_{*|U,V} : \text{Hom}_{\mathcal{P}(A)}(U, V) \rightarrow \text{Hom}_{\mathcal{P}(B)}(R_*(U), R_*(V))$$

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) For each $U, V \in \mathcal{P}(A)$, if $R_*(U) \subset R_*(V)$, then $U \subset V$.

We need to show that the condition

(\star) 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 6.4.4.1.3*, 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) For each $U, V \in \mathcal{P}(A)$, if $R_!(U) \subset R_!(V)$, then $U \subset V$.

We need to show that the condition

(\star) 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

$$X \xrightarrow[T]{\parallel} A \xrightarrow{R} B,$$

and suppose that $R \diamond S \subset R \diamond T$. Note that, by assumption, given a diagram of the form

$$\text{pt} \xrightarrow[V]{\parallel} A \xrightarrow{R} B,$$

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

$$\text{pt} \xrightarrow{[x]} X \xrightarrow[T]{\parallel} A \xrightarrow{R} B,$$

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

$$\text{pt} \xrightarrow[V]{\parallel} A \xrightarrow{R} B.$$

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

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].

5.3.9 Epimorphisms in Rel

In this section we characterise the epimorphisms in the category Rel , following ??.

Proposition 5.3.9.1.1. Let $R: A \nrightarrow B$ be a relation. The following conditions are equivalent:

1. The relation R is an epimorphism in Rel .
2. The weak inverse image function

$$R^{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

associated to R is injective.

3. The strong inverse image function

$$R_{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

associated to R is injective.

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

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ & \dashv\dashv & \downarrow \\ & U & V \\ & \dashv\dashv & \end{array} \text{pt.}$$

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

$$A \xrightarrow{R} B \rightrightarrows^S_T X,$$

and suppose that $S \diamond R = T \diamond R$. Note that, since R^{-1} is injective, given a diagram of the form

$$A \xrightarrow{R} B \rightrightarrows^U_V \text{pt},$$

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

$$A \xrightarrow{R} B \rightrightarrows^S_T X \xrightarrow{[x]} \text{pt},$$

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 $R^{-1}(B \setminus \{b\}) \subsetneq R^{-1}(B)$. 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

$$A \xrightarrow{R} B \rightrightarrows \begin{matrix} S \\ T \end{matrix} \{0, 1\},$$

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

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](#).

Proposition 5.3.10.1.1. Let $R: A \nrightarrow B$ be a relation.

1. *Corepresentably Faithful Morphisms in **Rel***. Every morphism of **Rel** is a corepresentably faithful morphism.
2. *Corepresentably Full Morphisms in **Rel***. The following conditions are equivalent:
 - (a) The morphism $R: A \nrightarrow B$ is a corepresentably full morphism.
 - (b) For each pair of relations $S, T: X \nrightarrow A$, the following condition is satisfied:
 - (*) If $S \diamond R \subset T \diamond R$, then $S \subset T$.
 - (c) The functor

$$R^{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

is full.

- (d) For each $U, V \in \mathcal{P}(B)$, if $R^{-1}(U) \subset R^{-1}(V)$, then $U \subset V$.
- (e) The functor

$$R_{-1}: (\mathcal{P}(B), \subset) \rightarrow (\mathcal{P}(A), \subset)$$

is full.

- (f) For each $U, V \in \mathcal{P}(B)$, if $R_{-1}(U) \subset R_{-1}(V)$, then $U \subset V$.

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 **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 **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:

(\star) 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

(\star) 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:

(\star) 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

- (\star) 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

$$A \xrightarrow{\quad R \quad} B \rightrightarrows^S_T X,$$

and suppose that $S \diamond R \subset T \diamond R$. Note that, by assumption, given a diagram of the form

$$A \xrightarrow{\quad R \quad} B \rightrightarrows^U_V \text{pt},$$

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

$$A \xrightarrow{\quad R \quad} B \rightrightarrows^S_T X \xrightarrow{[x]} \text{pt},$$

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

$$A \xrightarrow{\quad R \quad} B \rightrightarrows^U_V \text{pt.}$$

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. \square

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].

5.3.11 Co/Limits in **Rel**

Proposition 5.3.11.1.1. This will be properly written later on.

Proof. Omitted. \square

5.3.12 Kan Extensions and Kan Lifts in **Rel**

Remark 5.3.12.1.1. The 2-category **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.

5.3.13 Closedness of **Rel**

Proposition 5.3.13.1.1. The 2-category **Rel** is a closed bicategory, there being, for each $R: A \dashrightarrow B$ and set X , a pair of adjunctions

$$\begin{aligned} (R^* \dashv \text{Ran}_R): \quad \text{Rel}(B, X) &\xrightleftharpoons[\text{Ran}_R]{\perp} \text{Rel}(A, X), \\ (R_* \dashv \text{Rift}_R): \quad \text{Rel}(X, A) &\xrightleftharpoons[\text{Rift}_R]{\perp} \text{Rel}(X, B), \end{aligned}$$

witnessed by bijections

$$\begin{aligned} \text{Rel}(S \diamond R, T) &\cong \text{Rel}(S, \text{Ran}_R(T)), \\ \text{Rel}(R \diamond U, V) &\cong \text{Rel}(U, \text{Rift}_R(V)), \end{aligned}$$

natural in $S \in \text{Rel}(B, X)$, $T \in \text{Rel}(A, X)$, $U \in \text{Rel}(X, A)$, and $V \in \text{Rel}(X, B)$.

Proof. This follows from Propositions 6.2.3.1.1 and 6.2.4.1.1. \square

5.3.14 \mathbf{Rel} as a Category of Free Algebras

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 \mathbf{Sets} .

Proof. Omitted. \square

5.4 The Left Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

5.4.1 The Left Skew Monoidal Product

Let A and B be sets and let $J: A \nrightarrow B$ be a relation.

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

$$S \triangleleft_J R \stackrel{\text{def}}{=} S \diamond \text{Rift}_J(R), \quad \begin{array}{ccc} & & A \xrightarrow[S]{+} B. \\ & \swarrow \text{Rift}_J(R) & \downarrow J \\ A & \xrightarrow[R]{+} B & \end{array}$$

- *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

$$\beta \triangleleft_J \alpha \stackrel{\text{def}}{=} \beta \diamond \text{Rift}_J(\alpha), \quad \begin{array}{ccc} & & S \\ & \nearrow \text{Rift}_J(R) & \downarrow \beta \\ & \nearrow \text{Rift}_J(\alpha) & \downarrow \\ & \nearrow \text{Rift}_J(R') & \downarrow \\ A & \xrightarrow[R]{+} B & \end{array}$$

¹⁴Since $\mathbf{Rel}(A, B)$ is posetal, this is to say that if $S \subset S'$ and $R \subset R'$, then

for each $\beta \in \text{Hom}_{\mathbf{Rel}(A, B)}(S, S')$ and each $\alpha \in \text{Hom}_{\mathbf{Rel}(A, B)}(R, R')$.

5.4.2 The Left Skew Monoidal Unit

Let A and B be sets and let $J: A \nrightarrow B$ be a relation.

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 $\mathbf{Rel}(A, B)$.

5.4.3 The Left Skew Associators

Let A and B be sets and let $J: A \nrightarrow B$ be a relation.

Definition 5.4.3.1.1. The **left J -skew associator of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\alpha^{\mathbf{Rel}(A, B), \triangleleft_J}: \triangleleft_J \circ (\triangleleft_J \times \text{id}) \Rightarrow \triangleleft_J \circ (\text{id} \times \triangleleft_J) \circ \alpha_{\mathbf{Rel}(A, B), \mathbf{Rel}(A, B), \mathbf{Rel}(A, B)}^{\text{Cats}},$$

as in the diagram

$$\begin{array}{ccc}
 & \mathbf{Rel}(A, B) \times (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) & \\
 & \swarrow \alpha_{\mathbf{Rel}(A, B), \mathbf{Rel}(A, B), \mathbf{Rel}(A, B)}^{\text{Cats}} \quad \searrow \text{id} \times \triangleleft_J & \\
 (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) \times \mathbf{Rel}(A, B) & \xrightarrow{\triangleleft_J \times \text{id}} & \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \\
 & \downarrow \alpha_{\mathbf{Rel}(A, B), \triangleleft_J}^{\mathbf{Rel}(A, B), \triangleleft_J} & \downarrow \triangleleft_J \\
 \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) & \xrightarrow{\triangleleft_J} & \mathbf{Rel}(A, B),
 \end{array}$$

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 $\epsilon: J \diamond \text{Rift}_J \Rightarrow \text{id}_{\mathbf{Rel}(A, B)}$ is the counit of the adjunction $J_* \dashv \text{Rift}_J$.

5.4.4 The Left Skew Left Unitors

Let A and B be sets and let $J: A \nrightarrow B$ be a relation.

Definition 5.4.4.1.1. The **left J -skew left unit of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\lambda^{\mathbf{Rel}(A, B), \triangleleft_J}: \triangleleft_J \circ (\mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A, B)} \times \text{id}) \Rightarrow \lambda_{\mathbf{Rel}(A, B)}^{\text{Cats}_2}$$

as in the diagram

$$\begin{array}{ccc} \text{pt} \times \mathbf{Rel}(A, B) & \xrightarrow{\mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A, B)} \times \text{id}} & \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \\ & \searrow \lambda^{\mathbf{Rel}(A, B), \triangleleft_J} \quad \swarrow & \downarrow \triangleleft_J \\ & \text{Cats}_2^{\mathbf{Rel}(A, B)} & \mathbf{Rel}(A, B), \end{array}$$

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 $\epsilon: J_* \diamond \text{Rift}_J \Rightarrow \text{id}_{\mathbf{Rel}(A, B)}$ is the counit of the adjunction $J_* \dashv \text{Rift}_J$.

5.4.5 The Left Skew Right Unitors

Let A and B be sets and let $J: A \nrightarrow B$ be a relation.

Definition 5.4.5.1.1. The **left J -skew right unit of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\rho^{\mathbf{Rel}(A, B), \triangleleft_J} : \rho_{\mathbf{Rel}(A, B)}^{\mathrm{Cats}_2} \Rightarrow \triangleleft_J \circ (\mathrm{id} \times \mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A, B)})$$

as in the diagram

$$\begin{array}{ccc} \mathbf{Rel}(A, B) \times \mathrm{pt} & \xrightarrow{\mathrm{id} \times \mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A, B)}} & \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B), \\ & \swarrow \rho^{\mathbf{Rel}(A, B), \triangleleft_J} \quad \searrow & \downarrow \triangleleft_J \\ & \xrightarrow{\rho_{\mathbf{Rel}(A, B)}^{\mathrm{Cats}_2}} & \mathbf{Rel}(A, B) \end{array}$$

whose component

$$\rho_R^{\mathbf{Rel}(A, B), \triangleleft_J} : R \hookrightarrow \underbrace{R \triangleleft_J J}_{\stackrel{\mathrm{def}}{=} R \diamond \mathrm{Rift}_J(J)}$$

at R is given by the composition

$$\begin{aligned} R &\xrightarrow{\sim} R \diamond \chi_A \\ &\xrightarrow{\mathrm{id}_R \diamond \eta_{\chi_A}} R \diamond \mathrm{Rift}_J(J_*(\chi_A)) \\ &\stackrel{\mathrm{def}}{=} R \diamond \mathrm{Rift}_J(J \diamond \chi_A) \\ &\xrightarrow{\sim} R \diamond \mathrm{Rift}_J(J) \\ &\stackrel{\mathrm{def}}{=} R \triangleleft_J J, \end{aligned}$$

where $\eta : \mathrm{id}_{\mathbf{Rel}(A, A)} \Rightarrow \mathrm{Rift}_J \circ J_*$ is the unit of the adjunction $J_* \dashv \mathrm{Rift}_J$.

5.4.6 The Left Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

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 5.1.1.3.
- *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

$$\mathbb{1}^{\mathbf{Rel}(A, B), \triangleleft_J} : \mathbf{pt} \rightarrow \mathbf{Rel}(A, B)$$

of Definition 5.4.2.1.1.

- *The Left Skew Associators.* The natural transformation

$$\alpha^{\mathbf{Rel}(A, B), \triangleleft_J} : \triangleleft_J \circ (\triangleleft_J \times \mathbf{id}) \Rightarrow \triangleleft_J \circ (\mathbf{id} \times \triangleleft_J) \circ \alpha_{\mathbf{Rel}(A, B), \mathbf{Rel}(A, B), \mathbf{Rel}(A, B)}^{\mathbf{Cats}}$$

of Definition 5.4.3.1.1.

- *The Left Skew Left Unitors.* The natural transformation

$$\lambda^{\mathbf{Rel}(A, B), \triangleleft_J} : \triangleleft_J \circ (\mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A, B)} \times \mathbf{id}) \Rightarrow \lambda_{\mathbf{Rel}(A, B)}^{\mathbf{Cats}_2}$$

of Definition 5.4.4.1.1.

- *The Left Skew Right Unitors.* The natural transformation

$$\rho^{\mathbf{Rel}(A, B), \triangleleft_J} : \rho_{\mathbf{Rel}(A, B)}^{\mathbf{Cats}_2} \Rightarrow \triangleleft_J \circ (\mathbf{id} \times \mathbb{1}_{\triangleleft_J}^{\mathbf{Rel}(A, B)})$$

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

5.5 The Right Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

Let A and B be sets and let $J : A \rightarrow B$ be a relation.

5.5.1 The Right Skew Monoidal Product

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

$$S \triangleleft_J R \subset S' \triangleleft_J R'.$$

- *Action on Objects.* For each $R, S \in \text{Obj}(\mathbf{Rel}(A, B))$, we have

$$A \xrightarrow{R} B \xrightarrow{\text{Ran}_J(S)} B.$$

$S \triangleright_J R \stackrel{\text{def}}{=} \text{Ran}_J(S) \diamond R,$

- *Action on Morphisms.* For each $R, S, R', S' \in \text{Obj}(\mathbf{Rel}(A, B))$, the action on Hom-sets

$$(\triangleright_J)_{(S, R), (S', R')} : \text{Hom}_{\mathbf{Rel}(A, B)}(S, S') \times \text{Hom}_{\mathbf{Rel}(A, B)}(R, R') \rightarrow \text{Hom}_{\mathbf{Rel}(A, B)}(S \triangleright_J R, S' \triangleright_J R')$$

of \triangleright_J at $((S, R), (S', R'))$ is defined by¹⁵

$$\beta \triangleright_J \alpha \stackrel{\text{def}}{=} \text{Ran}_J(\beta) \diamond \alpha,$$

for each $\beta \in \text{Hom}_{\mathbf{Rel}(A, B)}(S, S')$ and each $\alpha \in \text{Hom}_{\mathbf{Rel}(A, B)}(R, R')$.

5.5.2 The Right Skew Monoidal Unit

Definition 5.5.2.1.1. The **right J -skew monoidal unit of $\mathbf{Rel}(A, B)$** is the functor

$$\mathbb{1}_{\triangleright_J}^{\mathbf{Rel}(A, B)} : \text{pt} \rightarrow \mathbf{Rel}(A, B)$$

picking the object

$$\mathbb{1}_{\mathbf{Rel}(A, B)}^{\triangleright_J} \stackrel{\text{def}}{=} J$$

of $\mathbf{Rel}(A, B)$.

5.5.3 The Right Skew Associators

Definition 5.5.3.1.1. The **right J -skew associator of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\alpha^{\mathbf{Rel}(A, B), \triangleright_J} : \triangleright_J \circ (\text{id} \times \triangleright_J) \Longrightarrow \triangleright_J \circ (\triangleright_J \times \text{id}) \circ \alpha_{\mathbf{Rel}(A, B), \mathbf{Rel}(A, B), \mathbf{Rel}(A, B)}^{\text{Cats}, -1},$$

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

$$\begin{array}{ccc}
 & (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) \times \mathbf{Rel}(A, B) & \\
 \alpha_{\mathbf{Rel}(A, B), \mathbf{Rel}(A, B), \mathbf{Rel}(A, B)}^{\mathbf{Cats}, -1} \swarrow & \nearrow \curvearrowright & \searrow \triangleright_J \times \text{id} \\
 \mathbf{Rel}(A, B) \times (\mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B)) \times \mathbf{Rel}(A, B) & & \\
 \downarrow \text{id} \times \triangleright_J & \alpha_{\mathbf{Rel}(A, B), \triangleright_J}^{\mathbf{Rel}(A, B), \triangleright_J} \swarrow & \downarrow \triangleright_J \\
 \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) & & \\
 \downarrow \triangleright_J & &
 \end{array}$$

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 $\epsilon : \text{Ran}_J \diamond J \Rightarrow \text{id}_{\mathbf{Rel}(A, B)}$ is the counit of the adjunction $J^* \dashv \text{Ran}_J$.

5.5.4 The Right Skew Left Unitors

Definition 5.5.4.1.1. The **right J -skew left unit of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\lambda^{\mathbf{Rel}(A, B), \triangleright_J} : \boldsymbol{\lambda}_{\mathbf{Rel}(A, B)}^{\mathbf{Cats}_2} \Rightarrow \triangleright_J \circ (\mathbb{1}_{\triangleright}^{\mathbf{Rel}(A, B)} \times \text{id}),$$

as in the diagram

$$\begin{array}{ccc}
 \text{pt} \times \mathbf{Rel}(A, B) & \xrightarrow{\mathbb{1}_{\triangleright_J}^{\mathbf{Rel}(A, B)} \times \text{id}} & \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \\
 & \searrow \lambda_{\mathbf{Rel}(A, B)}^{\mathbf{Cats}_2} & \downarrow \triangleright_J \\
 & \nearrow \lambda_{\mathbf{Rel}(A, B), \triangleright_J}^{\mathbf{Rel}(A, B)} & \\
 & \dashrightarrow \mathbf{Rel}(A, B), &
 \end{array}$$

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

$$\begin{aligned}
 R &\xrightarrow{\sim} \chi_B \diamond R \\
 &\xrightarrow{\eta \chi_B} \text{id}_{\mathbf{Ran}_J(J^*(\chi_A))} \diamond R \\
 &\stackrel{\text{def}}{=} \text{Ran}_J(J^* \diamond \chi_A) \diamond R \\
 &\xrightarrow{\sim} \text{Ran}_J(J) \diamond R \\
 &\stackrel{\text{def}}{=} R \triangleright_J J,
 \end{aligned}$$

where $\eta: \text{id}_{\mathbf{Rel}(B, B)} \Rightarrow \text{Ran}_J \circ J^*$ is the unit of the adjunction $J^* \dashv \text{Ran}_J$.

5.5.5 The Right Skew Right Unitors

Definition 5.5.5.1.1. The **right J -skew right unitor** of $\mathbf{Rel}(A, B)$ is the natural transformation

$$\rho^{\mathbf{Rel}(A, B), \triangleright_J}: \triangleright_J \circ (\text{id} \times \mathbb{1}_{\triangleright}^{\mathbf{Rel}(A, B)}) \Rightarrow \rho_{\mathbf{Rel}(A, B)}^{\mathbf{Cats}_2},$$

as in the diagram

$$\begin{array}{ccc}
 \mathbf{Rel}(A, B) \times \text{pt} & \xrightarrow{\text{id} \times \mathbb{1}_{\triangleright_J}^{\mathbf{Rel}(A, B)}} & \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B), \\
 & \searrow \rho_{\mathbf{Rel}(A, B)}^{\mathbf{Cats}_2} & \downarrow \triangleright_J \\
 & \nearrow \rho_{\mathbf{Rel}(A, B), \triangleright_J}^{\mathbf{Rel}(A, B)} & \\
 & \dashrightarrow \mathbf{Rel}(A, B) &
 \end{array}$$

whose component

$$\rho_S^{\mathbf{Rel}(A, B), \triangleright_J} : \underbrace{S \triangleright_J J}_{\stackrel{\text{def}}{=} \text{Ran}_J(S) \diamond J} \hookrightarrow S$$

at S is given by

$$\rho_S^{\mathbf{Rel}(A, B), \triangleright_J} \stackrel{\text{def}}{=} \epsilon_R,$$

where $\epsilon : J^* \circ \text{Ran}_J \Longrightarrow \text{id}_{\mathbf{Rel}(A, B)}$ is the counit of the adjunction $J^* \dashv \text{Ran}_J$.

5.5.6 The Right Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

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 5.1.1.3.
- *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

$$\alpha^{\mathbf{Rel}(A, B), \triangleright_J} : \triangleright_J \circ (\text{id} \times \triangleright_J) \Longrightarrow \triangleright_J \circ (\triangleright_J \times \text{id}) \circ \alpha_{\mathbf{Rel}(A, B), \mathbf{Rel}(A, B), \mathbf{Rel}(A, B)}^{\text{Cats}, -1}$$

of Definition 5.5.3.1.1.

- *The Right Skew Left Unitors.* The natural transformation

$$\lambda^{\mathbf{Rel}(A, B), \triangleright_J} : \lambda_{\mathbf{Rel}(A, B)}^{\text{Cats}_2} \Longrightarrow \triangleright_J \circ (\mathbb{1}_{\triangleright}^{\mathbf{Rel}(A, B)} \times \text{id})$$

of Definition 5.5.4.1.1.

- *The Right Skew Right Unitors.* The natural transformation

$$\rho^{\mathbf{Rel}(A, B), \triangleright_J} : \triangleright_J \circ (\text{id} \times \mathbb{1}_{\triangleright}^{\mathbf{Rel}(A, B)}) \Longrightarrow \rho_{\mathbf{Rel}(A, B)}^{\text{Cats}_2}$$

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

Constructions With 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

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

$$R_* \dashv R_{-1} : \mathcal{P}(A) \rightleftarrows \mathcal{P}(B), \\ R^{-1} \dashv R_! : \mathcal{P}(B) \rightleftarrows \mathcal{P}(A)$$

of functors (morphisms of posets) between $\mathcal{P}(A)$ and $\mathcal{P}(B)$ induced by a relation $R: A \nrightarrow B$, 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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6.1 Co/Limits in the Category of Relations

This section is currently just a stub, and will be properly developed later on.

6.2 Kan Extensions and Kan Lifts in the 2-Category of Relations

6.2.1 Left Kan Extensions in **Rel**

Proposition 6.2.1.1.1. Let $R: A \nrightarrow B$ be a relation.

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.* 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 Campion's answer](#) to [\[MO 460656\]](#). \square

Question 6.2.1.1.2. Given relations $S: A \nrightarrow X$ and $R: A \nrightarrow B$, is there a characterisation of when the left Kan extension

$$\text{Lan}_S(R): B \nrightarrow X$$

exists in terms of properties of R and S ?

This question also appears as [\[MO 461592\]](#).

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 [\[MO 461592\]](#).

6.2.2 Left Kan Lifts in **Rel**

Proposition 6.2.2.1.1. Let $R: A \nrightarrow B$ be a relation.

1. *Non-Existence of All Left Kan Lifts in **Rel**.* Not all relations in **Rel** admit left Kan lifts.
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 Campion's answer to](#) to [[MO 460656](#)]. \square

Question 6.2.2.1.2. Given relations $S: A \nrightarrow X$ and $R: A \nrightarrow B$, is there a characterisation of when the left Kan lift

$$\text{Lift}_S(R): X \nrightarrow A$$

exists in terms of properties of R and S ?

This question also appears as [[MO 461592](#)].

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 $R: A \nrightarrow B$ be a relation.

Proposition 6.2.3.1.1. The right Kan extension

$$\text{Ran}_R: \text{Rel}(A, X) \rightarrow \text{Rel}(B, X)$$

along R in **Rel** exists and is given by

$$\text{Ran}_R(S) \stackrel{\text{def}}{=} \int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^{-2}, S_a^{-1})$$

for each $S \in \text{Rel}(A, X)$, 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

$$\begin{aligned} \text{Hom}_{\text{Rel}(A, X)}(S \diamond R, T) &\cong \int_{a \in A} \int_{x \in X} \mathbf{Hom}_{\{\text{t}, \text{f}\}}((S \diamond R)_a^x, T_a^x) \\ &\cong \int_{a \in A} \int_{x \in X} \mathbf{Hom}_{\{\text{t}, \text{f}\}}\left(\left(\int^{b \in B} S_b^x \times R_a^b\right), T_a^x\right) \\ &\cong \int_{a \in A} \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(S_b^x \times R_a^b, T_a^x) \\ &\cong \int_{a \in A} \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(S_b^x, \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, T_a^x)) \\ &\cong \int_{b \in B} \int_{x \in X} \int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(S_b^x, \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, T_a^x)) \\ &\cong \int_{b \in B} \int_{x \in X} \mathbf{Hom}_{\{\text{t}, \text{f}\}}\left(S_b^x, \int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, T_a^x)\right) \\ &\cong \text{Hom}_{\text{Rel}(B, X)}\left(S, \int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^{-2}, T_a^{-1})\right) \end{aligned}$$

naturally in each $S \in \text{Rel}(B, X)$ and each $T \in \text{Rel}(A, X)$, showing that

$$\int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^{-2}, T_a^{-1})$$

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 5.1.1.5.
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 5.1.1.5.

This finishes the proof. \square

6.2.4 Right Kan Lifts in **Rel**

Let $R: A \nrightarrow B$ be a relation.

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

$$\text{Rift}_R(S) \stackrel{\text{def}}{=} \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_{-1}^b, S_{-2}^b)$$

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

$$\begin{aligned} \text{Hom}_{\text{Rel}(X, B)}(R \diamond S, T) &\cong \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}((R \diamond S)_x^b, T_x^b) \\ &\cong \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}\left(\left(\int^{a \in A} R_a^b \times S_x^a, T_x^b\right)\right) \\ &\cong \int_{x \in X} \int_{b \in B} \int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^b \times S_x^a, T_x^b) \\ &\cong \int_{x \in X} \int_{b \in B} \int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(S_x^a, \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, T_x^b)) \\ &\cong \int_{x \in X} \int_{a \in A} \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(S_x^a, \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, T_x^b)) \\ &\cong \int_{x \in X} \int_{a \in A} \mathbf{Hom}_{\{\text{t}, \text{f}\}}\left(S_x^a, \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, T_x^b)\right) \\ &\cong \text{Hom}_{\text{Rel}(X, A)}\left(S, \int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_{-1}^b, T_{-2}^b)\right) \end{aligned}$$

naturally in each $S \in \text{Rel}(X, A)$ and each $T \in \text{Rel}(X, B)$, showing that

$$\int_{b \in B} \mathbf{Hom}_{\{\text{t}, \text{f}\}}(R_{-1}^b, S_{-2}^b)$$

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. \square

6.3 More Constructions With Relations

6.3.1 The Graph of a Function

Let $f: A \rightarrow B$ be a function.

Definition 6.3.1.1.1. The **graph of f** is the relation $\text{Gr}(f): A \nrightarrow B$ 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 $(a, b) \in A \times B$.

- 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

$$A \xrightarrow{f} B \xrightarrow{\chi_B} \mathcal{P}(B).$$

Proposition 6.3.1.1.2. Let $f: A \rightarrow B$ be a function.

¹Further Notation: We write $\text{Gr}(A)$ for $\text{Gr}(\text{id}_A)$, and call it the **graph** of A .

1. *Functionality.* The assignment $A \mapsto \text{Gr}(A)$ defines a functor

$$\text{Gr}: \mathbf{Sets} \rightarrow \mathbf{Rel}$$

where

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

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

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

$$\text{Gr}_{A,B}: \mathbf{Sets}(A, B) \rightarrow \underbrace{\text{Rel}(\text{Gr}(A), \text{Gr}(B))}_{\text{def} \text{Rel}(A, B)}$$

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

- *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 $g: B \rightarrow C$.

2. *Adjointness Inside \mathbf{Rel} .* We have an adjunction

$$(\text{Gr}(f) \dashv f^{-1}): \quad \begin{array}{ccc} & \text{Gr}(f) & \\ A & \begin{array}{c} \xrightarrow{\quad} \\ \perp \\ \xleftarrow{\quad} \\ f^{-1} \end{array} & B \end{array}$$

in \mathbf{Rel} , where f^{-1} is the inverse of f of [Definition 6.3.2.1.1](#).

3. *Adjointness.* We have an adjunction

$$(\text{Gr} \dashv \mathcal{P}_*): \quad \begin{array}{ccc} & \text{Gr} & \\ \mathbf{Sets} & \begin{array}{c} \xrightarrow{\quad} \\ \perp \\ \xleftarrow{\quad} \\ \mathcal{P}_* \end{array} & \mathbf{Rel}, \end{array}$$

witnessed by a bijection of sets

$$\text{Rel}(\text{Gr}(A), B) \cong \mathbf{Sets}(A, \mathcal{P}(B))$$

natural in $A \in \text{Obj}(\mathbf{Sets})$ and $B \in \text{Obj}(\mathbf{Rel})$.

4. *Interaction With Inverses.* We have

$$\begin{aligned}\mathrm{Gr}(f)^\dagger &= f^{-1}, \\ (f^{-1})^\dagger &= \mathrm{Gr}(f).\end{aligned}$$

5. *Cocontinuity.* The functor $\mathrm{Gr}: \mathrm{Sets} \rightarrow \mathrm{Rel}$ of [Item 1](#) preserves colimits.

6. *Characterisations.* Let $R: A \nrightarrow B$ be a relation. The following conditions are equivalent:

- (a) There exists a function $f: A \rightarrow B$ such that $R = \mathrm{Gr}(f)$.
- (b) The relation R is total and functional.
- (c) The weak and strong inverse images of R agree, i.e. we have $R^{-1} = R_{-1}$.
- (d) The relation R has a right adjoint R^\dagger in Rel .

Proof. [Item 1](#), *Functionality:* Clear.

[Item 2](#), *Adjointness Inside Rel:* We need to check that there are inclusions

$$\begin{aligned}\chi_A &\subset f^{-1} \diamond \mathrm{Gr}(f), \\ \mathrm{Gr}(f) \diamond f^{-1} &\subset \chi_B.\end{aligned}$$

These correspond respectively to the following conditions:

- 1. For each $a \in A$, there exists some $b \in B$ such that $a \sim_{\mathrm{Gr}(f)} b$ and $b \sim_{f^{-1}} a$.
- 2. For each $a, b \in A$, if $a \sim_{\mathrm{Gr}(f)} b$ 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

6.3.2 The Inverse of a Function

Let $f: A \rightarrow B$ be a function.

Definition 6.3.2.1.1. The **inverse of f** is the relation $f^{-1}: B \nrightarrow A$ defined as follows:

- Viewing relations from B to A as subsets of $B \times A$, we define

$$f^{-1} \stackrel{\text{def}}{=} \left\{ (b, f^{-1}(b)) \in B \times A \mid a \in A \right\},$$

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 $b \in B$.

Proposition 6.3.2.1.2. Let $f: A \rightarrow B$ be a function.

1. *Functoriality.* The assignment $A \mapsto A$, $f \mapsto f^{-1}$ defines a functor

$$(-)^{-1}: \mathbf{Sets} \rightarrow \mathbf{Rel}$$

where

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

$$[(-)^{-1}](A) \stackrel{\text{def}}{=} A.$$

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

$$(-)^{-1}_{A,B}: \mathbf{Sets}(A, B) \rightarrow \mathbf{Rel}(A, B)$$

of $(-)^{-1}$ at (A, B) is defined by

$$(-)^{-1}_{A,B}(f) \stackrel{\text{def}}{=} [(-)^{-1}](f),$$

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

- *Preservation of Composition.* We have

$$(g \circ f)^{-1} = g^{-1} \diamond f^{-1}$$

for pair of functions $f: A \rightarrow B$ and $g: B \rightarrow C$.

2. *Adjointness Inside \mathbf{Rel} .* We have an adjunction

$$(\text{Gr}(f) \dashv f^{-1}): \quad A \begin{array}{c} \xrightarrow{\text{Gr}(f)} \\[-1ex] \perp \\[-1ex] \xleftarrow{f^{-1}} \end{array} B$$

in \mathbf{Rel} .

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 \mathbf{Rel} : This is proved in **Item 2** of **Proposition 6.3.1.1.2**.

Item 3, Interaction With Inverses of Relations: Clear. \square

6.3.3 Representable Relations

Let A and B be sets.

Definition 6.3.3.1.1. Let $f: A \rightarrow B$ and $g: B \rightarrow A$ be functions.²

1. The **representable relation associated to f** is the relation $\chi_f: A \nrightarrow B$ 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 $\chi^g: B \nrightarrow A$ 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 $g(b) = a$.

6.3.4 The Domain and Range of a Relation

Let A and B be sets.

²More generally, given functions

$$\begin{aligned} f: A &\rightarrow C, \\ g: B &\rightarrow D \end{aligned}$$

and a relation $B \nrightarrow D$, 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 $f(a) \sim_R g(b)$.

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

$$\text{dom}(R) \stackrel{\text{def}}{=} \left\{ a \in A \mid \begin{array}{l} \text{there exists some } b \in B \\ \text{such that } a \sim_R b \end{array} \right\}.$$

2. The **range of R** is the subset $\text{range}(R)$ of B defined by

$$\text{range}(R) \stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{there exists some } a \in A \\ \text{such that } a \sim_R b \end{array} \right\}.$$

6.3.5 Binary Unions of Relations

Let A and B be sets and let R and S be relations from A to B .

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

$$R \cup S \stackrel{\text{def}}{=} \{(a, b) \in B \times A \mid \text{we have } a \sim_R b \text{ or } a \sim_S b\}.$$

³Following ??, we may compute the (characteristic functions associated to the) domain and range of a relation using the following colimit formulas:

$$\begin{aligned} \chi_{\text{dom}(R)}(a) &\cong \text{colim}_{b \in B}(R_a^b) \quad (a \in A) \\ &\cong \bigvee_{b \in B} R_a^b, \\ \chi_{\text{range}(R)}(b) &\cong \text{colim}_{a \in A}(R_a^b) \quad (b \in B) \\ &\cong \bigvee_{a \in A} R_a^b, \end{aligned}$$

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

$$\begin{aligned} \text{dom}(R) &\cong \text{colim}_{y \in Y}(R(y)) \\ &\cong \bigcup_{y \in Y} R(y), \\ \text{range}(R) &\cong \text{colim}_{x \in X}(R(x)) \\ &\cong \bigcup_{x \in X} R(x), \end{aligned}$$

⁵Further 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 $A \times B$.

- 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 $a \in A$.

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 .

1. *Interaction With Inverses.* We have

$$(R \cup S)^\dagger = R^\dagger \cup S^\dagger.$$

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

- i. $a \sim_{R_2} b$ 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:

- i. $a \sim_{R_1} b$ or $a \sim_{R_2} b$;

and

- i. $b \sim_{S_1} c$ 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

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 .

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 $a \in A$.

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 .

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. □

6.3.7 Binary Intersections of Relations

Let A and B be sets and let R and S be relations from A to B .

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

$$R \cap S \stackrel{\text{def}}{=} \{(a, b) \in B \times A \mid \text{we have } a \sim_R b \text{ and } a \sim_S b\}.$$

- 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 $a \in A$.

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 .

⁷This is the same as the union of $\{R_i\}_{i \in I}$ as a collection of subsets of $A \times B$.

⁸Further 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 $A \times B$.

1. *Interaction With Inverses.* We have

$$(R \cap S)^\dagger = R^\dagger \cap S^\dagger.$$

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

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

$$\bigcup_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a, b) \in (A \times B)^{\times I} \mid \begin{array}{l} \text{for each } i \in I, \\ \text{we have } a \sim_{R_i} b \end{array} \right\}.$$

¹⁰This is the same as the intersection of $\{R_i\}_{i \in I}$ as a collection of subsets of $A \times B$.

- 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 $a \in A$.

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 .

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. \square

6.3.9 Binary Products of Relations

Let A , B , X , and Y be sets, let $R: A \nrightarrow B$ be a relation from A to B , and let $S: X \nrightarrow Y$ be a relation from X to Y .

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
- 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 $(a, x) \in A \times X$.

Proposition 6.3.9.1.2. Let A , B , X , and Y be sets.

¹¹Further 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 $x \sim_S y$.

1. *Interaction With Inverses.* Let

$$\begin{aligned} R: A &\not\rightarrow A, \\ S: X &\not\rightarrow X \end{aligned}$$

We have

$$(R \times S)^\dagger = R^\dagger \times S^\dagger.$$

2. *Interaction With Composition.* Let

$$\begin{aligned} R_1: A &\not\rightarrow B, \\ S_1: B &\not\rightarrow C, \\ R_2: X &\not\rightarrow Y, \\ S_2: Y &\not\rightarrow Z \end{aligned}$$

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 $(a, x) \sim_{(S_1 \diamond R_1) \times (S_2 \diamond R_2)} (c, z)$ iff:
 - (a) We have $a \sim_{S_1 \diamond R_1} c$ and $x \sim_{S_2 \diamond R_2} z$, 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 $(a, x) \sim_{(S_1 \times S_2) \diamond (R_1 \times R_2)} (c, z)$ 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

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 $\{R_i : A_i \nrightarrow B_i\}_{i \in I}$ be a family of relations.

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

$$\prod_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a_i, b_i)_{i \in I} \in \prod_{i \in I} (A_i \times B_i) \mid \begin{array}{l} \text{for each } i \in I, \\ \text{we have } a_i \sim_{R_i} b_i \end{array} \right\}.$$

- 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 $(a_i)_{i \in I} \in \prod_{i \in I} R_i$.

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.

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

$$R^\dagger \stackrel{\text{def}}{=} \{(b, a) \in B \times A \mid \text{we have } b \sim_R a\}.$$

¹³Further Terminology: Also called the **opposite of R** , the **transpose of R** , or the **converse of R** .

- 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 $\{b\}$.

Example 6.3.11.1.2. Here are some examples of inverses of relations.

1. *Less Than Equal Signs.* We have $(\leq)^\dagger = \geq$.
2. *Greater Than Equal Signs.* Dually to [Item 1](#), we have $(\geq)^\dagger = \leq$.
3. *Functions.* Let $f: A \rightarrow B$ be a function. We have

$$\begin{aligned} \text{Gr}(f)^\dagger &= f^{-1}, \\ (f^{-1})^\dagger &= \text{Gr}(f). \end{aligned}$$

Proposition 6.3.11.1.3. Let $R: A \nrightarrow B$ and $S: B \nrightarrow C$ be relations.

1. *Functionality.* 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 $R, S: A \nrightarrow B$, we have:

(*) If $R \subset S$, then $R^\dagger \subset S^\dagger$.

2. *Interaction With Ranges and Domains.* We have

$$\begin{aligned} \text{dom}(R^\dagger) &= \text{range}(R), \\ \text{range}(R^\dagger) &= \text{dom}(R). \end{aligned}$$

3. *Interaction With Composition I.* We have

$$(S \diamond R)^\dagger = R^\dagger \diamond S^\dagger.$$

4. *Interaction With Composition II.* We have

$$\begin{aligned} \chi_B &\subset R \diamond R^\dagger, \\ \chi_A &\subset R^\dagger \diamond R. \end{aligned}$$

5. *Invertibility.* We have

$$(R^\dagger)^\dagger = R.$$

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. \square

6.3.12 Composition of Relations

Let A , B , and C be sets and let $R: A \nrightarrow B$ and $S: B \nrightarrow C$ be relations.

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

$$S \diamond R \stackrel{\text{def}}{=} \left\{ (a, c) \in A \times C \mid \begin{array}{l} \text{there exists some } b \in B \text{ such} \\ \text{that } a \sim_R b \text{ and } b \sim_S c \end{array} \right\}.$$

- Viewing relations as functions $A \times B \rightarrow \{\text{true}, \text{false}\}$, we define

$$\begin{aligned} (S \diamond R)^{-1}_{-2} &\stackrel{\text{def}}{=} \int^{b \in B} S_b^{-1} \times R_{-2}^b \\ &= \bigvee_{b \in B} S_b^{-1} \times R_{-2}^b, \end{aligned}$$

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

$$\begin{aligned} S \diamond R &\stackrel{\text{def}}{=} \text{Lan}_{\chi_B}(S) \circ R, & B &\xrightarrow{S} \mathcal{P}(C), \\ && \chi_B \downarrow & \swarrow \nearrow \text{Lan}_{\chi_B}(S) \\ A &\xrightarrow[R]{} \mathcal{P}(B) & & \end{aligned}$$

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 $a \in A$.

Example 6.3.12.1.2. Here are some examples of composition of relations.

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

$$\begin{aligned} \leq \diamond \leq &= \leq, \\ \geq \diamond \geq &= \geq. \end{aligned}$$

Proposition 6.3.12.1.3. Let $R: A \nrightarrow B$, $S: B \nrightarrow C$, and $T: C \nrightarrow D$ be relations.

1. *Interaction With Ranges and Domains.* We have

$$\begin{aligned} \text{dom}(S \diamond R) &\subset \text{dom}(R), \\ \text{range}(S \diamond R) &\subset \text{range}(S). \end{aligned}$$

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 .

2. *Associativity.* We have

$$(T \diamond S) \diamond R = T \diamond (S \diamond R).$$

3. *Unitality.* We have

$$\begin{aligned}\chi_B \diamond R &= R, \\ R \diamond \chi_A &= R.\end{aligned}$$

4. *Interaction With Inverses.* We have

$$(S \diamond R)^\dagger = R^\dagger \diamond S^\dagger.$$

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:
- We have $b \sim_S c$;
 - 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:
- We have $a \sim_{S \diamond R} c$, i.e. there exists some $b \in B$ such that:
 - We have $a \sim_R b$;
 - We have $b \sim_S c$;
 - 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. □

6.3.13 The Collage of a Relation

Let A and B be sets and let $R: A \nrightarrow B$ be a relation from A to B .

Definition 6.3.13.1.1. The **collage** of R ¹⁵ is the poset $\text{Coll}(R) \stackrel{\text{def}}{=} (\text{Coll}(R), \preceq_{\text{Coll}(R)})$ consisting of:

- *The Underlying Set.* The set $\text{Coll}(R)$ defined by

$$\text{Coll}(R) \stackrel{\text{def}}{=} A \coprod B.$$

- *The Partial Order.* The partial order

$$\preceq_{\text{Coll}(R)}: \text{Coll}(R) \times \text{Coll}(R) \rightarrow \{\text{true}, \text{false}\}$$

on $\text{Coll}(R)$ defined by

$$\preceq(a, b) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } a = b \text{ or } a \sim_R b, \\ \text{false} & \text{otherwise.} \end{cases}$$

Proposition 6.3.13.1.2. Let A and B be sets and let $R: A \nrightarrow B$ be a relation from A to B .

¹⁵Further Terminology: Also called the **cograph** of R .

1. *Functoriality I.* The assignment $R \mapsto \mathbf{Coll}(R)$ defines a functor¹⁶

$$\mathbf{Coll}: \mathbf{Rel}(A, B) \rightarrow \mathbf{Pos}_{/\Delta^1}(A, B),$$

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

$$\mathbf{Coll}_{R,S}: \text{Hom}_{\mathbf{Rel}(A, B)}(R, S) \rightarrow \mathbf{Pos}(\mathbf{Coll}(R), \mathbf{Coll}(S))$$

of \mathbf{Coll} at (R, S) is given by sending an inclusion

$$\iota: R \subset S$$

¹⁶Here $\mathbf{Pos}_{/\Delta^1}(A, B)$ is the category defined as the pullback

$$\mathbf{Pos}_{/\Delta^1}(A, B) \stackrel{\text{def}}{=} \underset{[A], \mathbf{Pos}, \text{fib}_0}{\text{pt}} \times_{\underset{\text{fib}_1, \mathbf{Pos}, [B]}{\text{pt}}} \mathbf{Pos}_{/\Delta^1}$$

as in the diagram

$$\begin{array}{ccccc} & & \mathbf{Pos}_{/\Delta^1}(A, B) & & \\ & \swarrow & & \searrow & \\ \mathbf{Pos}_{/\Delta^1} \times_{\mathbf{Pos}} \text{pt} & & & \text{pt} \times_{\mathbf{Pos}} \mathbf{Pos}_{/\Delta^1} & \\ \swarrow & \searrow & & \swarrow & \searrow \\ \text{pt} & & \mathbf{Pos}_{/\Delta^1} & & \text{pt.} \\ \searrow & \swarrow & \searrow & \swarrow & \searrow \\ [A] & & \mathbf{Pos} & & [B] \\ & \text{fib}_{[0]} & & \text{fib}_{[1]} & \end{array}$$

Explicitly, an object of $\mathbf{Pos}_{/\Delta^1}(A, B)$ is a pair (X, ϕ_X) consisting of

- A poset X ;
- A morphism $\phi_X: X \rightarrow \Delta^1$;

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

2. *Equivalence.* The functor of [Item 1](#) is an equivalence of categories.

Proof. [Item 1](#), *Functoriality:* Clear.

[Item 2](#), *Equivalence:* Omitted. \square

6.4 Functoriality of Powersets

6.4.1 Direct Images

Let A and B be sets and let $R: A \nrightarrow B$ be a relation.

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 $U \in \mathcal{P}(A)$.

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

$$R_*: \underbrace{\mathcal{P}(A)}_{\cong \text{Rel(pt, } A)} \rightarrow \underbrace{\mathcal{P}(B)}_{\cong \text{Rel(pt, } B)}$$

such that $\phi_X^{-1}(0) = A$ and $\phi_X^{-1}(0) = B$, 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 $x \preceq_{\mathbf{Coll}(S)} y$.

¹⁸Further Terminology: The set $R(U)$ is called the **direct image of U by R** .

¹⁹We also have

$$R_*(U) = B \setminus R_!(A \setminus U);$$

defined by

$$R_*(U) \stackrel{\text{def}}{=} R \diamond U$$

for each $U \in \mathcal{P}(A)$, where $R \diamond U$ is the composition

$$\text{pt} \xrightarrow{U} A \xrightarrow{R} B.$$

Proposition 6.4.1.1.3. Let $R: A \nrightarrow B$ be a relation.

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 $R_*(U) \subset R_*(V)$.

2. *Adjointness.* We have an adjunction

$$(R_* \dashv R_{-1}): \quad \mathcal{P}(A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{R_{-1}} \end{array} \mathcal{P}(B),$$

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 $U \subset R_{-1}(V)$.

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 $U, V \in \mathcal{P}(A)$.

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 $U, V \in \mathcal{P}(A)$.

5. *Symmetric Strict Monoidality With Respect to Unions.* The direct image function of [Item 1](#) has a symmetric strict monoidal structure

$$(R_*, R_*^\otimes, R_{*|1}^\otimes) : (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} R_{*|U,V}^\otimes : R_*(U) \cup R_*(V) &\xrightarrow{\sim} R_*(U \cup V), \\ R_{*|1}^\otimes : \emptyset &\xrightarrow{\sim} \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

6. *Symmetric Oplax Monoidality With Respect to Intersections.* The direct image function of [Item 1](#) has a symmetric oplax monoidal structure

$$(R_*, R_*^\otimes, R_{*|1}^\otimes) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} R_{*|U,V}^\otimes : R_*(U \cap V) &\subset R_*(U) \cap R_*(V), \\ R_{*|1}^\otimes : R_*(A) &\subset B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

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.

see [Item 7 of Proposition 6.4.1.1.3](#).

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

Proposition 6.4.1.1.4. Let $R: A \nrightarrow B$ be a relation.

1. *Functionality I.* The assignment $R \mapsto R_*$ defines a function

$$(-)_*: \text{Rel}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

2. *Functionality II.* The assignment $R \mapsto R_*$ defines a function

$$(-)_*: \text{Rel}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have²⁰

$$(\chi_A)_* = \text{id}_{\mathcal{P}(A)}.$$

4. *Interaction With Composition.* For each pair of composable rela-

²⁰That is, the postcomposition function

$$(\chi_A)_*: \text{Rel}(\text{pt}, A) \rightarrow \text{Rel}(\text{pt}, A)$$

is equal to $\text{id}_{\text{Rel}(\text{pt}, A)}$.

tions $R: A \rightarrow B$ and $S: B \rightarrow C$, we have²¹

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{R_*} & \mathcal{P}(B) \\ (S \diamond R)_* = S_* \circ R_*, & \searrow & \downarrow S_* \\ & (S \diamond R)_* & \\ & & \mathcal{P}(C). \end{array}$$

Proof. **Item 1, Functionality I:** Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: Indeed, we have

$$\begin{aligned} (\chi_A)_*(U) &\stackrel{\text{def}}{=} \bigcup_{a \in U} \chi_A(a) \\ &\stackrel{\text{def}}{=} \bigcup_{a \in U} \{a\} \\ &= U \\ &\stackrel{\text{def}}{=} \text{id}_{\mathcal{P}(A)}(U) \end{aligned}$$

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

²¹That is, we have

$$\begin{array}{ccc} \text{Rel(pt, } A) & \xrightarrow{R_*} & \text{Rel(pt, } B) \\ (S \diamond R)_* = S_* \circ R_*, & \searrow & \downarrow S_* \\ & (S \diamond R)_* & \\ & & \text{Rel(pt, } C). \end{array}$$

6.4.2 Strong Inverse Images

Let A and B be sets and let $R: A \nrightarrow B$ be a relation.

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 $V \in \mathcal{P}(B)$.

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

$$R_{-1}: \underbrace{\mathcal{P}(B)}_{\cong \text{Rel(pt, } B)} \rightarrow \underbrace{\mathcal{P}(A)}_{\cong \text{Rel(pt, } A)}$$

defined by

$$R_{-1}(V) \stackrel{\text{def}}{=} \text{Rift}_R(V), \quad \begin{array}{ccc} & A & \\ \text{Rift}_R(V) & \nearrow \swarrow & \downarrow R \\ \text{pt} & \xrightarrow[V]{} & B, \end{array}$$

and being explicitly computed by

$$\begin{aligned} R_{-1}(V) &\stackrel{\text{def}}{=} \text{Rift}_R(V) \\ &\cong \int_{b \in B} \text{Hom}_{\{\text{t}, \text{f}\}}(R_{-1}^b, V_{-2}^b), \end{aligned}$$

where we have used Proposition 6.2.4.1.1.

²²Further Terminology: The set $R_{-1}(V)$ is called the **strong inverse image of V by R** .

Proof. We have

$$\begin{aligned}
 \text{Rift}_R(V) &\cong \int_{b \in B} \text{Hom}_{\{\text{t}, \text{f}\}}(R_{-1}^b, V_{-2}^b) \\
 &= \left\{ a \in A \mid \int_{b \in B} \text{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, V_\star^b) = \text{true} \right\} \\
 &= \left\{ a \in A \mid \begin{array}{l} \text{for each } b \in B, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } R_a^b = \text{false} \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} (a) \text{ We have } R_a^b = \text{true} \\ (b) \text{ We have } V_\star^b = \text{true} \end{array} \right\} \\
 &= \left\{ a \in A \mid \begin{array}{l} \text{for each } b \in B, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } b \notin R(a) \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} (a) \text{ We have } b \in R(a) \\ (b) \text{ We have } b \in V \end{array} \right\} \\
 &= \{a \in A \mid \text{for each } b \in R(a), \text{ we have } b \in V\} \\
 &= \{a \in A \mid R(a) \subset V\} \\
 &\stackrel{\text{def}}{=} R_{-1}(V).
 \end{aligned}$$

This finishes the proof. \square

Proposition 6.4.2.1.3. Let $R: A \nrightarrow B$ be a relation.

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 $R_{-1}(U) \subset R_{-1}(V)$.

2. *Adjointness.* We have an adjunction

$$(R_* \dashv R_{-1}): \quad \mathcal{P}(A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{R_{-1}} \end{array} \mathcal{P}(B),$$

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:

(\star) The following conditions are equivalent:

- We have $R_*(U) \subset V$.
- We have $U \subset R_{-1}(V)$.

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 $U, V \in \mathcal{P}(B)$.

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 $U, V \in \mathcal{P}(B)$.

5. *Symmetric Lax Monoidality With Respect to Unions.* The direct image with compact support function of [Item 1](#) has a symmetric lax monoidal structure

$$(R_{-1}, R_{-1}^{\otimes}, R_{-1|1}^{\otimes}): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with inclusions

$$\begin{aligned} R_{-1|U,V}^{\otimes}: R_{-1}(U) \cup R_{-1}(V) &\subset R_{-1}(U \cup V), \\ R_{-1|1}^{\otimes}: \emptyset &\subset R_{-1}(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

6. *Symmetric Strict Monoidality With Respect to Intersections.* The direct image function of [Item 1](#) has a symmetric strict monoidal structure

$$(R_{-1}, R_{-1}^\otimes, R_{-1|1\!\!1}^\otimes) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

$$\begin{aligned} R_{-1|U,V}^\otimes : R_{-1}(U \cap V) &\xrightarrow{\cong} R_{-1}(U) \cap R_{-1}(V), \\ R_{-1|1\!\!1}^\otimes : R_{-1}(A) &\xrightarrow{\cong} B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

7. *Interaction With Weak Inverse Images I.* We have

$$R_{-1}(V) = A \setminus R^{-1}(B \setminus V)$$

for each $V \in \mathcal{P}(B)$.

8. *Interaction With Weak Inverse Images II.* Let $R: A \nrightarrow B$ be a relation from A to B .

- (a) If R is a total relation, then we have an inclusion of sets

$$R_{-1}(V) \subset R^{-1}(V)$$

natural in $V \in \mathcal{P}(B)$.

- (b) If R is total and functional, then the above inclusion is in fact an equality.
(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

Proposition 6.4.2.1.4. Let $R: A \nrightarrow B$ be a relation.

1. *Functionality I.* The assignment $R \mapsto R_{-1}$ defines a function

$$(-)_{-1}: \text{Sets}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

2. *Functionality II.* The assignment $R \mapsto R_{-1}$ defines a function

$$(-)_{-1}: \text{Sets}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have

$$(\text{id}_A)_{-1} = \text{id}_{\mathcal{P}(A)}.$$

4. *Interaction With Composition.* For each pair of composable relations $R: A \nrightarrow B$ and $S: B \nrightarrow C$, we have

$$\begin{array}{ccc} \mathcal{P}(C) & \xrightarrow{S_{-1}} & \mathcal{P}(B) \\ (S \diamond R)_{-1} = R_{-1} \circ S_{-1}, & \searrow & \downarrow R_{-1} \\ & (S \diamond R)_{-1} & \\ & & \mathcal{P}(A). \end{array}$$

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 $(S \diamond R)_{-1} = R_{-1} \circ S_{-1}$. \square

6.4.3 Weak Inverse Images

Let A and B be sets and let $R: A \nrightarrow B$ be a relation.

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 $V \in \mathcal{P}(B)$.

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

$$R^{-1}(V) \stackrel{\text{def}}{=} V \diamond R$$

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

$$\begin{aligned} R^{-1}(V) &\stackrel{\text{def}}{=} V \diamond R \\ &\stackrel{\text{def}}{=} \int^{b \in B} V_b^{-1} \times R_{-2}^b. \end{aligned}$$

²³Further Terminology: Also called simply the **inverse image function associated to R** .

²⁴Further Terminology: The set $R^{-1}(V)$ is called the **weak inverse image of V by R** or simply the **inverse image of V by R** .

Proof. We have

$$\begin{aligned}
V \diamond R &\stackrel{\text{def}}{=} \int^{b \in B} V_b^{-1} \times R_{-2}^b \\
&= \left\{ a \in A \mid \int^{b \in B} V_b^* \times R_a^b = \text{true} \right\} \\
&= \left\{ a \in A \mid \begin{array}{l} \text{there exists } b \in B \text{ such that the} \\ \text{following conditions hold:} \end{array} \right. \\
&\quad \left. \begin{array}{l} 1. \text{ We have } V_b^* = \text{true} \\ 2. \text{ We have } R_a^b = \text{true} \end{array} \right\} \\
&= \left\{ a \in A \mid \begin{array}{l} \text{there exists } b \in B \text{ such that the} \\ \text{following conditions hold:} \end{array} \right. \\
&\quad \left. \begin{array}{l} 1. \text{ We have } b \in V \\ 2. \text{ We have } b \in R(a) \end{array} \right\} \\
&= \{a \in A \mid \text{there exists } b \in V \text{ such that } b \in R(a)\} \\
&= \{a \in A \mid R(a) \cap V \neq \emptyset\} \\
&\stackrel{\text{def}}{=} R^{-1}(V)
\end{aligned}$$

This finishes the proof. \square

Proposition 6.4.3.1.3. Let $R: A \dashrightarrow B$ be a relation.

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 $R^{-1}(U) \subset R^{-1}(V)$.

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:

(\star) The following conditions are equivalent:

- We have $R^{-1}(U) \subset V$.
- We have $U \subset R_!(V)$.

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 $U, V \in \mathcal{P}(B)$.

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 $U, V \in \mathcal{P}(B)$.

5. *Symmetric Strict Monoidality With Respect to Unions.* The direct image function of [Item 1](#) has a symmetric strict monoidal structure

$$(R^{-1}, R^{-1,\otimes}, R_{\mathbb{1}}^{-1,\otimes}) : (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} R_{U,V}^{-1,\otimes} : R^{-1}(U) \cup R^{-1}(V) &\xrightarrow{\equiv} R^{-1}(U \cup V), \\ R_{\mathbb{1}}^{-1,\otimes} : \emptyset &\xrightarrow{\equiv} \emptyset, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

6. *Symmetric Oplax Monoidality With Respect to Intersections.* The direct image function of [Item 1](#) has a symmetric oplax monoidal structure

$$\left(R^{-1}, R^{-1,\otimes}, R_{\mathbb{1}}^{-1,\otimes} \right) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} R_{U,V}^{-1,\otimes} &: R^{-1}(U \cap V) \subset R^{-1}(U) \cap R^{-1}(V), \\ R_{\mathbb{1}}^{-1,\otimes} &: R^{-1}(A) \subset B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(B)$.

7. *Interaction With Strong Inverse Images I.* We have

$$R^{-1}(V) = A \setminus R_{-1}(B \setminus V)$$

for each $V \in \mathcal{P}(B)$.

8. *Interaction With Strong Inverse Images II.* Let $R: A \nrightarrow B$ be a relation from A to B .

- (a) If R is a total relation, then we have an inclusion of sets

$$R_{-1}(V) \subset R^{-1}(V)$$

natural in $V \in \mathcal{P}(B)$.

- (b) If R is total and functional, then the above inclusion is in fact an equality.
(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

Proposition 6.4.3.1.4. Let $R: A \nrightarrow B$ be a relation.

1. *Functionality I.* The assignment $R \mapsto R^{-1}$ defines a function

$$(-)^{-1}: \text{Rel}(A, B) \rightarrow \text{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

2. *Functionality II.* The assignment $R \mapsto R^{-1}$ defines a function

$$(-)^{-1}: \text{Rel}(A, B) \rightarrow \text{Pos}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

3. *Interaction With Identities.* For each $A \in \text{Obj}(\text{Sets})$, we have²⁵

$$(\chi_A)^{-1} = \text{id}_{\mathcal{P}(A)}.$$

4. *Interaction With Composition.* For each pair of composable relations $R: A \nrightarrow B$ and $S: B \nrightarrow C$, we have²⁶

$$\begin{array}{ccc} \mathcal{P}(C) & \xrightarrow{S^{-1}} & \mathcal{P}(B) \\ (S \diamond R)^{-1} = R^{-1} \circ S^{-1}, & \searrow & \downarrow R^{-1} \\ & (S \diamond R)^{-1} & \\ & & \mathcal{P}(A). \end{array}$$

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

6.4.4 Direct Images With Compact Support

Let A and B be sets and let $R: A \nrightarrow B$ be a relation.

²⁵That is, the postcomposition

$$(\chi_A)^{-1}: \text{Rel}(\text{pt}, A) \rightarrow \text{Rel}(\text{pt}, A)$$

is equal to $\text{id}_{\text{Rel}(\text{pt}, A)}$.

²⁶That is, we have

$$\begin{array}{ccc} \text{Rel}(\text{pt}, C) & \xrightarrow{R^{-1}} & \text{Rel}(\text{pt}, B) \\ (S \diamond R)^{-1} = R^{-1} \circ S^{-1}, & \searrow & \downarrow S^{-1} \\ & (S \diamond R)^{-1} & \\ & & \text{Rel}(\text{pt}, A). \end{array}$$

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}

$$\begin{aligned} R_!(U) &\stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ if we have} \\ b \in R(a), \text{ then } a \in U \end{array} \right\} \\ &= \left\{ b \in B \mid R^{-1}(b) \subset U \right\} \end{aligned}$$

for each $U \in \mathcal{P}(A)$.

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

$$R_!(U) \stackrel{\text{def}}{=} \text{Ran}_R(U), \quad \begin{array}{ccc} & B & \\ & \nearrow R & \dashdown \text{Ran}_R(U) \\ A & \xrightarrow[U]{\quad} & \text{pt}, \end{array}$$

being explicitly computed by

$$\begin{aligned} R^*(U) &\stackrel{\text{def}}{=} \text{Ran}_R(U) \\ &\cong \int_{a \in A} \text{Hom}_{\{\text{t,f}\}}(R_a^{-2}, U_a^{-1}), \end{aligned}$$

where we have used Proposition 6.2.3.1.1.

²⁷Further Terminology: The set $R_!(U)$ is called the **direct image with compact support of U by R** .

²⁸We also have

$$R_!(U) = B \setminus R_*(A \setminus U);$$

see Item 7 of Proposition 6.4.4.1.3.

Proof. We have

$$\begin{aligned}
\text{Ran}_R(V) &\cong \int_{a \in A} \text{Hom}_{\{\text{t}, \text{f}\}}(R_a^{-2}, U_a^{-1}) \\
&= \left\{ b \in B \mid \int_{a \in A} \text{Hom}_{\{\text{t}, \text{f}\}}(R_a^b, U_a^\star) = \text{true} \right\} \\
&= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
&\quad \left. \begin{array}{l} 1. \text{ We have } R_a^b = \text{false} \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
&\quad \left. \begin{array}{l} (a) \text{ We have } R_a^b = \text{true} \\ (b) \text{ We have } U_a^\star = \text{true} \end{array} \right\} \\
&= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
&\quad \left. \begin{array}{l} 1. \text{ We have } b \notin R(A) \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
&\quad \left. \begin{array}{l} (a) \text{ We have } b \in R(a) \\ (b) \text{ We have } a \in U \end{array} \right\} \\
&= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ if we have} \\ b \in R(a), \text{ then } a \in U \end{array} \right\} \\
&= \{b \in B \mid R^{-1}(b) \subset U\} \\
&\stackrel{\text{def}}{=} R^{-1}(U).
\end{aligned}$$

This finishes the proof. \square

Proposition 6.4.4.1.3. Let $R: A \nrightarrow B$ be a relation.

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 $R_!(U) \subset R_!(V)$.

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:

(\star) The following conditions are equivalent:

- We have $R^{-1}(U) \subset V$.
- We have $U \subset R_!(V)$.

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 $U, V \in \mathcal{P}(A)$.

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 $U, V \in \mathcal{P}(A)$.

5. *Symmetric Lax Monoidality With Respect to Unions.* The direct image with compact support function of **Item 1** has a symmetric lax monoidal structure

$$(R_!, R_!^\otimes, R_{!|\mathbb{1}}^\otimes): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with inclusions

$$\begin{aligned} R_{!|U,V}^\otimes : R_!(U) \cup R_!(V) &\subset R_!(U \cup V), \\ R_{!|\mathbb{1}}^\otimes : \emptyset &\subset R_!(\emptyset), \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

6. *Symmetric Strict Monoidality With Respect to Intersections.* The direct image function of [Item 1](#) has a symmetric strict monoidal structure

$$(R_!, R_!^\otimes, R_{!|\mathbb{1}}^\otimes) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

$$\begin{aligned} R_{!|U,V}^\otimes : R_!(U \cap V) &\xrightarrow{\cong} R_!(U) \cap R_!(V), \\ R_{!|\mathbb{1}}^\otimes : R_!(A) &\xrightarrow{\cong} B, \end{aligned}$$

natural in $U, V \in \mathcal{P}(A)$.

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 6.4.1.3](#). 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

Proposition 6.4.4.1.4. Let $R: A \nrightarrow B$ be a relation.

1. *Functionality I.* The assignment $R \mapsto R_!$ defines a function

$$(-)_!: \mathbf{Sets}(A, B) \rightarrow \mathbf{Sets}(\mathcal{P}(A), \mathcal{P}(B)).$$

2. *Functionality II.* The assignment $R \mapsto R_!$ defines a function

$$(-)_!: \mathbf{Sets}(A, B) \rightarrow \text{Hom}_{\mathbf{Pos}}((\mathcal{P}(A), \subset), (\mathcal{P}(B), \subset)).$$

3. *Interaction With Identities.* For each $A \in \text{Obj}(\mathbf{Sets})$, we have

$$(\text{id}_A)_! = \text{id}_{\mathcal{P}(A)}.$$

4. *Interaction With Composition.* For each pair of composable relations $R: A \nrightarrow B$ and $S: B \nrightarrow C$, we have

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{R_!} & \mathcal{P}(B) \\ (S \diamond R)_! = S_! \circ R_!, & \searrow & \downarrow S_! \\ & (S \diamond R)_! & \\ & & \mathcal{P}(C). \end{array}$$

Proof. **Item 1, Functionality I:** Clear.

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: Indeed, we have

$$\begin{aligned} (\chi_A)_!(U) &\stackrel{\text{def}}{=} \left\{ a \in A \mid \chi_A^{-1}(a) \subset U \right\} \\ &\stackrel{\text{def}}{=} \left\{ a \in A \mid \{a\} \subset U \right\} \\ &= U \end{aligned}$$

for each $U \in \mathcal{P}(A)$. Thus $(\chi_A)_! = \text{id}_{\mathcal{P}(A)}$.

Item 4, Interaction With Composition: Indeed, we have

$$\begin{aligned} (S \diamond R)_!(U) &\stackrel{\text{def}}{=} \left\{ c \in C \mid [S \diamond R]^{-1}(c) \subset U \right\} \\ &\stackrel{\text{def}}{=} \left\{ c \in C \mid S^{-1}(R^{-1}(c)) \subset U \right\} \\ &= \left\{ c \in C \mid R^{-1}(c) \subset S_!(U) \right\} \\ &\stackrel{\text{def}}{=} R_!(S_!(U)) \\ &\stackrel{\text{def}}{=} [R_! \circ S_!](U) \end{aligned}$$

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 $(S \diamond R)_! = S_! \circ R_!$. \square

6.4.5 Functoriality of Powersets

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

$$\begin{aligned} \mathcal{P}_*(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}_{-1}(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}^{-1}(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}_!(A) &\stackrel{\text{def}}{=} \mathcal{P}(A). \end{aligned}$$

- *Action on Morphisms.* For each morphism $R: A \rightarrow B$ of Rel, the images

$$\begin{aligned} \mathcal{P}_*(R) &: \mathcal{P}(A) \rightarrow \mathcal{P}(B), \\ \mathcal{P}_{-1}(R) &: \mathcal{P}(B) \rightarrow \mathcal{P}(A), \\ \mathcal{P}^{-1}(R) &: \mathcal{P}(B) \rightarrow \mathcal{P}(A), \\ \mathcal{P}_!(R) &: \mathcal{P}(A) \rightarrow \mathcal{P}(B) \end{aligned}$$

²⁹The functor $\mathcal{P}_*: \text{Rel} \rightarrow \text{Sets}$ admits a left adjoint; see *Item 3* of

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

Let A and B be sets and let $R: A \nrightarrow B$ be a relation.

Definition 6.4.6.1.1. The **relation on powersets associated to R** is the relation

$$\mathcal{P}(R): \mathcal{P}(A) \nrightarrow \mathcal{P}(B)$$

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 $V \in \mathcal{P}(B)$.

Remark 6.4.6.1.2. In detail, we have $U \sim_{\mathcal{P}(R)} V$ iff the following equivalent conditions hold:

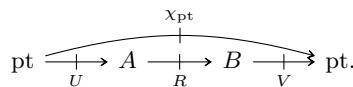
- We have $\chi_{\text{pt}} \subset V \diamond R \diamond U$.
- We have $(V \diamond R \diamond U)_*^\star = \text{true}$, i.e. we have

$$\int^{a \in A} \int^{b \in B} V_b^\star \times R_a^b \times U_*^a = \text{true}.$$

- There exists some $a \in A$ and some $b \in B$ such that:
 - We have $U_*^a = \text{true}$.
 - We have $R_a^b = \text{true}$.
 - We have $V_b^\star = \text{true}$.

Proposition 6.3.1.1.2.

³⁰Illustration:



- 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 $b \in V$.

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

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| 1. Sets | 7. Equivalence Relations and Apartness Relations |
| 2. Constructions With Sets | |
| 3. Pointed Sets | Category Theory |
| 4. Tensor Products of Pointed Sets | 8. Categories |
| 5. Relations | Bicategories |
| Relations | 9. Types of Morphisms in Bicategories |

Chapter 7

Equivalence Relations and Apartness Relations

This chapter contains some material about reflexive, symmetric, transitive, equivalence, and apartness relations.

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7.1 Reflexive Relations

7.1.1 Foundations

Let A be a set.

Definition 7.1.1.1.1. A **reflexive relation** is equivalently:¹

- An \mathbb{E}_0 -monoid in $(N_\bullet(\mathbf{Rel}(A, A)), \chi_A)$.
- A pointed object in $(\mathbf{Rel}(A, A), \chi_A)$.

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 $a \sim_R a$.

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.
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.

Proposition 7.1.1.1.4. Let R and S be relations on A .

1. *Interaction With Inverses.* If R is reflexive, then so is R^\dagger .
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. \square

7.1.2 The Reflexive Closure of a Relation

Let R be a relation on A .

Definition 7.1.2.1.1. The **reflexive closure** of \sim_R is the relation \sim_R^{refl} ² satisfying the following universal property.³

- (\star) Given another reflexive relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{refl}} \subset \sim_S$.

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

$$\begin{aligned} R^{\text{refl}} &\stackrel{\text{def}}{=} R \coprod^{\mathbf{Rel}(A, A)} \Delta_A \\ &= R \cup \Delta_A \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } a = b\}. \end{aligned}$$

¹Note that since $\mathbf{Rel}(A, A)$ is posetal, reflexivity is a property of a relation, rather than extra structure.

²Further Notation: Also written R^{refl} .

³Slogan: The reflexive closure of R is the smallest reflexive relation containing R .

⁴Or, equivalently, the free \mathbb{E}_0 -monoid on R in $(N_\bullet(\mathbf{Rel}(A, A)), \chi_A)$.

Proof. Clear. \square

Proposition 7.1.2.1.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$\left((-)^{\text{refl}} \dashv \overline{\vdash} \right) : \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{refl}}} \\[-1ex] \perp \\[-1ex] \xleftarrow{\overline{\vdash}} \end{array} \mathbf{Rel}^{\text{refl}}(A, A),$$

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 $S \in \text{Obj}(\mathbf{Rel}(A, A))$.

2. *The Reflexive Closure of a Reflexive Relation.* If R is reflexive, then $R^{\text{refl}} = R$.

3. *Idempotency.* We have

$$(R^{\text{refl}})^{\text{refl}} = R^{\text{refl}}.$$

4. *Interaction With Inverses.* We have

$$\begin{array}{ccc} \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{refl}}} & \mathbf{Rel}(A, A) \\ (R^\dagger)^{\text{refl}} = (R^{\text{refl}})^\dagger, & \downarrow (-)^\dagger & \downarrow (-)^\dagger \\ \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{refl}}} & \mathbf{Rel}(A, A). \end{array}$$

5. *Interaction With Composition.* We have

$$\begin{array}{ccc} \mathbf{Rel}(A, A) \times \mathbf{Rel}(A, A) & \xrightarrow{\diamond} & \mathbf{Rel}(A, A) \\ (S \diamond R)^{\text{refl}} = S^{\text{refl}} \diamond R^{\text{refl}}, & \downarrow (-)^{\text{refl}} \times (-)^{\text{refl}} & \downarrow (-)^{\text{refl}} \\ \mathbf{Rel}(A, A) \times \mathbf{Rel}(A, A) & \xrightarrow{\diamond} & \mathbf{Rel}(A, A). \end{array}$$

Proof. **Item 1, Adjointness:** This is a rephrasing of the universal property of the 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

7.2 Symmetric Relations

7.2.1 Foundations

Let A be a set.

Definition 7.2.1.1.1. A relation R on A is **symmetric** if we have $R^\dagger = R$.

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 $b \sim_R a$.

Definition 7.2.1.1.3. Let A be a set.

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.
2. The **poset of relations on A** is the subposet $\text{Rel}^{\text{symm}}(A, A)$ of $\text{Rel}(A, A)$ spanned by the symmetric relations.

Proposition 7.2.1.1.4. Let R and S be relations on A .

1. *Interaction With Inverses.* If R is symmetric, then so is R^\dagger .
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

7.2.2 The Symmetric Closure of a Relation

Let R be a relation on A .

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

- (\star) Given another symmetric relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{symm}} \subset \sim_S$.

Construction 7.2.2.1.2. Concretely, \sim_R^{symm} is the symmetric relation on A defined by

$$\begin{aligned} R^{\text{symm}} &\stackrel{\text{def}}{=} R \cup R^\dagger \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } b \sim_R a\}. \end{aligned}$$

⁵Further Notation: Also written R^{symm} .

⁶Slogan: The symmetric closure of R is the smallest symmetric relation containing

Proof. Clear. \square

Proposition 7.2.2.1.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$((-)^{\text{symm}} \dashv \text{忘}): \quad \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{symm}}} \\[-1ex] \xleftarrow[\text{忘}]{\perp} \end{array} \mathbf{Rel}^{\text{symm}}(A, A),$$

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 $S \in \text{Obj}(\mathbf{Rel}(A, A))$.

2. *The Symmetric Closure of a Symmetric Relation.* If R is symmetric, then $R^{\text{symm}} = R$.
3. *Idempotency.* We have

$$(R^{\text{symm}})^{\text{symm}} = R^{\text{symm}}.$$

4. *Interaction With Inverses.* We have

$$\begin{array}{ccc} \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{symm}}} & \mathbf{Rel}(A, A) \\ \left(R^{\dagger}\right)^{\text{symm}} = \left(R^{\text{symm}}\right)^{\dagger}, & \downarrow (-)^{\dagger} & \downarrow (-)^{\dagger} \\ \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{symm}}} & \mathbf{Rel}(A, A). \end{array}$$

5. *Interaction With Composition.* We have

$$\begin{array}{ccc} \mathbf{Rel}(A, A) \times \mathbf{Rel}(A, A) & \xrightarrow{\diamond} & \mathbf{Rel}(A, A) \\ (S \diamond R)^{\text{symm}} = S^{\text{symm}} \diamond R^{\text{symm}}, & \downarrow (-)^{\text{symm}} \times (-)^{\text{symm}} & \downarrow (-)^{\text{symm}} \\ \mathbf{Rel}(A, A) \times \mathbf{Rel}(A, A) & \xrightarrow{\diamond} & \mathbf{Rel}(A, A). \end{array}$$

Proof. **Item 1, Adjointness:** This is a rephrasing of the universal property of the 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

7.3 Transitive Relations

7.3.1 Foundations

Let A be a set.

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 $(\mathbf{Rel}(A, A), \diamond)$.

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 $a \sim_R c$.

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.
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.

Proposition 7.3.1.1.4. Let R and S be relations on A .

1. *Interaction With Inverses.* If R is transitive, then so is R^\dagger .
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

R .

⁷Note that since $\mathbf{Rel}(A, A)$ is posetal, transitivity is a property of a relation, rather than extra structure.

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. $b \sim_S c$;

7.3.2 The Transitive Closure of a Relation

Let R be a relation on A .

Definition 7.3.2.1.1. The **transitive closure** of \sim_R is the relation $\sim_R^{\text{trans}}\text{\footnotesize9}$ satisfying the following universal property:¹⁰

- (\star) Given another transitive relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{trans}} \subset \sim_S$.

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

$$\begin{aligned} R^{\text{trans}} &\stackrel{\text{def}}{=} \coprod_{n=1}^{\infty} R^{\diamond n} \\ &\stackrel{\text{def}}{=} \bigcup_{n=1}^{\infty} R^{\diamond n} \\ &\stackrel{\text{def}}{=} \left\{ (a, b) \in A \times B \mid \begin{array}{l} \text{there exists some } (x_1, \dots, x_n) \in R^{\times n} \\ \text{such that } a \sim_R x_1 \sim_R \dots \sim_R x_n \sim_R b \end{array} \right\}. \end{aligned}$$

Proof. Clear. □

Proposition 7.3.2.1.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$\left((-)^{\text{trans}} \dashv \text{忘} \right): \quad \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{trans}}} \\ \perp \\ \xleftarrow{\text{忘}} \end{array} \mathbf{Rel}^{\text{trans}}(A, A),$$

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 $S \in \text{Obj}(\mathbf{Rel}(A, B))$.

2. *The Transitive Closure of a Transitive Relation.* If R is transitive, then $R^{\text{trans}} = R$.

-
- (b) There is some $d \in A$ such that:

- i. $c \sim_R d$;
- ii. $d \sim_S e$.

⁹Further Notation: Also written R^{trans} .

¹⁰Slogan: 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 $(N_{\bullet}(\mathbf{Rel}(A, A)), \diamond)$.

3. *Idempotency.* We have

$$(R^{\text{trans}})^{\text{trans}} = R^{\text{trans}}.$$

4. *Interaction With Inverses.* We have

$$\begin{array}{ccc} \text{Rel}(A, A) & \xrightarrow{(-)^{\text{trans}}} & \text{Rel}(A, A) \\ (R^\dagger)^{\text{trans}} = (R^{\text{trans}})^\dagger, & \downarrow (-)^\dagger & \downarrow (-)^\dagger \\ \text{Rel}(A, A) & \xrightarrow{(-)^{\text{trans}}} & \text{Rel}(A, A). \end{array}$$

5. *Interaction With Composition.* We have

$$\begin{array}{ccc} \text{Rel}(A, A) \times \text{Rel}(A, A) & \xrightarrow{\diamond} & \text{Rel}(A, A) \\ (S \diamond R)^{\text{trans}} \stackrel{\text{poss.}}{\neq} S^{\text{trans}} \diamond R^{\text{trans}}, & \downarrow (-)^{\text{trans}} \times (-)^{\text{trans}} & \downarrow (-)^{\text{trans}} \\ \text{Rel}(A, A) \times \text{Rel}(A, A) & \xrightarrow{\diamond} & \text{Rel}(A, A). \end{array}$$

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

7.4 Equivalence Relations

7.4.1 Foundations

Let A be a set.

Definition 7.4.1.1.1. A relation R is an **equivalence relation** if it is reflexive, symmetric, and transitive.¹²

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

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.

7.4.2 The Equivalence Closure of a Relation

Let R be a relation on A .

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

- (\star) Given another equivalence relation \sim_S on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{eq}} \subset \sim_S$.

Construction 7.4.2.1.2. Concretely, \sim_R^{eq} is the equivalence relation on

¹²Further Terminology: If instead R is just symmetric and transitive, then it is called a **partial equivalence relation**.

¹³The kernel $\text{Ker}(f): A \dashv A$ of f is the underlying functor of the monad induced by the adjunction $\text{Gr}(f) \dashv f^{-1}: A \rightleftarrows B$ in \mathbf{Rel} of Item 2 of Proposition 6.3.1.1.2.

¹⁴Further Terminology: Also called the **equivalence relation associated to \sim_R** .

¹⁵Further Notation: Also written R^{eq} .

¹⁶Slogan: The equivalence closure of R is the smallest equivalence relation containing R .

A defined by

$$R^{\text{eq}} \stackrel{\text{def}}{=} \left((R^{\text{refl}})^{\text{symm}} \right)^{\text{trans}}$$

$$= \left((R^{\text{symm}})^{\text{trans}} \right)^{\text{refl}}$$

$$= \left\{ (a, b) \in A \times B \mid \begin{array}{l} \text{there exists } (x_1, \dots, x_n) \in R^{\times n} \text{ satisfying at} \\ \text{least one of the following conditions:} \end{array} \right\}$$

- 1. The following conditions are satisfied:
 - (a) We have $a \sim_R x_1$ or $x_1 \sim_R a$;
 - (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 $b \sim_R x_n$ or $x_n \sim_R b$;
- 2. We have $a = b$.

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:

1. The symmetric closure of a reflexive relation is still reflexive.
2. The transitive closure of a symmetric relation is still symmetric.

which are both clear. \square

Proposition 7.4.2.1.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$((-)^{\text{eq}} \dashv \overline{\text{忘}}) : \mathbf{Rel}(A, B) \begin{array}{c} \xrightarrow{(-)^{\text{eq}}} \\[-1ex] \xleftarrow[\text{忘}]{\perp} \end{array} \mathbf{Rel}^{\text{eq}}(A, B),$$

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 $S \in \text{Obj}(\mathbf{Rel}(A, B))$.

2. *The Equivalence Closure of an Equivalence Relation.* If R is an equivalence relation, then $R^{\text{eq}} = R$.

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

7.5 Quotients by Equivalence Relations

7.5.1 Equivalence Classes

Let A be a set, let R be a relation on A , and let $a \in A$.

Definition 7.5.1.1.1. The **equivalence class associated to a** is the set $[a]$ defined by

$$\begin{aligned} [a] &\stackrel{\text{def}}{=} \{x \in X \mid x \sim_R a\} \\ &= \{x \in X \mid a \sim_R x\}. \end{aligned} \quad (\text{since } R \text{ is symmetric})$$

7.5.2 Quotients of Sets by Equivalence Relations

Let A be a set and let R be a relation on A .

Definition 7.5.2.1.1. The **quotient of X by R** is the set X/\sim_R defined by

$$X/\sim_R \stackrel{\text{def}}{=} \{[a] \in \mathcal{P}(X) \mid a \in X\}.$$

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 equivalences 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.

Proposition 7.5.2.1.3. Let $f: X \rightarrow Y$ be a function and let R be a relation on X .

¹⁷When categorifying equivalence relations, one finds that $[a]$ and $[a]'$ correspond to presheaves and copresheaves; see ??.

1. *As a Coequaliser.* We have an isomorphism of sets

$$X/\sim_R^{\text{eq}} \cong \text{CoEq}\left(R \hookrightarrow X \times X \xrightarrow{\text{pr}_1} X\right),$$

where \sim_R^{eq} is the equivalence relation generated by \sim_R .

2. *As a Pushout.* We have an isomorphism of sets¹⁸

$$X/\sim_R^{\text{eq}} \cong X \coprod_{\text{Eq}(\text{pr}_1, \text{pr}_2)} X,$$

$$\begin{array}{ccc} X/\sim_R^{\text{eq}} & \xleftarrow{\quad \lrcorner \quad} & X \\ \uparrow & & \uparrow \\ X & \xleftarrow{\quad \text{Eq}(\text{pr}_1, \text{pr}_2) \quad} & \end{array}$$

where \sim_R^{eq} is the equivalence relation generated by \sim_R .

3. *The First Isomorphism Theorem for Sets.* We have an isomorphism of sets^{19,20}

$$X/\sim_{\text{Ker}(f)} \cong \text{Im}(f).$$

4. *Descending Functions to Quotient Sets, I.* Let R be an equivalence relation on X . The following conditions are equivalent:

¹⁸Dually, we also have an isomorphism of sets

$$\begin{array}{ccc} \text{Eq}(\text{pr}_1, \text{pr}_2) & \longrightarrow & X \\ \downarrow & \lrcorner & \downarrow \\ \text{Eq}(\text{pr}_1, \text{pr}_2) & \cong & X \times_{X/\sim_R^{\text{eq}}} X, \\ \downarrow & & \downarrow \\ X & \longrightarrow & X/\sim_R^{\text{eq}}. \end{array}$$

¹⁹Further 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

$$\begin{aligned} \text{Ker}(f): X &\dashrightarrow X, \\ \text{Im}(f) &\subset Y \end{aligned}$$

of f are the underlying functors of (respectively) the induced monad and comonad of the adjunction

$$(\text{Gr}(f) \dashv f^{-1}): A \begin{array}{c} \xrightarrow{\text{Gr}(f)} \\ \perp \\ \xleftarrow{f^{-1}} \end{array} B$$

of Item 2 of Proposition 6.3.1.1.2.

(a) There exists a map

$$\bar{f}: X/\sim_R \rightarrow Y$$

making the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ q \downarrow & \nearrow \exists! \bar{f} & \\ X/\sim_R & & \end{array}$$

commute.

(b) We have $R \subset \text{Ker}(f)$.

(c) For each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$.

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

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ q \downarrow & \nearrow \exists! \bar{f} & \\ X/\sim_R & & \end{array}$$

commute.

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

$$\text{Hom}_{\text{Sets}}^R(X, Y) \stackrel{\text{def}}{=} \left\{ f \in \text{Hom}_{\text{Sets}}(X, Y) \mid \begin{array}{l} \text{for each } x, y \in X, \\ \text{if } x \sim_R y, \text{ then } \\ f(x) = f(y) \end{array} \right\}.$$

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 $f(x) = f(y)$.

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.

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:

(a) The map f satisfies the equivalent conditions of [Item 4](#):

- There exists a map

$$\bar{f}: X/\sim_R^{\text{eq}} \rightarrow Y$$

making the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ q \downarrow & \nearrow \exists \bar{f} & \\ X/\sim_R^{\text{eq}} & & \end{array}$$

commute.

• For each $x, y \in X$, if $x \sim_R^{\text{eq}} y$, then $f(x) = f(y)$.

(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:

- (\star) 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 $x = y$.

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

| | |
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| Sets | 6. Constructions With Relations |
| 1. Sets | 7. Equivalence Relations and |
| 2. Constructions With Sets | Apartness Relations |
| 3. Pointed Sets | Category Theory |
| 4. Tensor Products of Pointed Sets | 8. Categories |
| Relations | Bicategories |
| 5. Relations | 9. Types of Morphisms in Bicategories |

Part III

Category Theory

Chapter 8

Categories

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 pseudomonadic, 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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8.1 Categories

8.1.1 Foundations

Definition 8.1.1.1. A category $(C, \circ^C, \mathbb{1}^C)$ 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 $A \in \text{Obj}(\mathcal{C})$, a map of sets

$$\mathbb{1}_A^{\mathcal{C}}: \text{pt} \rightarrow \text{Hom}_{\mathcal{C}}(A, A),$$

called the **unit map of \mathcal{C} at A** , determining a morphism

$$\text{id}_A: A \rightarrow A$$

of \mathcal{C} , called the **identity morphism of A** .

- *Composition.* For each $A, B, C \in \text{Obj}(\mathcal{C})$, a map of sets

$$\circ_{A,B,C}^{\mathcal{C}}: \text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{C}}(A, C),$$

called the **composition map of \mathcal{C} at (A, B, C)** .

such that the following conditions are satisfied:

1. *Associativity.* The diagram

$$\begin{array}{ccc}
 & \text{Hom}_{\mathcal{C}}(C, D) \times (\text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(A, B)) & \\
 & \swarrow \alpha_{\text{Hom}_{\mathcal{C}}(C,D), \text{Hom}_{\mathcal{C}}(B,C), \text{Hom}_{\mathcal{C}}(A,B)}^{\text{Sets}} & \searrow \text{id}_{\text{Hom}_{\mathcal{C}}(C,D) \times \circ_{A,B,C}^{\mathcal{C}}} \\
 (\text{Hom}_{\mathcal{C}}(C, D) \times \text{Hom}_{\mathcal{C}}(B, C)) \times \text{Hom}_{\mathcal{C}}(A, B) & & \text{Hom}_{\mathcal{C}}(C, D) \times \text{Hom}_{\mathcal{C}}(A, C) \\
 & \swarrow \circ_{B,C,D}^{\mathcal{C}} \times \text{id}_{\text{Hom}_{\mathcal{C}}(A,B)} & \searrow \circ_{A,C,D}^{\mathcal{C}} \\
 & \text{Hom}_{\mathcal{C}}(B, D) \times \text{Hom}_{\mathcal{C}}(A, B) & \xrightarrow{\circ_{A,B,D}^{\mathcal{C}}} \text{Hom}_{\mathcal{C}}(A, D)
 \end{array}$$

commutes, i.e. for each composable triple (f, g, h) of morphisms of \mathcal{C} , we have

$$(f \circ g) \circ h = f \circ (g \circ h).$$

2. *Left Unitality.* The diagram

$$\begin{array}{ccc}
 & \text{pt} \times \text{Hom}_{\mathcal{C}}(A, B) & \\
 & \downarrow \mathbb{1}_B^{\mathcal{C}} \times \text{id}_{\text{Hom}_{\mathcal{C}}(A,B)} & \searrow \lambda_{\text{Hom}_{\mathcal{C}}(A,B)}^{\text{Sets}} \sim \\
 \text{Hom}_{\mathcal{C}}(B, B) \times \text{Hom}_{\mathcal{C}}(A, B) & \xrightarrow{\circ_{A,B,B}^{\mathcal{C}}} & \text{Hom}_{\mathcal{C}}(A, B)
 \end{array}$$

commutes, i.e. for each morphism $f: A \rightarrow B$ of \mathcal{C} , we have

$$\text{id}_B \circ f = f.$$

3. *Right Unitality.* The diagram

$$\begin{array}{ccc}
 \text{Hom}_C(A, B) \times \text{pt} & & \\
 \downarrow \text{id}_{\text{Hom}_C(A, B)} \times \mathbb{1}_A^C & \nearrow \rho_{\text{Hom}_C(A, B)}^{\text{Sets}} & \\
 \text{Hom}_C(A, B) \times \text{Hom}_C(A, A) & \xrightarrow{\circ_{A, A, B}^C} & \text{Hom}_C(A, B)
 \end{array}$$

commutes, i.e. for each morphism $f: A \rightarrow B$ of \mathcal{C} , we have

$$f \circ \text{id}_A = f.$$

Notation 8.1.1.1.2. Let \mathcal{C} be a category.

1. We also write $\mathcal{C}(A, B)$ for $\text{Hom}_C(A, B)$.
2. We write $\text{Mor}(\mathcal{C})$ for the class of all morphisms of \mathcal{C} .

Definition 8.1.1.1.3. Let κ be a regular cardinal. A category \mathcal{C} is

1. **Locally small** if, for each $A, B \in \text{Obj}(\mathcal{C})$, the class $\text{Hom}_C(A, B)$ is a set.
2. **Locally essentially small** if, for each $A, B \in \text{Obj}(\mathcal{C})$, the class

$$\text{Hom}_C(A, B)/\{\text{isomorphisms}\}$$

is a set.

3. **Small** if \mathcal{C} is locally small and $\text{Obj}(\mathcal{C})$ is a set.
4. **κ -Small** if \mathcal{C} is locally small, $\text{Obj}(\mathcal{C})$ is a set, and we have $\#\text{Obj}(\mathcal{C}) < \kappa$.

8.1.2 Examples of Categories

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

$$\text{Hom}_{\text{pt}}(\star, \star) \stackrel{\text{def}}{=} \{\text{id}_\star\}.$$

¹Further Terminology: Also called the **singleton category**.

- *Identities.* The unit map

$$\mathbb{1}_*^{\text{pt}} : \text{pt} \rightarrow \text{Hom}_{\text{pt}}(\star, \star)$$

of pt at \star is defined by

$$\text{id}_*^{\text{pt}} \stackrel{\text{def}}{=} \text{id}_\star.$$

- *Composition.* The composition map

$$\circ_{*,*,*}^{\text{pt}} : \text{Hom}_{\text{pt}}(\star, \star) \times \text{Hom}_{\text{pt}}(\star, \star) \rightarrow \text{Hom}_{\text{pt}}(\star, \star)$$

of pt at (\star, \star, \star) is given by the bijection $\text{pt} \times \text{pt} \cong \text{pt}$.

Example 8.1.2.1.2. We have an isomorphism of categories²

$$\begin{array}{ccc} \text{Mon} & \longrightarrow & \text{Cats} \\ \downarrow \lrcorner & & \downarrow \text{Obj} \\ \text{Mon} \cong \text{pt} \times_{\text{Sets}} \text{Cats}, & & \\ \downarrow & & \downarrow \\ \text{pt} & \xrightarrow{[\text{pt}]} & \text{Sets} \end{array}$$

via the delooping functor $B : \text{Mon} \rightarrow \text{Cats}$ of ?? of ??, exhibiting monoids as exactly those categories having a single object.

Proof. Omitted. □

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.

²This can be enhanced to an isomorphism of 2-categories

$$\begin{array}{ccc} \text{Mon}_{2\text{disc}} & \longrightarrow & \text{Cats}_{2,*} \\ \downarrow \lrcorner & & \downarrow \text{Obj} \\ \text{Mon}_{2\text{disc}} \cong \text{pt}_{\text{bi}} \times_{\text{Sets}_{2\text{disc}}} \text{Cats}_{2,*}, & & \\ \downarrow & & \downarrow \\ \text{pt}_{\text{bi}} & \xrightarrow{[\text{pt}]} & \text{Sets}_{2\text{disc}} \end{array}$$

Example 8.1.2.1.4. The n th ordinal category is the category \mathbb{n} where³

- *Objects.* We have

$$\text{Obj}(\mathbb{n}) \stackrel{\text{def}}{=} \{[0], \dots, [n]\}.$$

- *Morphisms.* For each $[i], [j] \in \text{Obj}(\mathbb{n})$, we have

$$\text{Hom}_{\mathbb{n}}([i], [j]) \stackrel{\text{def}}{=} \begin{cases} \{\text{id}_{[i]}\} & \text{if } [i] = [j], \\ \{[i] \rightarrow [j]\} & \text{if } [j] < [i], \\ \emptyset & \text{if } [j] > [i]. \end{cases}$$

- *Identities.* For each $[i] \in \text{Obj}(\mathbb{n})$, the unit map

$$\mathbb{1}_{[i]}^{\mathbb{n}} : \text{pt} \rightarrow \text{Hom}_{\mathbb{n}}([i], [i])$$

of \mathbb{n} at $[i]$ is defined by

$$\text{id}_{[i]}^{\mathbb{n}} \stackrel{\text{def}}{=} \text{id}_{[i]}.$$

- *Composition.* For each $[i], [j], [k] \in \text{Obj}(\mathbb{n})$, the composition map

$$\circ_{[i], [j], [k]}^{\mathbb{n}} : \text{Hom}_{\mathbb{n}}([j], [k]) \times \text{Hom}_{\mathbb{n}}([i], [j]) \rightarrow \text{Hom}_{\mathbb{n}}([i], [k])$$

of \mathbb{n} at $([i], [j], [k])$ is defined by

$$\begin{aligned} \text{id}_{[i]} \circ \text{id}_{[i]} &= \text{id}_{[i]}, \\ ([j] \rightarrow [k]) \circ ([i] \rightarrow [j]) &= ([i] \rightarrow [k]). \end{aligned}$$

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, \mathbb{n} is the category associated to the poset

$$[0] \rightarrow [1] \rightarrow \cdots \rightarrow [n-1] \rightarrow [n].$$

The category \mathbb{n} for $n \geq 2$ may also be defined in terms of \emptyset and joins (??): we have

Example 8.1.2.1.5. Here we list some of the other categories appearing throughout this work.

1. The category Sets_* of pointed sets of [Definition 3.1.3.1.1](#).
2. The category Rel of sets and relations of [Definition 5.2.1.1.1](#).
3. The category $\text{Span}(A, B)$ of spans from a set A to a set B of [??](#).
4. The category $\text{ISets}(K)$ of K -indexed sets of [??](#).
5. The category ISets of indexed sets of [??](#).
6. The category $\text{FibSets}(K)$ of K -fibred sets of [??](#).
7. The category FibSets of fibred sets of [??](#).
8. Categories of functors $\text{Fun}(C, \mathcal{D})$ as in [Definition 8.9.1.1.1](#).
9. The category of categories Cats of [Definition 8.9.2.1.1](#).
10. The category of groupoids Grpd of [Definition 8.9.4.1.1](#).

8.1.3 Posetal Categories

Definition 8.1.3.1.1. Let (X, \preceq_X) be a poset.

1. The **posetal category associated to** (X, \preceq_X) is the category X_{pos} where
 - *Objects.* We have

$$\text{Obj}(X_{\text{pos}}) \stackrel{\text{def}}{=} X.$$

isomorphisms of categories

$$\begin{aligned} 1 &\cong \emptyset * \emptyset, \\ 2 &\cong 1 * \emptyset \\ &\cong (\emptyset * \emptyset) * \emptyset, \\ 3 &\cong 2 * \emptyset \\ &\cong (1 * \emptyset) * \emptyset \\ &\cong ((\emptyset * \emptyset) * \emptyset) * \emptyset, \\ 4 &\cong 3 * \emptyset \\ &\cong (2 * \emptyset) * \emptyset \\ &\cong ((1 * \emptyset) * \emptyset) * \emptyset \\ &\cong (((\emptyset * \emptyset) * \emptyset) * \emptyset) * \emptyset, \end{aligned}$$

and so on.

- *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 $a \preceq_X c$.

2. A category C is **posetal**⁴ if C is equivalent to X_{pos} for some poset (X, \preceq_X) .

Proposition 8.1.3.1.2. Let (X, \preceq_X) be a poset and let C be a category.

1. *Functoriality.* The assignment $(X, \preceq_X) \mapsto X_{\text{pos}}$ defines a functor

$$(-)_{\text{pos}} : \text{Pos} \rightarrow \text{Cats}.$$

2. *Fully Faithfulness.* The functor $(-)_{\text{pos}}$ of Item 1 is fully faithful.

3. *Characterisations.* The following conditions are equivalent:

- (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 $f = g$.

Proof. Item 1, Functoriality: Omitted.

Item 2, Fully Faithfulness: Omitted.

Item 3, Characterisations: Clear. □

8.1.4 Subcategories

Let C be a category.

⁴Further Terminology: Also called a **thin** category or a **(0, 1)-category**.

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

$$\circ_{A,B,C}^{\mathcal{A}} = \circ_{A,B,C}^C.$$

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).

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

Definition 8.1.4.1.4. A subcategory \mathcal{A} of C is **wide**⁶ if $\text{Obj}(\mathcal{A}) = \text{Obj}(C)$.

8.1.5 Skeletons of Categories

Definition 8.1.5.1.1. A ⁷skeleton of a category C is a full subcategory $\text{Sk}(C)$ with one object from each isomorphism class of objects of C .

Definition 8.1.5.1.2. A category C is **skeletal** if $C \cong \text{Sk}(C)$.⁸

Proposition 8.1.5.1.3. Let C be a category.

⁵That is, given $A \in \text{Obj}(\mathcal{A})$ and $C \in \text{Obj}(C)$, if $C \cong A$, then $C \in \text{Obj}(\mathcal{A})$.

⁶Further Terminology: Also called **Iluf**.

⁷Due to Item 3 of Proposition 8.1.5.1.3, we often refer to any such full subcategory $\text{Sk}(C)$ of C as *the* skeleton of C .

⁸That is, C is **skeletal** if isomorphic objects of C are equal.

1. *Existence.* Assuming the axiom of choice, $\text{Sk}(C)$ always exists.
2. *Pseudofunctoriality.* The assignment $C \mapsto \text{Sk}(C)$ defines a pseudofunctor

$$\text{Sk}: \text{Cats}_2 \rightarrow \text{Cats}_2.$$

3. *Uniqueness Up to Equivalence.* Any two skeletons of C are equivalent.
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

8.1.6 Precomposition and Postcomposition

Let C be a category and let $A, B, C \in \text{Obj}(C)$.

Definition 8.1.6.1.1. Let $f: A \rightarrow B$ and $g: B \rightarrow C$ be morphisms of C .

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 $\phi \in \text{Hom}_C(B, C)$.

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 $\phi \in \text{Hom}_C(A, B)$.

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 .

1. *Interaction Between Precomposition and Postcomposition.* We have

$$\begin{array}{ccc} \text{Hom}_C(B, C) & \xrightarrow{g_*} & \text{Hom}_C(B, D) \\ g_* \circ f^* = f^* \circ g_*, & \downarrow f^* & \downarrow f^* \\ \text{Hom}_C(A, C) & \xrightarrow{g_*} & \text{Hom}_C(A, D). \end{array}$$

2. *Interaction With Composition I.* We have

$$\begin{array}{ccc} \text{Hom}_C(X, A) & \xrightarrow{f_*} & \text{Hom}_C(X, B) \\ (g \circ f)^* = f^* \circ g^*, & \searrow (g \circ f)_* & \downarrow g_* \\ & & \text{Hom}_C(X, C), \\ \text{Hom}_C(C, X) & \xrightarrow{g^*} & \text{Hom}_C(B, X) \\ (g \circ f)_* = g_* \circ f_*, & \searrow (g \circ f)^* & \downarrow f^* \\ & & \text{Hom}_C(A, X). \end{array}$$

3. *Interaction With Composition II.* We have

$$\begin{array}{ccc} \text{pt} & \xrightarrow{[f]} & \text{Hom}_C(A, B) \\ & \searrow [g \circ f] & \downarrow g_* \\ & & \text{Hom}_C(A, C) \end{array} \quad \begin{array}{c} [g \circ f] = g_* \circ [f], \\ [g \circ f] = f^* \circ [g], \end{array} \quad \begin{array}{ccc} \text{pt} & \xrightarrow{[g]} & \text{Hom}_C(B, C) \\ & \searrow [g \circ f] & \downarrow f^* \\ & & \text{Hom}_C(A, C). \end{array}$$

4. *Interaction With Composition III.* We have

$$\begin{array}{ccc} \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_C(A, C) \\ f^* \circ \circ_{A,B,C}^C = \circ_{X,B,C}^C \circ (f^* \times \text{id}), & \downarrow \text{id} \times f^* & \downarrow f^* \\ \text{Hom}_C(B, C) \times \text{Hom}_C(X, B) & \xrightarrow{\circ_{X,B,C}^C} & \text{Hom}_C(X, C), \\ \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_C(A, C) \\ g_* \circ \circ_{A,B,C}^C = \circ_{A,B,D}^C \circ (\text{id} \times g_*), & \downarrow g_* \times \text{id} & \downarrow g^* \\ \text{Hom}_C(B, D) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,D}^C} & \text{Hom}_C(A, D). \end{array}$$

5. *Interaction With Identities.* We have

$$(\text{id}_A)^* = \text{id}_{\text{Hom}_C(A, B)},$$

$$(\text{id}_B)_* = \text{id}_{\text{Hom}_C(A, B)}.$$

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.

8.2 The Quadruple Adjunction With Sets

8.2.1 Statement

Let C be a category.

Proposition 8.2.1.1.1. We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}): \quad \begin{array}{ccc} \text{Sets} & \xrightarrow{\perp} & \text{Cats}, \\ \downarrow & \perp & \uparrow \\ \text{Obj} & \perp & \text{(-)indisc} \end{array}$$

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

$$(-)_{\text{disc}} : \mathbf{Sets} \rightarrow \mathbf{Cats}.$$

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. □

8.2.2 Connected Components and Connected Categories

8.2.2.1 Connected Components of Categories

Let C be a category.

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} .

8.2.2.2 Sets of Connected Components of Categories

Let C be a category.

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 .

Proposition 8.2.2.2.2. Let C be a category.

1. *Functoriality.* The assignment $C \mapsto \pi_0(C)$ defines a functor

$$\pi_0: \text{Cats} \rightarrow \text{Sets}.$$

2. *Adjointness.* We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}): \text{Sets} \rightleftarrows \text{Cats.}$$

```

    \begin{array}{ccc}
    \text{Sets} & \rightleftarrows & \text{Cats.} \\
    \pi_0 \downarrow & \swarrow (-)_{\text{disc}} & \downarrow \perp \\
    & \text{Obj} & \uparrow \perp \\
    & \uparrow \perp & \nearrow (-)_{\text{indisc}}
    \end{array}
  
```

⁹In other words, a **connected component** of C is an element of the set $\text{Obj}(C)/\sim$

3. *Interaction With Groupoids.* If C is a groupoid, then we have an isomorphism of categories

$$\pi_0(C) \cong K(C),$$

where $K(C)$ is the set of isomorphism classes of C of ??.

4. *Preservation of Colimits.* The functor π_0 of Item 1 preserves colimits. In particular, we have bijections of sets

$$\begin{aligned} \pi_0(C \coprod \mathcal{D}) &\cong \pi_0(C) \coprod \pi_0(\mathcal{D}), \\ \pi_0(C \coprod_{\mathcal{E}} \mathcal{D}) &\cong \pi_0(C) \coprod_{\pi_0(\mathcal{E})} \pi_0(\mathcal{D}), \\ \pi_0\left(\text{CoEq}\left(C \xrightarrow[G]{F} \mathcal{D}\right)\right) &\cong \text{CoEq}\left(\pi_0(C) \xrightarrow[\pi_0(G)]{\pi_0(F)} \pi_0(\mathcal{D})\right), \end{aligned}$$

natural in $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$.

5. *Symmetric Strong Monoidality With Respect to Coproducts.* The connected components functor of Item 1 has a symmetric strong monoidal structure

$$\left(\pi_0, \pi_0^{\coprod}, \pi_{0|1}^{\coprod}\right): (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Sets}, \coprod, \emptyset),$$

being equipped with isomorphisms

$$\begin{aligned} \pi_{0|C,\mathcal{D}}^{\coprod}: \pi_0(C) \coprod \pi_0(\mathcal{D}) &\xrightarrow{\cong} \pi_0(C \coprod \mathcal{D}), \\ \pi_{0|1}^{\coprod}: \emptyset &\xrightarrow{\cong} \pi_0(\emptyset_{\text{cat}}), \end{aligned}$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$.

6. *Symmetric Strong Monoidality With Respect to Products.* The connected components functor of Item 1 has a symmetric strong monoidal structure

$$\left(\pi_0, \pi_0^{\times}, \pi_{0|1}^{\times}\right): (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Sets}, \times, \text{pt}),$$

being equipped with isomorphisms

$$\begin{aligned} \pi_{0|C,\mathcal{D}}^{\times}: \pi_0(C) \times \pi_0(\mathcal{D}) &\xrightarrow{\cong} \pi_0(C \times \mathcal{D}), \\ \pi_{0|1}^{\times}: \text{pt} &\xrightarrow{\cong} \pi_0(\text{pt}), \end{aligned}$$

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.

□

8.2.2.3 Connected Categories

Definition 8.2.2.3.1. A category C is **connected** if $\pi_0(C) \cong \text{pt}$.^{10,11}

8.2.3 Discrete Categories

Definition 8.2.3.1.1. Let X be a set.

1. The **discrete category on X** is the category X_{disc} where

- *Objects.* We have

$$\text{Obj}(X_{\text{disc}}) \stackrel{\text{def}}{=} X.$$

- *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

$$\text{id}_A \circ \text{id}_A \stackrel{\text{def}}{=} \text{id}_A.$$

with \sim 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 .

¹⁰Further Terminology: A category is **disconnected** if it is not connected.

¹¹Example: A groupoid is connected iff any two of its objects are isomorphic.

2. A category C is **discrete** if it is equivalent to X_{disc} for some set X .

Proposition 8.2.3.1.2. Let X be a set.

1. *Functoriality.* The assignment $X \mapsto X_{\text{disc}}$ defines a functor

$$(-)_{\text{disc}} : \mathbf{Sets} \rightarrow \mathbf{Cats}.$$

2. *Adjointness.* We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}) : \mathbf{Sets} \rightleftarrows \mathbf{Cats.}$$

3. *Symmetric Strong Monoidality With Respect to Coproducts.* The functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left((-)_{\text{disc}}, (-)_{\text{disc}}^{\coprod}, (-)_{\text{disc}|\mathbb{1}}^{\coprod} \right) : (\mathbf{Sets}, \coprod, \emptyset) \rightarrow (\mathbf{Cats}, \coprod, \emptyset_{\text{cat}}),$$

being equipped with isomorphisms

$$\begin{aligned} (-)_{\text{disc}|X,Y}^{\coprod} : X_{\text{disc}} \coprod Y_{\text{disc}} &\xrightarrow{\cong} (X \coprod Y)_{\text{disc}}, \\ (-)_{\text{disc}|\mathbb{1}}^{\coprod} : \emptyset_{\text{cat}} &\xrightarrow{\cong} \emptyset_{\text{disc}}, \end{aligned}$$

natural in $X, Y \in \text{Obj}(\mathbf{Sets})$.

4. *Symmetric Strong Monoidality With Respect to Products.* The functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left((-)_{\text{disc}}, (-)_{\text{disc}}^{\times}, (-)_{\text{disc}|\mathbb{1}}^{\times} \right) : (\mathbf{Sets}, \times, \text{pt}) \rightarrow (\mathbf{Cats}, \times, \text{pt}),$$

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 $X, Y \in \text{Obj}(\mathbf{Sets})$.

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

8.2.4 Indiscrete Categories

Definition 8.2.4.1.1. Let X be a set.

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

$$\begin{aligned} \text{Hom}_{X_{\text{disc}}}(A, B) &\stackrel{\text{def}}{=} \{[A] \rightarrow [B]\} \\ &\cong \text{pt}. \end{aligned}$$

- *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

$$([B] \rightarrow [C]) \circ ([A] \rightarrow [B]) \stackrel{\text{def}}{=} ([A] \rightarrow [C]).$$

2. A category C is **indiscrete** if it is equivalent to X_{indisc} for some set X .

Proposition 8.2.4.1.2. Let X be a set.

1. *Functoriality.* The assignment $X \mapsto X_{\text{indisc}}$ defines a functor

$$(-)_{\text{indisc}} : \mathbf{Sets} \rightarrow \mathbf{Cats}.$$

2. *Adjointness.* We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}) : \mathbf{Sets} \rightleftarrows \mathbf{Cats}.$$

```

    \begin{array}{ccc}
    \mathbf{Sets} & \rightleftarrows & \mathbf{Cats} \\
    \pi_0 \downarrow & \swarrow (-)_{\text{disc}} & \downarrow \perp \\
    & \text{Obj} & \uparrow \perp \\
    \downarrow \perp & \nearrow (-)_{\text{indisc}} & \\
    \end{array}
  
```

¹²Further Terminology: Sometimes called the **chaotic category on X** .

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

$$\begin{aligned} (-)_{\text{indisc}|X,Y}^{\times}: X_{\text{indisc}} \times Y_{\text{indisc}} &\xrightarrow{\cong} (X \times Y)_{\text{indisc}}, \\ (-)_{\text{indisc}|\mathbb{1}}^{\times}: \text{pt} &\xrightarrow{\cong} \text{pt}_{\text{indisc}}, \end{aligned}$$

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 Products:* Clear. \square

8.3 Groupoids

8.3.1 Foundations

Let C be a category.

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

$$\begin{aligned} f \circ f^{-1} &= \text{id}_B, \\ f^{-1} \circ f &= \text{id}_A. \end{aligned}$$

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 .

Definition 8.3.1.1.3. A **groupoid** is a category in which every morphism is an isomorphism.

8.3.2 The Groupoid Completion of a Category

Let C be a category.

Definition 8.3.2.1.1. The **groupoid completion of C** ¹³ is the pair $(K_0(C), \iota_C)$ consisting of

- A groupoid $K_0(C)$;

¹³Further Terminology: Also called the **Grothendieck groupoid of C** or the **Grothendieck groupoid completion of 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

$$\begin{array}{ccc} & K_0(C) & \\ \iota_C \nearrow & \downarrow \exists! & \\ C & \xrightarrow{i} & \mathcal{G} \end{array}$$

commute.

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. □

Proposition 8.3.2.1.3. Let C be a category.

1. *Functoriality.* The assignment $C \mapsto K_0(C)$ defines a functor

$$K_0 : \mathbf{Cats} \rightarrow \mathbf{Grpd}.$$

2. *2-Functoriality.* The assignment $C \mapsto K_0(C)$ defines a 2-functor

$$K_0 : \mathbf{Cats}_2 \rightarrow \mathbf{Grpd}_2.$$

3. *Adjointness.* We have an adjunction

$$(K_0 \dashv \iota) : \mathbf{Cats} \begin{array}{c} \xrightarrow{K_0} \\[-1ex] \perp \\[-1ex] \xleftarrow{\iota} \end{array} \mathbf{Grpd},$$

witnessed by a bijection of sets

$$\text{Hom}_{\mathbf{Grpd}}(K_0(C), \mathcal{G}) \cong \text{Hom}_{\mathbf{Cats}}(C, \mathcal{G}),$$

natural in $C \in \text{Obj}(\mathbf{Cats})$ and $\mathcal{G} \in \text{Obj}(\mathbf{Grpd})$, forming, together with the functor Core of Item 1 of Proposition 8.3.3.1.4, a triple adjunction

$$(K_0 \dashv \iota \dashv \text{Core}) : \mathbf{Cats} \begin{array}{c} \xleftarrow{\perp} \\[-1ex] \iota \\[-1ex] \xrightarrow{\perp} \\[-1ex] \text{Core} \end{array} \mathbf{Grpd},$$

¹⁴See Item 5 of Proposition 8.3.2.1.3 for an explicit construction.

witnessed by bijections of sets

$$\begin{aligned}\mathrm{Hom}_{\mathbf{Grpd}}(K_0(C), \mathcal{G}) &\cong \mathrm{Hom}_{\mathbf{Cats}}(C, \mathcal{G}), \\ \mathrm{Hom}_{\mathbf{Cats}}(\mathcal{G}, \mathcal{D}) &\cong \mathrm{Hom}_{\mathbf{Grpd}}(\mathcal{G}, \mathrm{Core}(\mathcal{D})),\end{aligned}$$

natural in $C, \mathcal{D} \in \mathrm{Obj}(\mathbf{Cats})$ and $\mathcal{G} \in \mathrm{Obj}(\mathbf{Grpd})$.

4. *2-Adjointness.* We have a 2-adjunction

$$(K_0 \dashv \iota): \quad \mathbf{Cats} \begin{array}{c} \xrightarrow{\quad K_0 \quad} \\[-1ex] \xleftarrow[\iota]{\perp_2} \end{array} \mathbf{Grpd},$$

witnessed by an isomorphism of categories

$$\mathrm{Fun}(K_0(C), \mathcal{G}) \cong \mathrm{Fun}(C, \mathcal{G}),$$

natural in $C \in \mathrm{Obj}(\mathbf{Cats})$ and $\mathcal{G} \in \mathrm{Obj}(\mathbf{Grpd})$, forming, together with the 2-functor Core of [Item 2 of Proposition 8.3.3.1.4](#), a triple 2-adjunction

$$(K_0 \dashv \iota \dashv \mathrm{Core}): \quad \mathbf{Cats} \begin{array}{c} \xrightarrow{\quad K_0 \quad} \\[-1ex] \xleftarrow[\iota]{\perp_2} \xrightarrow{\quad \mathrm{Core} \quad} \\[-1ex] \xleftarrow[\mathrm{Core}]{\perp_2} \end{array} \mathbf{Grpd},$$

witnessed by isomorphisms of categories

$$\begin{aligned}\mathrm{Fun}(K_0(C), \mathcal{G}) &\cong \mathrm{Fun}(C, \mathcal{G}), \\ \mathrm{Fun}(\mathcal{G}, \mathcal{D}) &\cong \mathrm{Fun}(\mathcal{G}, \mathrm{Core}(\mathcal{D})),\end{aligned}$$

natural in $C, \mathcal{D} \in \mathrm{Obj}(\mathbf{Cats})$ and $\mathcal{G} \in \mathrm{Obj}(\mathbf{Grpd})$.

5. *Interaction With Classifying Spaces.* We have an isomorphism of groupoids

$$K_0(C) \cong \Pi_{\leq 1}(|N_\bullet(C)|),$$

natural in $C \in \mathrm{Obj}(\mathbf{Cats})$; i.e. the diagram

$$\begin{array}{ccc} \mathbf{Cats} & \xrightarrow{K_0} & \mathbf{Grp} \\ N_\bullet \downarrow & \nwarrow \Sigma^\bullet & \uparrow \Pi_{\leq 1} \\ \mathbf{sSets} & \xrightarrow{|-|} & \mathbf{Top} \end{array}$$

commutes up to natural isomorphism.

6. *Symmetric Strong Monoidality With Respect to Coproducts.* The groupoid completion functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left(K_0, K_0^{\coprod}, K_{0|1}^{\coprod} \right) : (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Grpd}, \coprod, \emptyset_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned} K_{0|C,D}^{\coprod} &: K_0(C) \coprod K_0(D) \xrightarrow{\cong} K_0(C \coprod D), \\ K_{0|1}^{\coprod} &: \emptyset_{\text{cat}} \xrightarrow{\cong} K_0(\emptyset_{\text{cat}}), \end{aligned}$$

natural in $C, D \in \text{Obj}(\text{Cats})$.

7. *Symmetric Strong Monoidality With Respect to Products.* The groupoid completion functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left(K_0, K_0^{\times}, K_{0|1}^{\times} \right) : (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned} K_{0|C,D}^{\times} &: K_0(C) \times K_0(D) \xrightarrow{\cong} K_0(C \times D), \\ K_{0|1}^{\times} &: \text{pt} \xrightarrow{\cong} K_0(\text{pt}), \end{aligned}$$

natural in $C, D \in \text{Obj}(\text{Cats})$.

Proof. [Item 1](#), *Functionality*: Omitted.

[Item 2](#), *2-Functionality*: 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/dafra/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.

□

8.3.3 The Core of a Category

Let C be a category.

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

$$\begin{array}{ccc} & \text{Core}(C) & \\ \exists! \nearrow & \nearrow \iota_C & \\ \mathcal{G} & \xrightarrow{i} & C \end{array}$$

commute.

Notation 8.3.3.1.2. We also write C^\simeq for $\text{Core}(C)$.

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). \square

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

$$(\iota \dashv \text{Core}) : \text{Grpd} \begin{array}{c} \xrightarrow{\iota} \\ \perp \\ \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

¹⁵*Slogan:* The groupoid $\text{Core}(C)$ is the maximal subgroupoid of C .

witnessed by a bijection of sets

$$\text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) \cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

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

$$(K_0 \dashv \iota \dashv \text{Core}): \quad \text{Cats} \begin{array}{c} \xleftarrow{\iota} \\[-1ex] \xrightarrow{\perp} \\[-1ex] \xleftarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by bijections of sets

$$\text{Hom}_{\text{Grpd}}(K_0(C), \mathcal{G}) \cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}),$$

$$\text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) \cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

4. *2-Adjointness.* We have an adjunction

$$(\iota \dashv \text{Core}): \quad \text{Grpd} \begin{array}{c} \xleftarrow{\iota} \\[-1ex] \xrightarrow{\perp_2} \\[-1ex] \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

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

$$(K_0 \dashv \iota \dashv \text{Core}): \quad \text{Cats} \begin{array}{c} \xleftarrow{\iota} \\[-1ex] \xrightarrow{\perp_2} \\[-1ex] \xleftarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by isomorphisms of categories

$$\text{Fun}(K_0(C), \mathcal{G}) \cong \text{Fun}(C, \mathcal{G}),$$

$$\text{Fun}(\mathcal{G}, \mathcal{D}) \cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

natural in $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

5. *Symmetric Strong Monoidality With Respect to Products.* The core functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left(\text{Core}, \text{Core}^{\times}, \text{Core}_{\mathbb{1}}^{\times} \right) : (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned} \text{Core}_{C,D}^{\times} : \text{Core}(C) \times \text{Core}(D) &\xrightarrow{\cong} \text{Core}(C \times D), \\ \text{Core}_{\mathbb{1}}^{\times} : \text{pt} &\xrightarrow{\cong} \text{Core}(\text{pt}), \end{aligned}$$

natural in $C, D \in \text{Obj}(\text{Cats})$.

6. *Symmetric Strong Monoidality With Respect to Coproducts.* The core functor of [Item 1](#) has a symmetric strong monoidal structure

$$\left(\text{Core}, \text{Core}^{\coprod}, \text{Core}_{\mathbb{1}}^{\coprod} \right) : (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Grpd}, \coprod, \emptyset_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned} \text{Core}_{C,D}^{\coprod} : \text{Core}(C) \coprod \text{Core}(D) &\xrightarrow{\cong} \text{Core}(C \coprod D), \\ \text{Core}_{\mathbb{1}}^{\coprod} : \emptyset_{\text{cat}} &\xrightarrow{\cong} \text{Core}(\emptyset_{\text{cat}}), \end{aligned}$$

natural in $C, D \in \text{Obj}(\text{Cats})$.

Proof. [Item 1](#), *Functionality:* Omitted.

[Item 2](#), *2-Functionality:* 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

8.4 Functors

8.4.1 Foundations

Let C and D be categories.

Definition 8.4.1.1.1. A functor $F: C \rightarrow D$ from C to D ¹⁶ consists of:

¹⁶Further Terminology: Also called a **covariant functor**.

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

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(A), F(B)),$$

called the **action on morphisms of F at (A, B)** ¹⁷.

satisfying the following conditions:

1. *Preservation of Identities.* For each $A \in \text{Obj}(\mathcal{C})$, the diagram

$$\begin{array}{ccc} & \text{pt} & \\ \mathbb{1}_A^{\mathcal{C}} \downarrow & \searrow \mathbb{1}_{F(A)}^{\mathcal{D}} & \\ \text{Hom}_{\mathcal{C}}(A, A) & \xrightarrow{F_{A,A}} & \text{Hom}_{\mathcal{D}}(F(A), F(A)) \end{array}$$

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

$$\begin{array}{ccc} \text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(A, B) & \xrightarrow{\circ_{A,B,C}^{\mathcal{C}}} & \text{Hom}_{\mathcal{C}}(A, C) \\ F_{B,C} \times F_{A,B} \downarrow & & \downarrow F_{A,C} \\ \text{Hom}_{\mathcal{D}}(F(B), F(C)) \times \text{Hom}_{\mathcal{D}}(F(A), F(B)) & \xrightarrow{\circ_{F(A), F(B), F(C)}^{\mathcal{D}}} & \text{Hom}_{\mathcal{D}}(F(A), F(C)) \end{array}$$

commutes, i.e. for each composable pair (g, f) of morphisms of \mathcal{C} , we have

$$F(g \circ f) = F(g) \circ F(f).$$

Notation 8.4.1.1.2. Let \mathcal{C} and \mathcal{D} be categories, and write \mathcal{C}^{op} for the opposite category of \mathcal{C} of ??.

1. Given a functor

$$F: \mathcal{C} \rightarrow \mathcal{D},$$

we also write F_A for $F(A)$.

¹⁷Further Terminology: Also called **action on Hom-sets of F at (A, B) .**

2. Given a functor

$$F: \mathcal{C}^{\text{op}} \rightarrow \mathcal{D},$$

we also write F^A for $F(A)$.

3. Given a functor

$$F: \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{D},$$

we also write $F_{A,B}$ for $F(A, B)$.

4. Given a functor

$$F: \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \mathcal{D},$$

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 $F: \mathcal{C} \rightarrow \mathcal{D}$.

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 $F: \mathcal{C} \rightarrow \mathcal{D}$ 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.

Example 8.4.1.1.4. The **identity functor** of a category \mathcal{C} is the functor $\text{id}_{\mathcal{C}}: \mathcal{C} \rightarrow \mathcal{C}$ where

1. *Action on Objects.* For each $A \in \text{Obj}(\mathcal{C})$, we have

$$\text{id}_{\mathcal{C}}(A) \stackrel{\text{def}}{=} A.$$

2. *Action on Morphisms.* For each $A, B \in \text{Obj}(\mathcal{C})$, the action on morphisms

$$(\text{id}_{\mathcal{C}})_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \underbrace{\text{Hom}_{\mathcal{C}}(\text{id}_{\mathcal{C}}(A), \text{id}_{\mathcal{C}}(B))}_{\stackrel{\text{def}}{=} \text{Hom}_{\mathcal{C}}(A, B)}$$

of $\text{id}_{\mathcal{C}}$ at (A, B) is defined by

$$(\text{id}_{\mathcal{C}})_{A,B} \stackrel{\text{def}}{=} \text{id}_{\text{Hom}_{\mathcal{C}}(A, B)}.$$

Proof. Preservation of Identities: We have $\text{id}_{\mathcal{C}}(\text{id}_A) \stackrel{\text{def}}{=} \text{id}_A$ for each $A \in \text{Obj}(\mathcal{C})$ by definition.

Preservation of Compositions: For each composable pair $A \xrightarrow{f} B \xrightarrow{g} C$ of morphisms of \mathcal{C} , we have

$$\begin{aligned} \text{id}_{\mathcal{C}}(g \circ f) &\stackrel{\text{def}}{=} g \circ f \\ &\stackrel{\text{def}}{=} \text{id}_{\mathcal{C}}(g) \circ \text{id}_{\mathcal{C}}(f). \end{aligned}$$

This finishes the proof. □

Definition 8.4.1.1.5. The **composition** of two functors $F: \mathcal{C} \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{E}$ is the functor $G \circ F$ where

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

$$[G \circ F](A) \stackrel{\text{def}}{=} G(F(A)).$$

- *Action on Morphisms.* For each $A, B \in \text{Obj}(\mathcal{C})$, the action on morphisms

$$(G \circ F)_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{E}}(G_{F_A}, G_{F_B})$$

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 $A \in \text{Obj}(\mathcal{C})$, 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 \mathcal{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

Proposition 8.4.1.1.6. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Preservation of Isomorphisms.* If f is an isomorphism in \mathcal{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.

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 ??.

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} .

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

$$\begin{array}{ccccc} & \text{Hom}_{\mathcal{D}}(F(C), F(B)) \times \text{Hom}_{\mathcal{D}}(F(B), F(A)) & & & \\ & \nearrow F_{B,C} \times F_{A,B} & \searrow \sigma_{\text{Hom}_{\mathcal{D}}(F(C), F(B)), \text{Hom}_{\mathcal{D}}(F(B), F(A))}^{\text{Sets}} & & \\ \text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(A, B) & \xrightarrow{\circlearrowleft} & \text{Hom}_{\mathcal{D}}(F(B), F(A)) \times \text{Hom}_{\mathcal{D}}(F(C), F(B)) & \xrightarrow{\circlearrowright} & \\ & \swarrow \circ_{A,B,C}^{\mathcal{C}} & & \searrow \circ_{F(C), F(B), F(A)}^{\mathcal{D}} & \\ & \text{Hom}_{\mathcal{C}}(A, C) & \xrightarrow{F_{A,C}} & \text{Hom}_{\mathcal{D}}(F(C), F(A)) & \end{array}$$

commutes, i.e. for each composable pair (g, f) of morphisms of \mathcal{C} , we have

$$F(g \circ f) = F(f) \circ F(g).$$

Remark 8.4.2.1.3. Throughout this work we will not use the term “contravariant” functor, speaking instead simply of functors $F: \mathcal{C}^{\text{op}} \rightarrow \mathcal{D}$. We will usually, however, write

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(B), F(A))$$

for the action on morphisms

$$F_{A,B}: \text{Hom}_{\mathcal{C}^{\text{op}}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(A), F(B))$$

of F , as well as write $F(g \circ f) = F(f) \circ F(g)$.

8.4.3 Forgetful Functors

Definition 8.4.3.1.1. There isn’t a precise definition of a **forgetful functor**.

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).

Example 8.4.3.1.3. Examples of forgetful functors that forget structure include:

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 .
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 .
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 .

Example 8.4.3.1.4. Examples of forgetful functors that forget properties include:

1. *Forgetting Commutativity.* The inclusion functor $\iota: \text{CMon} \hookrightarrow \text{Mon}$ which forgets the property of being commutative.

2. *Forgetting Inverses.* The inclusion functor $\iota: \mathbf{Grp} \hookrightarrow \mathbf{Mon}$ which forgets the property of having inverses.

Notation 8.4.3.1.5. Throughout this work, we will denote forgetful functors that forget structure by 忘, e.g. as in

$$\text{忘}: \mathbf{Grp} \rightarrow \mathbf{Sets}.$$

The symbol 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:

1. 忘れる, transcribed as *wasureru*, meaning *to forget*.
2. 忘却関手, transcribed as *boukyaku kanshu*, meaning *forgetful functor*.
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*.

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.

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: [uɸäsiɸrərɯŋ̩].

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: [bø:kłäkuu kãũqeuu].
- IPA narrow transcription: [bø:kłäkɯŋ̩ kãũqeuŋ̩].

3. Pronunciation of 忘记:

- Audio: see <https://topological-modular-forms.github.io/the-clowder-project/static/sounds/wasureru-03.ogg>
- Broad IPA transcription: [wan̥tei].
- Sinological IPA transcription: [wan᷑ŋ⁵¹⁻⁵³t̥ei᷑⁵¹].

4. Pronunciation of 遗忘函子:

- Audio: see <https://topological-modular-forms.github.io/the-clowder-project/static/sounds/wasureru-04.mp3>
- Broad IPA transcription: [iwaŋ xäñfsz̩].
- Sinological IPA transcription: [i³⁵wɑŋ⁵¹ xān³⁵fʂz̩²¹⁴⁻²¹⁽⁴⁾].

8.4.4 The Natural Transformation Associated to a Functor

Definition 8.4.4.1.1. Every functor $F: \mathcal{C} \rightarrow \mathcal{D}$ defines a natural transformation¹⁹

$$F^\dagger: \text{Hom}_{\mathcal{C}} \Rightarrow \text{Hom}_{\mathcal{D}} \circ (F^{\text{op}} \times F), \quad \begin{array}{ccc} \mathcal{C}^{\text{op}} \times \mathcal{C} & \xrightarrow{F^{\text{op}} \times F} & \mathcal{D}^{\text{op}} \times \mathcal{D} \\ \text{Hom}_{\mathcal{C}} \searrow & \nearrow F^\dagger & \swarrow \text{Hom}_{\mathcal{D}} \\ & \text{Sets}, & \end{array}$$

called the **natural transformation associated to F** , consisting of the collection

$$\left\{ F_{A,B}^\dagger: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B) \right\}_{(A,B) \in \text{Obj}(\mathcal{C}^{\text{op}} \times \mathcal{C})}$$

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 $\mathcal{C}^{\text{op}} \times \mathcal{C}$, the diagram

$$\begin{array}{ccc} \text{Hom}_{\mathcal{C}}(X, Y) & \xrightarrow{\phi^* \circ \psi_* = \psi_* \circ \phi^*} & \text{Hom}_{\mathcal{C}}(A, B) \\ F_{X,Y} \downarrow & & \downarrow F_{A,B} \\ \text{Hom}_{\mathcal{D}}(F_X, F_Y) & \xrightarrow[F(\phi)^* \circ F(\psi)_* = F(\psi)_* \circ F(\phi)^*]{} & \text{Hom}_{\mathcal{D}}(F_A, F_B), \end{array}$$

acting on elements as

$$\begin{array}{ccc} f & \longmapsto & \psi \circ f \circ \phi \\ \downarrow & & \downarrow \\ F(f) & \mapsto & F(\psi) \circ F(f) \circ F(\phi) = F(\psi \circ f \circ \phi) \end{array}$$

commutes, which follows from the functoriality of F . \square

¹⁹This is the 1-categorical version of Item 1 of Proposition 2.4.1.1.3.

Proposition 8.4.4.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{E}$ be functors.

1. *Interaction With Natural Isomorphisms.* The following conditions are equivalent:

- (a) The natural transformation $F^\dagger: \text{Hom}_{\mathcal{C}} \Rightarrow \text{Hom}_{\mathcal{D}} \circ (F^{\text{op}} \times F)$ associated to F is a natural isomorphism.
- (b) The functor F is fully faithful.

2. *Interaction With Composition.* We have an equality of pasting diagrams

$$\begin{array}{ccc} \mathcal{C}^{\text{op}} \times \mathcal{C} & \xrightarrow{F^{\text{op}} \times F} & \mathcal{D}^{\text{op}} \times \mathcal{D} \xrightarrow{G^{\text{op}} \times G} \mathcal{E}^{\text{op}} \times \mathcal{E} \\ \searrow \text{Hom}_{\mathcal{C}} \quad \nearrow F^\dagger \quad \downarrow \text{Hom}_{\mathcal{D}} \quad \nearrow G^\dagger \quad \downarrow \text{Hom}_{\mathcal{E}} \\ & \text{Sets} & \\ & = & \\ \mathcal{C}^{\text{op}} \times \mathcal{C} & \xrightarrow{(G \circ F)^{\text{op}} \times (G \circ F)} & \mathcal{E}^{\text{op}} \times \mathcal{E}, \\ \searrow \text{Hom}_{\mathcal{C}} \quad \nearrow (G \circ F)^\dagger \quad \downarrow \text{Hom}_{\mathcal{E}} \\ & \text{Sets} & \end{array}$$

in Cats_2 , i.e. we have

$$(G \circ F)^\dagger = (G^\dagger \star \text{id}_{F^{\text{op}} \times F}) \circ F^\dagger.$$

3. *Interaction With Identities.* We have

$$\text{id}_C^\dagger = \text{id}_{\text{Hom}_{\mathcal{C}}(-1, -2)},$$

i.e. the natural transformation associated to id_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. \square

8.5 Conditions on Functors

8.5.1 Faithful Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.5.1.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **faithful** if, for each $A, B \in \text{Obj}(\mathcal{C})$, the action on morphisms

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is injective.

Proposition 8.5.1.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Interaction With Postcomposition.* The following conditions are equivalent:

- (a) The functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is faithful.
- (b) For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the postcomposition functor

$$F_*: \mathsf{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \mathsf{Fun}(\mathcal{X}, \mathcal{D})$$

is faithful.

- (c) The functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is a representably faithful morphism in \mathbf{Cats}_2 in the sense of [Definition 9.1.1.1.1](#).

2. *Interaction With Precomposition I.* Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

- (a) If F is faithful, then the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

can fail to be faithful.

- (b) Conversely, if the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is faithful, then F *can fail* to be faithful.

3. *Interaction With Precomposition II.* If F is essentially surjective, then the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is faithful.

4. *Interaction With Precomposition III.* The following conditions are equivalent:

- (a) For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is faithful.

- (b) For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is conservative.

(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.

(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](#).

(e) The components

$$\eta_G: G \Rightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta: \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})} \Rightarrow \text{Ran}_F \circ F^*$$

of the adjunction $F^* \dashv \text{Ran}_F$ are all monomorphisms.

(f) The components

$$\epsilon_G: \text{Lan}_F(G \circ F) \Rightarrow G$$

of the counit

$$\epsilon: \text{Lan}_F \circ F^* \Rightarrow \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction $\text{Lan}_F \dashv F^*$ are all epimorphisms.

(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 $\text{Im}(F)$:

(\star) 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. \square

8.5.2 Full Functors

Let C and \mathcal{D} be categories.

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.

Proposition 8.5.2.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor.

1. *Interaction With Postcomposition.* The following conditions are equivalent:
 - (a) The functor $F: C \rightarrow \mathcal{D}$ is full.
 - (b) For each $X \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(X, C) \rightarrow \text{Fun}(X, \mathcal{D})$$

is full.

- (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](#).

2. *Interaction With Precomposition I.* If F is full, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(C, X)$$

can fail to be full.

3. *Interaction With Precomposition II.* If the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(C, X)$$

is full, then F can fail to be full.

4. *Interaction With Precomposition III.* If F is essentially surjective

and full, then the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is full (and also faithful by Item 3 of Proposition 8.5.1.1.2).

5. *Interaction With Precomposition IV.* The following conditions are equivalent:

- (a) For each $\mathcal{X} \in \mathbf{Obj}(\mathbf{Cats})$, the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is full.

- (b) The functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is a corepresentably full morphism in \mathbf{Cats}_2 in the sense of Definition 9.2.1.1.1.

- (c) The components

$$\eta_G: G \Rightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta: \text{id}_{\mathsf{Fun}(\mathcal{D}, \mathcal{X})} \Rightarrow \text{Ran}_F \circ F^*$$

of the adjunction $F^* \dashv \text{Ran}_F$ are all retractions/split epimorphisms.

- (d) The components

$$\epsilon_G: \text{Lan}_F(G \circ F) \Rightarrow G$$

of the counit

$$\epsilon: \text{Lan}_F \circ F^* \Rightarrow \text{id}_{\mathsf{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction $\text{Lan}_F \dashv F^*$ are all sections/split monomorphisms.

- (e) For each $B \in \mathbf{Obj}(\mathcal{D})$, 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:

- (\star) For each $A \in \mathbf{Obj}(\mathcal{C})$ and each pair of morphisms

$$r: F(A) \rightarrow B,$$

$$s: B \rightarrow F(A)$$

of \mathcal{D} , we have

$$[(A_B, s_B, r_B)] = [(A, s, r \circ s_B \circ r_B)]$$

in $\int^{A \in \mathcal{C}} h_{F_A}^{B'} \times h_B^{F_A}$.

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.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

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 [\[MO 468121b\]](#).

8.5.3 Fully Faithful Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.5.3.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **fully faithful** if F is full and faithful, i.e. if, for each $A, B \in \text{Obj}(\mathcal{C})$, the action on morphisms

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is bijective.

Proposition 8.5.3.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* The following conditions are equivalent:
 - (a) The functor F is fully faithful.
 - (b) We have a pullback square

$$\begin{array}{ccc} \text{Arr}(\mathcal{C}) & \xrightarrow{\text{Arr}(F)} & \text{Arr}(\mathcal{D}) \\ \text{Arr}(\mathcal{C}) \cong (\mathcal{C} \times \mathcal{C}) \times_{\mathcal{D} \times \mathcal{D}} \text{Arr}(\mathcal{D}), & \downarrow \text{src} \times \text{tgt} & \downarrow \text{src} \times \text{tgt} \\ \mathcal{C} \times \mathcal{C} & \xrightarrow{F \times F} & \mathcal{D} \times \mathcal{D} \end{array}$$

in Cats .

2. *Conservativity.* If F is fully faithful, then F is conservative.
3. *Essential Injectivity.* If F is fully faithful, then F is essentially injective.
4. *Interaction With Co/Limits.* If F is fully faithful, then F reflects co/limits.
5. *Interaction With Postcomposition.* The following conditions are equivalent:
 - (a) The functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is fully faithful.
 - (b) 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 fully faithful.

- (c) The functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is a representably fully faithful morphism in Cats_2 in the sense of [Definition 9.1.3.1.1](#).

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.

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).

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.

9. *Interaction With Precomposition IV.* The following conditions are equivalent:

- (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.

(b) The precomposition functor

$$F^*: \mathbf{Fun}(\mathcal{D}, \mathbf{Sets}) \rightarrow \mathbf{Fun}(\mathcal{C}, \mathbf{Sets})$$

is fully faithful.

(c) The functor

$$\text{Lan}_F: \mathbf{Fun}(\mathcal{C}, \mathbf{Sets}) \rightarrow \mathbf{Fun}(\mathcal{D}, \mathbf{Sets})$$

is fully faithful.

(d) The functor F is a corepresentably fully faithful morphism in \mathbf{Cats}_2 in the sense of [Definition 9.2.3.1.1](#).

(e) The functor F is absolutely dense.

(f) The components

$$\eta_G: G \Longrightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta: \text{id}_{\mathbf{Fun}(\mathcal{D}, \mathcal{X})} \Longrightarrow \text{Ran}_F \circ F^*$$

of the adjunction $F^* \dashv \text{Ran}_F$ are all isomorphisms.

(g) The components

$$\epsilon_G: \text{Lan}_F(G \circ F) \Longrightarrow G$$

of the counit

$$\epsilon: \text{Lan}_F \circ F^* \Longrightarrow \text{id}_{\mathbf{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction $\text{Lan}_F \dashv F^*$ are all isomorphisms.

(h) The natural transformation

$$\alpha: \text{Lan}_{h_F}(h^F) \Longrightarrow h$$

with components

$$\alpha_{B', B}: \int^{A \in \mathcal{C}} h_{F_A}^{B'} \times h_B^{F_A} \rightarrow h_B^{B'}$$

given by

$$\alpha_{B', B}([\phi, \psi]) = \psi \circ \phi$$

is a natural isomorphism.

(i) 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 conditions:

- i. The triple $(F(A_B), r_B, s_B)$ is a retract of B , i.e. we have $r_B \circ s_B = \text{id}_B$.
- ii. For each morphism $f: B' \rightarrow B$ of \mathcal{D} , we have

$$[(A_B, s_{B'}, f \circ r_{B'})] = [(A_B, s_B \circ f, r_B)]$$

$$\text{in } \int^{A \in \mathcal{C}} h_{F_A}^{B'} \times h_B^{F_A}.$$

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.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. □

8.5.4 Conservative Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.5.4.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **conservative** if it satisfies the following condition:²⁰

- (\star) For each $f \in \text{Mor}(\mathcal{C})$, if $F(f)$ is an isomorphism in \mathcal{D} , then f is an isomorphism in \mathcal{C} .

Proposition 8.5.4.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* The following conditions are equivalent:
 - (a) The functor F is conservative.
 - (b) For each $f \in \text{Mor}(\mathcal{C})$, the morphism $F(f)$ is an isomorphism in \mathcal{D} iff f is an isomorphism in \mathcal{C} .
2. *Interaction With Fully Faithfulness.* Every fully faithful functor is conservative.
3. *Interaction With Precomposition.* The following conditions are equivalent:
 - (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 conservative.

- (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 $F: \mathcal{C} \rightarrow \mathcal{D}$ be a fully faithful functor, let $f: A \rightarrow B$ be a morphism of \mathcal{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

²⁰Slogan: A functor F is **conservative** if it reflects isomorphisms.

Question 8.5.4.1.3. Is there a characterisation of functors $F: \mathcal{C} \rightarrow \mathcal{D}$ satisfying the following condition:

- (\star) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is conservative?

This question also appears as [MO 468121a].

8.5.5 Essentially Injective Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.5.5.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **essentially injective** if it satisfies the following condition:

- (\star) For each $A, B \in \text{Obj}(\mathcal{C})$, if $F(A) \cong F(B)$, then $A \cong B$.

Question 8.5.5.1.2. Is there a characterisation of functors $F: \mathcal{C} \rightarrow \mathcal{D}$ such that:

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 essentially injective, i.e. if $\phi \circ F \cong \psi \circ F$, then $\phi \cong \psi$ for all functors ϕ and ψ ?

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 essentially injective, i.e. if $F \circ \phi \cong F \circ \psi$, then $\phi \cong \psi$?

This question also appears as [MO 468121a].

8.5.6 Essentially Surjective Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.5.6.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **essentially surjective**²¹ if it satisfies the following condition:

- (\star) For each $D \in \text{Obj}(\mathcal{D})$, there exists some object A of \mathcal{C} such that $F(A) \cong D$.

²¹Further Terminology: Also called an **eso** functor, where the name “eso” comes

Question 8.5.6.1.2. Is there a characterisation of functors $F: \mathcal{C} \rightarrow \mathcal{D}$ such that:

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 essentially surjective?

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 essentially surjective?

This question also appears as [MO 468121a].

8.5.7 Equivalences of Categories

Definition 8.5.7.1.1. Let \mathcal{C} and \mathcal{D} be categories.

1. An **equivalence of categories** between \mathcal{C} and \mathcal{D} consists of a pair of functors

$$\begin{aligned} F: \mathcal{C} &\rightarrow \mathcal{D}, \\ G: \mathcal{D} &\rightarrow \mathcal{C} \end{aligned}$$

together with natural isomorphisms

$$\begin{aligned} \eta: \text{id}_{\mathcal{C}} &\xrightarrow{\sim} G \circ F, \\ \epsilon: F \circ G &\xrightarrow{\sim} \text{id}_{\mathcal{D}}. \end{aligned}$$

2. An **adjoint equivalence of categories** between \mathcal{C} and \mathcal{D} is an equivalence (F, G, η, ϵ) between \mathcal{C} and \mathcal{D} which is also an adjunction.

Proposition 8.5.7.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* If \mathcal{C} and \mathcal{D} are small²², then the following conditions are equivalent:²³

from *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.

- (a) The functor F is an equivalence of categories.
- (b) The functor F is fully faithful and essentially surjective.
- (c) The induced functor

$$F|_{\text{Sk}(\mathcal{C})}: \text{Sk}(\mathcal{C}) \rightarrow \text{Sk}(\mathcal{D})$$

is an *isomorphism* of categories.

- (d) For each $X \in \text{Obj}(\mathbf{Cats})$, the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, X) \rightarrow \mathsf{Fun}(\mathcal{C}, X)$$

is an equivalence of categories.

- (e) For each $X \in \text{Obj}(\mathbf{Cats})$, the postcomposition functor

$$F_*: \mathsf{Fun}(X, \mathcal{C}) \rightarrow \mathsf{Fun}(X, \mathcal{D})$$

is an equivalence of categories.

2. *Two-Out-of-Three.* Let

$$\begin{array}{ccc} \mathcal{C} & \xrightarrow{G \circ F} & \mathcal{E} \\ & \searrow F \quad \nearrow G & \\ & \mathcal{D} & \end{array}$$

be a diagram in \mathbf{Cats} . If two out of the three functors among F , G , and $G \circ F$ are equivalences of categories, then so is the third.

3. *Stability Under Composition.* Let

$$\begin{array}{ccccc} \mathcal{C} & \xleftarrow[G]{F} & \mathcal{D} & \xleftarrow[G']{F'} & \mathcal{E} \end{array}$$

be a diagram in \mathbf{Cats} . If (F, G) and (F', G') are equivalences of categories, then so is their composite $(F' \circ F, G' \circ G)$.

4. *Equivalences vs. Adjoint Equivalences.* Every equivalence of categories can be promoted to an adjoint equivalence.²⁴

5. *Interaction With Groupoids.* If \mathcal{C} and \mathcal{D} are groupoids, then the following conditions are equivalent:

- (a) The functor F is an equivalence of groupoids.
- (b) The following conditions are satisfied:

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') .

- i. The functor F induces a bijection

$$\pi_0(F): \pi_0(\mathcal{C}) \rightarrow \pi_0(\mathcal{D})$$

of sets.

- ii. For each $A \in \text{Obj}(\mathcal{C})$, the induced map

$$F_{x,x}: \text{Aut}_{\mathcal{C}}(A) \rightarrow \text{Aut}_{\mathcal{D}}(F_A)$$

is an isomorphism of groups.

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 \mathcal{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 \mathcal{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 $j: \mathcal{D} \rightarrow \mathcal{C}$ 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 $\epsilon: \text{id}_{\mathcal{C}} \xrightarrow{\sim} j \circ F$. 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

8.5.8 Isomorphisms of Categories

Definition 8.5.8.1.1. An **isomorphism of categories** is a pair of functors

$$\begin{aligned} F: \mathcal{C} &\rightarrow \mathcal{D}, \\ G: \mathcal{D} &\rightarrow \mathcal{C} \end{aligned}$$

such that we have

$$G \circ F = \text{id}_C,$$

$$F \circ G = \text{id}_{\mathcal{D}}.$$

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.

Proposition 8.5.8.1.3. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* If \mathcal{C} and \mathcal{D} are small, then the following conditions are equivalent:
 - (a) The functor F is an isomorphism of categories.
 - (b) The functor F is fully faithful and bijective on objects.
 - (c) For each $X \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(\mathcal{C}, X)$$

is an isomorphism of categories.

- (d) For each $X \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(X, \mathcal{C}) \rightarrow \text{Fun}(X, \mathcal{D})$$

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. □

8.6 More Conditions on Functors

8.6.1 Dominant Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.6.1.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ 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

$$\begin{array}{ccc} B & \xrightarrow{s} & F(A) \\ r \circ s = \text{id}_B, & \searrow_{\text{id}_B} & \downarrow r \\ & & B. \end{array}$$

Proposition 8.6.1.1.2. Let $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$ be functors and let $I: \mathcal{X} \rightarrow \mathcal{C}$ be a functor.

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.

2. *Interaction With Adjunctions.* Let $(F, G): \mathcal{C} \rightleftarrows \mathcal{D}$ be an adjunction.

- (a) If F is dominant, then G is faithful.
- (b) The following conditions are equivalent:
 - i. The functor G is full.
 - ii. The restriction

$$G|_{\text{Im}_F}: \text{Im}(F) \rightarrow \mathcal{C}$$

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

Question 8.6.1.1.3. Is there a characterisation of functors $F: \mathcal{C} \rightarrow \mathcal{D}$ such that:

1. For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the precomposition functor

$$F^*: \mathbf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathbf{Fun}(\mathcal{C}, \mathcal{X})$$

is dominant?

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 dominant?

This question also appears as [MO 468121a].

8.6.2 Monomorphisms of Categories

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.6.2.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is a **monomorphism of categories** if it is a monomorphism in Cats (see ??).

Proposition 8.6.2.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor F is a monomorphism of categories.
- (b) The functor F is injective on objects and morphisms, i.e. F is injective on objects and the map

$$F: \text{Mor}(\mathcal{C}) \rightarrow \text{Mor}(\mathcal{D})$$

is injective.

Proof. Item 1, Characterisations: Omitted. \square

Question 8.6.2.1.3. Is there a characterisation of functors $F: \mathcal{C} \rightarrow \mathcal{D}$ such that:

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 a monomorphism of categories?

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 a monomorphism of categories?

This question also appears as [MO 468121a].

8.6.3 Epimorphisms of Categories

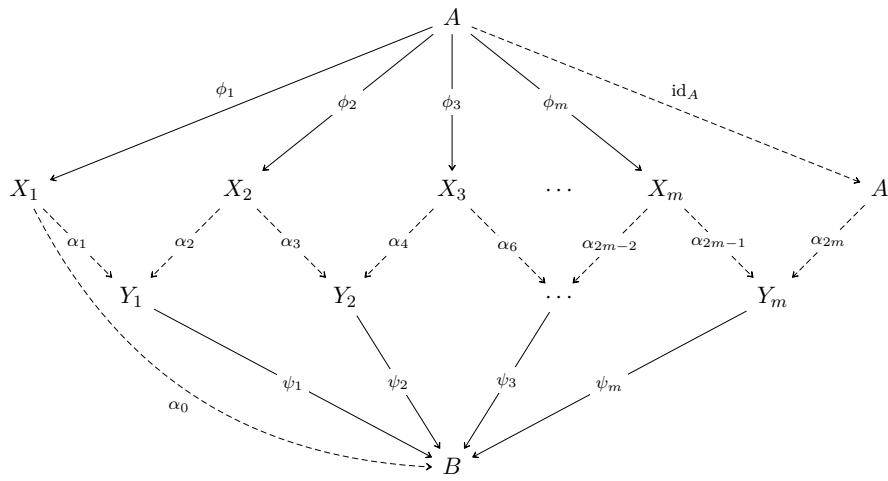
Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.6.3.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is a **epimorphism of categories** if it is a epimorphism in Cats (see ??).

Proposition 8.6.3.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* The following conditions are equivalent:²⁵

- (a) The functor F is a epimorphism of categories.
- (b) For each morphism $f: A \rightarrow B$ of \mathcal{D} , we have a diagram



in \mathcal{D} satisfying the following conditions:

- i. We have $f = \alpha_0 \circ \phi_1$.
 - ii. We have $f = \psi_m \circ \alpha_{2m}$.
 - iii. For each $0 \leq i \leq 2m$, we have $\alpha_i \in \text{Mor}(\text{Im}(F))$.
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. \square

Question 8.6.3.1.3. Is there a characterisation of functors $F: \mathcal{C} \rightarrow \mathcal{D}$ such that:

1. For each $X \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(\mathcal{C}, X)$$

is an epimorphism of categories?

²⁵Further Terminology: This statement is known as **Isbell's zigzag theorem**.

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].

8.6.4 Pseudomonic Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.6.4.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **pseudomonic** if it satisfies the following conditions:

1. For all diagrams of the form

$$\mathcal{X} \xrightarrow[\psi]{\alpha \parallel \beta} \mathcal{C} \xrightarrow{F} \mathcal{D},$$

if we have

$$\text{id}_F \star \alpha = \text{id}_F \star \beta,$$

then $\alpha = \beta$.

2. For each $\mathcal{X} \in \text{Obj}(\text{Cats})$ and each natural isomorphism

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad \mathcal{X} \xrightarrow[\psi]{\beta \Downarrow} \mathcal{D},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{X} \xrightarrow[\psi]{\alpha \Downarrow} \mathcal{C}$$

such that we have an equality

$$\mathcal{X} \xrightarrow[\psi]{\phi} \mathcal{C} \xrightarrow{F} \mathcal{D} = \mathcal{X} \xrightarrow[\psi]{\beta \Downarrow} \mathcal{D}$$

of pasting diagrams, i.e. such that we have

$$\beta = \text{id}_F \star \alpha.$$

Proposition 8.6.4.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor F is pseudomonic.
- (b) The functor F satisfies the following conditions:
 - i. The functor F is faithful, i.e. for each $A, B \in \text{Obj}(\mathcal{C})$, the action on morphisms

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is injective.

- ii. For each $A, B \in \text{Obj}(\mathcal{C})$, the restriction

$$F_{A,B}^{\text{iso}}: \text{Iso}_{\mathcal{C}}(A, B) \rightarrow \text{Iso}_{\mathcal{D}}(F_A, F_B)$$

of the action on morphisms of F at (A, B) to isomorphisms is surjective.

- (c) We have an isocomma square of the form

$$\begin{array}{ccc} C & \xrightarrow{\text{id}_C} & C \\ \text{eq.} \quad \downarrow \text{id}_C & \swarrow \text{dashed} & \downarrow F \\ C & \xrightarrow{F} & \mathcal{D} \end{array}$$

in \mathbf{Cats}_2 up to equivalence.

- (d) We have an isocomma square of the form

$$\begin{array}{ccc} C & \hookrightarrow \text{Arr}(\mathcal{C}) & \\ \text{eq.} \quad \downarrow F & \swarrow \text{dashed} & \downarrow \text{Arr}(F) \\ \mathcal{D} & \hookrightarrow \text{Arr}(\mathcal{D}) & \end{array}$$

in \mathbf{Cats}_2 up to equivalence.

- (e) For each $X \in \text{Obj}(\mathbf{Cats})$, the postcomposition²⁶ functor

$$F_*: \mathbf{Fun}(X, \mathcal{C}) \rightarrow \mathbf{Fun}(X, \mathcal{D})$$

is pseudomonic.

²⁶ Asking the precomposition functors

$$F^*: \mathbf{Fun}(\mathcal{D}, X) \rightarrow \mathbf{Fun}(\mathcal{C}, X)$$

2. *Conservativity.* If F is pseudomonic, then F is conservative.
3. *Essential Injectivity.* If F is pseudomonic, then F is essentially injective.

Proof. *Item 1, Characterisations:* Omitted.

Item 2, Conservativity: Omitted.

Item 3, Essential Injectivity: Omitted. \square

8.6.5 Pseudoepic Functors

Let C and \mathcal{D} be categories.

Definition 8.6.5.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **pseudoepic** if it satisfies the following conditions:

1. For all diagrams of the form

$$C \xrightarrow{F} \mathcal{D} \xrightarrow{\phi} X, \quad \alpha \parallel \beta \downarrow \psi$$

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-isomorphism

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad C \xrightarrow{\phi \circ F} X \xrightarrow{\beta \parallel \psi \circ F} X$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \xrightarrow{\phi \parallel \psi} X$$

of C such that we have an equality

$$C \xrightarrow{F} \mathcal{D} \xrightarrow{\phi \parallel \psi} X = C \xrightarrow{\phi \circ F \parallel \psi \circ F} X$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

Proposition 8.6.5.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor F is pseudoepic.
- (b) For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

given by precomposition by F is pseudomonadic.

- (c) We have an isococomma square of the form

$$\begin{array}{ccc} & \mathcal{D} & \\ & \xleftarrow{\text{id}_{\mathcal{D}}} & \\ \mathcal{D} \xrightarrow{\text{eq.}} \mathcal{D} \overset{\leftrightarrow}{\amalg}_{\mathcal{C}} \mathcal{D} & \uparrow \text{id}_{\mathcal{D}} & \uparrow F \\ & \nwarrow \text{?} & \\ & \mathcal{D} & \\ & \xleftarrow{F} & \\ & \mathcal{C} & \end{array}$$

in \mathbf{Cats}_2 up to equivalence.

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

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is pseudomonadic for all $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, 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. \square

Question 8.6.5.1.3. Is there a nice characterisation of the pseudoepic functors, similarly to the characterisation of pseudomonadic functors given in [Item 1b of Item 1 of Proposition 8.6.4.1.2](#)?

This question also appears as [[MO 321971](#)].

Question 8.6.5.1.4. A pseudomonadic 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 pseudomonadic and pseudoepic functor be from an equivalence of categories?

This question also appears as [[MO 468334](#)].

to be pseudomonadic leads to pseudoepic functors; see [Item 1b of Item 1 of Proposition 8.6.5.1.2](#).

Question 8.6.5.1.5. Is there a characterisation of functors $F: \mathcal{C} \rightarrow \mathcal{D}$ such that:

1. For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the precomposition functor

$$F^*: \mathsf{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \mathsf{Fun}(\mathcal{C}, \mathcal{X})$$

is pseudoepic?

2. For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$, the postcomposition functor

$$F_*: \mathsf{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \mathsf{Fun}(\mathcal{X}, \mathcal{D})$$

is pseudoepic?

This question also appears as [MO 468121a].

8.7 Even More Conditions on Functors

8.7.1 Injective on Objects Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.7.1.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **injective on objects** if the action on objects

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D})$$

of F is injective.

Proposition 8.7.1.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor F is injective on objects.
- (b) The functor F is an isocofibration in \mathbf{Cats}_2 .

Proof. *Item 1, Characterisations:* Omitted. □

8.7.2 Surjective on Objects Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.7.2.1.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **surjective on objects** if the action on objects

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D})$$

of F is surjective.

8.7.3 Bijective on Objects Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 8.7.3.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **bijective on objects**²⁷ if the action on objects

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D})$$

of F is a bijection.

8.7.4 Functors Representably Faithful on Cores

Let \mathcal{C} and \mathcal{D} be categories.

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.

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

$$\begin{array}{ccc} X & \xrightarrow[\psi]{\alpha \parallel \beta} & \mathcal{C} \xrightarrow{F} \mathcal{D}, \\ & \phi & \end{array}$$

if α and β are natural isomorphisms and we have

$$\text{id}_F * \alpha = \text{id}_F * \beta,$$

then $\alpha = \beta$.

Question 8.7.4.1.3. Is there a characterisation of functors representably faithful on cores?

8.7.5 Functors Representably Full on Cores

Let \mathcal{C} and \mathcal{D} be categories.

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.

²⁷Further Terminology: Also called a **bo** functor.

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

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C}$$

such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \psi \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = X \begin{array}{c} \xrightarrow{\phi} \\ \beta \Downarrow \\ F \circ \psi \end{array} \mathcal{D}$$

of pasting diagrams in Cats_2 , i.e. such that we have

$$\beta = \text{id}_F * \alpha.$$

Question 8.7.5.1.3. Is there a characterisation of functors representably full on cores?

This question also appears as [MO 468121a].

8.7.6 Functors Representably Fully Faithful on Cores

Let \mathcal{C} and \mathcal{D} be categories.

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.

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.:

1. For all diagrams of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \beta \\ \psi \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D},$$

with α and β natural isomorphisms, if we have $\text{id}_F * \alpha = \text{id}_F * \beta$, then $\alpha = \beta$.

2. For each $X \in \text{Obj}(\text{Cats})$ and each natural isomorphism

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad X \xrightarrow[\substack{F \circ \psi \\ \beta \Downarrow \\ F \circ \phi}]{} \mathcal{D}$$

of C , there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \xrightarrow[\substack{\psi \\ \alpha \Downarrow \\ \phi}]{} C$$

of C such that we have an equality

$$X \xrightarrow[\substack{\psi \\ \alpha \Downarrow \\ \phi}]{} C \xrightarrow{F} \mathcal{D} = X \xrightarrow[\substack{F \circ \psi \\ \beta \Downarrow \\ F \circ \phi}]{} \mathcal{D}$$

of pasting diagrams in Cats_2 , i.e. such that we have

$$\beta = \text{id}_F \star \alpha.$$

Question 8.7.6.1.3. Is there a characterisation of functors representably fully faithful on cores?

8.7.7 Functors Corepresentably Faithful on Cores

Let C and \mathcal{D} be categories.

Definition 8.7.7.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **corepresentably faithful on cores** if, for each $X \in \text{Obj}(\text{Cats})$, the postcomposition by F functor

$$F_*: \text{Core}(\text{Fun}(X, C)) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is faithful.

Remark 8.7.7.1.2. In detail, a functor $F: C \rightarrow \mathcal{D}$ is **corepresentably faithful on cores** if, given a diagram of the form

$$C \xrightarrow{F} \mathcal{D} \xrightarrow[\substack{\psi \\ \alpha \parallel \beta}]{} X,$$

if α and β are natural isomorphisms and we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then $\alpha = \beta$.

Question 8.7.7.1.3. Is there a characterisation of functors corepresentably faithful on cores?

8.7.8 Functors Corepresentably Full on Cores

Let \mathcal{C} and \mathcal{D} be categories.

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.

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

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad \mathcal{C} \xrightarrow[\psi \circ F]{\beta \Downarrow} X,$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \xrightarrow[\psi]{\alpha \Downarrow} X$$

such that we have an equality

$$X \xrightarrow[\psi]{\alpha \Downarrow} \mathcal{C} \xrightarrow{F} \mathcal{D} = X \xrightarrow[\psi]{\beta \Downarrow} \mathcal{D}$$

of pasting diagrams in Cats_2 , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

Question 8.7.8.1.3. Is there a characterisation of functors corepresentably full on cores?

This question also appears as [MO 468121a].

8.7.9 Functors Corepresentably Fully Faithful on Cores

Let \mathcal{C} and \mathcal{D} be categories.

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.

Remark 8.7.9.1.2. In detail, a functor $F: \mathcal{C} \rightarrow \mathcal{D}$ 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.:

1. For all diagrams of the form

$$\mathcal{C} \xrightarrow{F} \mathcal{D} \xrightarrow{\phi} \mathcal{X},$$

$\alpha \Downarrow \beta$

if α and β are natural isomorphisms and we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then $\alpha = \beta$.

2. For each $\mathcal{X} \in \text{Obj}(\mathbf{Cats})$ and each natural isomorphism

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad \mathcal{C} \xrightarrow[\psi \circ F]{\phi \circ F} \mathcal{X},$$

$\beta \Downarrow$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \xrightarrow[\psi]{\phi} \mathcal{X}$$

$\alpha \Downarrow$

such that we have an equality

$$\mathcal{X} \xrightarrow[\psi]{\phi} \mathcal{C} \xrightarrow{F} \mathcal{D} = \mathcal{X} \xrightarrow[\psi \circ F]{F \circ \phi} \mathcal{D}$$

$\beta \Downarrow$

of pasting diagrams in \mathbf{Cats}_2 , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

Question 8.7.9.1.3. Is there a characterisation of functors corepresentably fully faithful on cores?

8.8 Natural Transformations

8.8.1 Transformations

Let \mathcal{C} and \mathcal{D} be categories and $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$ be functors.

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} .

Notation 8.8.1.1.2. We write $\text{Trans}(F, G)$ for the set of transformations from F to G .

8.8.2 Natural Transformations

Let C and \mathcal{D} be categories and $F, G: C \rightrightarrows \mathcal{D}$ be functors.

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

Remark 8.8.2.1.2. We denote natural transformations in diagrams as

$$\begin{array}{ccc} C & \begin{array}{c} \xrightarrow{F} \\ \Downarrow \alpha \\ \xrightarrow{G} \end{array} & \mathcal{D}. \end{array}$$

Notation 8.8.2.1.3. We write $\text{Nat}(F, G)$ for the set of natural transformations from F to G .

Example 8.8.2.1.4. The identity natural transformation $\text{id}_F: F \Rightarrow F$ 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

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** .

morphism $f: A \rightarrow B$ of \mathcal{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 \mathcal{C} . \square

Definition 8.8.2.1.5. Two natural transformations $\alpha, \beta: F \Rightarrow G$ are **equal** if we have

$$\alpha_A = \beta_A$$

for each $A \in \text{Obj}(\mathcal{C})$.

8.8.3 Vertical Composition of Natural Transformations

Definition 8.8.3.1.1. The **vertical composition** of two natural transformations $\alpha: F \Rightarrow G$ and $\beta: G \Rightarrow H$ as in the diagram

$$\begin{array}{ccc} & F & \\ C & \xrightarrow[G]{\quad} & \mathcal{D} \\ & \alpha \Downarrow & \\ & \beta \Downarrow & \\ & H & \end{array}$$

is the natural transformation $\beta \circ \alpha: F \Rightarrow H$ consisting of the collection

$$\{(\beta \circ \alpha)_A: F(A) \rightarrow H(A)\}_{A \in \text{Obj}(\mathcal{C})}$$

with

$$(\beta \circ \alpha)_A \stackrel{\text{def}}{=} \beta_A \circ \alpha_A$$

for each $A \in \text{Obj}(\mathcal{C})$.

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

Proposition 8.8.3.1.2. Let \mathcal{C} , \mathcal{D} , and \mathcal{E} be categories.

1. *Functionality.* The assignment $(\beta, \alpha) \mapsto \beta \circ \alpha$ defines a function

$$\circ_{F,G,H}: \text{Nat}(G, H) \times \text{Nat}(F, G) \rightarrow \text{Nat}(F, H).$$

2. *Associativity.* Let $F, G, H, K: \mathcal{C} \rightrightarrows \mathcal{D}$ be functors. The diagram

$$\begin{array}{ccc}
 & \text{Nat}(H, K) \times (\text{Nat}(G, H) \times \text{Nat}(F, G)) & \\
 & \swarrow \alpha_{\text{Nat}(H, K), \text{Nat}(G, H), \text{Nat}(F, G)}^{\text{Sets}} \quad \searrow \text{id}_{\text{Nat}(H, K) \times \circ_{F,G,H}} & \\
 (\text{Nat}(H, K) \times \text{Nat}(G, H)) \times \text{Nat}(F, G) & & \text{Nat}(H, K) \times \text{Nat}(F, H) \\
 & \swarrow \circ_{G,H,K} \times \text{id}_{\text{Nat}(F, G)} & \searrow \circ_{F,H,K} \\
 & \text{Nat}(G, K) \times \text{Nat}(F, G) & \xrightarrow[F,G,K]{} \text{Nat}(F, K)
 \end{array}$$

commutes, i.e. given natural transformations

$$F \xrightarrow{\alpha} G \xrightarrow{\beta} H \xrightarrow{\gamma} K,$$

we have

$$(\gamma \circ \beta) \circ \alpha = \gamma \circ (\beta \circ \alpha).$$

3. *Unitality.* Let $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$ be functors.

(a) *Left Unitality.* The diagram

$$\begin{array}{ccc}
 \text{pt} \times \text{Nat}(F, G) & & \\
 \downarrow [\text{id}_G] \times \text{id}_{\text{Nat}(F, G)} & \nearrow \lambda_{\text{Nat}(F, G)}^{\text{Sets}} & \\
 \text{Nat}(G, G) \times \text{Nat}(F, G) & \xrightarrow[\circ_{F,G,G}]{} & \text{Nat}(F, G)
 \end{array}$$

commutes, i.e. given a natural transformation $\alpha: F \Rightarrow G$, we have

$$\text{id}_G \circ \alpha = \alpha.$$

(b) *Right Unitality.* The diagram

$$\begin{array}{ccc}
 \text{Nat}(F, G) \times \text{pt} & & \\
 \downarrow \text{id}_{\text{Nat}(F, G)} \times [\text{id}_F] & \nearrow \rho_{\text{Nat}(F, G)}^{\text{Sets}} & \\
 \text{Nat}(F, G) \times \text{Nat}(F, F) & \xrightarrow{\circ_{F, F, G}^C} & \text{Nat}(F, G)
 \end{array}$$

commutes, i.e. given a natural transformation $\alpha: F \Rightarrow G$, we have

$$\alpha \circ \text{id}_F = \alpha.$$

4. *Middle Four Exchange.* Let $F_1, F_2, F_3: \mathcal{C} \rightarrow \mathcal{D}$ and $G_1, G_2, G_3: \mathcal{D} \rightarrow \mathcal{E}$ be functors. The diagram

$$\begin{array}{ccc}
 (\text{Nat}(G_2, G_3) \times \text{Nat}(G_1, G_2)) \times (\text{Nat}(F_2, F_3) \times \text{Nat}(F_1, F_2)) & \xrightarrow{\mu_4} & (\text{Nat}(G_2, G_3) \times \text{Nat}(F_2, F_3)) \times (\text{Nat}(G_1, G_2) \times \text{Nat}(F_1, F_2)) \\
 \downarrow \circ_{G_1, G_2, G_3} \times \circ_{F_1, F_2, F_3} & & \downarrow \star_{F_2, F_3, G_2, G_3} \times \star_{F_1, F_2, G_1, G_2} \\
 \text{Nat}(G_1, G_3) \times \text{Nat}(F_1, F_3) & & \text{Nat}(G_2 \circ F_2, G_3 \circ F_3) \times \text{Nat}(G_1 \circ F_1, G_2 \circ F_2) \\
 & \searrow \star_{F_1, F_3, G_1, G_3} & \swarrow \circ_{G_1 \circ F_1, G_2 \circ F_2, G_3 \circ F_3} \\
 & \text{Nat}(G_1 \circ F_1, G_3 \circ F_3) &
 \end{array}$$

commutes, i.e. given a diagram

$$\begin{array}{ccccc}
 & F_1 & & G_1 & \\
 & \alpha \Downarrow & & \beta \Downarrow & \\
 \mathcal{C} & \xrightarrow{F_2} & \mathcal{D} & \xrightarrow{G_2} & \mathcal{E} \\
 & \alpha' \Downarrow & \nearrow & \beta' \Downarrow & \\
 & F_3 & & G_3 &
 \end{array}$$

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

8.8.4 Horizontal Composition of Natural Transformations

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

$$\begin{array}{ccc} C & \xrightarrow[F]{\alpha \parallel} & \mathcal{D} \\ & \downarrow G & \downarrow H \\ & & K \end{array}$$

of α and β is the natural transformation

$$\beta \star \alpha: (H \circ F) \Rightarrow (K \circ G),$$

as in the diagram

$$\begin{array}{ccc} C & \xrightarrow[H \circ F]{\beta \star \alpha \parallel} & \mathcal{E} \\ & \downarrow K \circ G & \end{array}$$

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

$$\begin{aligned} (\beta \star \alpha)_A &\stackrel{\text{def}}{=} \beta_{G(A)} \circ H(\alpha_A) \\ &= K(\alpha_A) \circ \beta_{F(A)}, \end{aligned}$$

$$\begin{array}{ccc} H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\ \beta_{F(A)} \downarrow & & \downarrow \beta_{G(A)} \\ K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)). \end{array}$$

³⁰Further Terminology: Also called the **Godement product** of α and β .

³¹Horizontal composition forms a map

$$\star_{(F,H),(G,K)}: \text{Nat}(H,K) \times \text{Nat}(F,G) \rightarrow \text{Nat}(H \circ F, K \circ G).$$

Proof. First, we claim that we indeed have

$$\begin{array}{ccc} H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\ \beta_{G(A)} \circ H(\alpha_A) = K(\alpha_A) \circ \beta_{F(A)}, & \beta_{F(A)} \downarrow & \downarrow \beta_{G(A)} \\ K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)). \end{array}$$

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

□

Definition 8.8.4.1.2. Let

$$\mathcal{X} \xrightarrow{F} \mathcal{C} \xrightarrow{\phi} \mathcal{D} \xrightarrow{G} \mathcal{Y}$$

be a diagram in Cats_2 .

1. The **left whiskering of α with G** is the natural transformation³³

$$\text{id}_G \star \alpha: G \circ \phi \Rightarrow G \circ \psi.$$

³²Reference: [Bor94, Proposition 1.3.4].

³³Further Notation: Also written $G\alpha$ or $G \star \alpha$, although we won't use either of these

2. The **right whiskering of α with F** is the natural transformation³⁴

$$\alpha \star \text{id}_F : \phi \circ F \Rightarrow \psi \circ F.$$

Proposition 8.8.4.1.3. Let \mathcal{C} , \mathcal{D} , and \mathcal{E} be categories.

1. *Functionality.* The assignment $(\beta, \alpha) \mapsto \beta \star \alpha$ defines a function

$$\star_{(F,G),(H,K)} : \text{Nat}(H, K) \times \text{Nat}(F, G) \rightarrow \text{Nat}(H \circ F, K \circ G).$$

2. *Associativity.* Let

$$\mathcal{C} \xrightarrow[G_1]{F_1} \mathcal{D} \xrightarrow[G_2]{F_2} \mathcal{E} \xrightarrow[G_3]{F_3} \mathcal{F}$$

be a diagram in \mathbf{Cats}_2 . The diagram

$$\begin{array}{ccc} \text{Nat}(F_3, G_3) \times \text{Nat}(F_2, G_2) \times \text{Nat}(F_1, G_1) & \xrightarrow{\star_{(F_2, G_2), (F_3, G_3)} \times \text{id}} & \text{Nat}(F_3 \circ F_2, G_3 \circ G_2) \times \text{Nat}(F_1, G_1) \\ \downarrow \text{id} \times \star_{(F_1, G_1), (F_2, G_2)} & & \downarrow \star_{(F_3 \circ F_2), (G_3 \circ G_2, F_1, G_1)} \\ \text{Nat}(F_3, G_3) \times \text{Nat}(F_2 \circ F_1, G_2 \circ G_1) & \xrightarrow{\star_{(F_2 \circ F_1), (G_2 \circ G_1, F_3, G_3)}} & \text{Nat}(F_3 \circ F_2 \circ F_1, G_3 \circ G_2 \circ G_1) \end{array}$$

commutes, i.e. given natural transformations

$$\mathcal{C} \xrightarrow[G_1]{F_1} \mathcal{D} \xrightarrow[G_2]{F_2} \mathcal{E} \xrightarrow[G_3]{F_3} \mathcal{F},$$

we have

$$(\gamma \star \beta) \star \alpha = \gamma \star (\beta \star \alpha).$$

3. *Interaction With Identities.* Let $F: \mathcal{C} \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{E}$ be functors. The diagram

$$\begin{array}{ccc} \text{pt} \times \text{pt} & \xrightarrow{[\text{id}_G] \times [\text{id}_F]} & \text{Nat}(G, G) \times \text{Nat}(F, F) \\ \uparrow \gamma & & \downarrow \star_{(F, F), (G, G)} \\ \text{pt} & \xrightarrow{[\text{id}_{G \circ F}]} & \text{Nat}(G \circ F, G \circ F) \end{array}$$

commutes, i.e. we have

$$\text{id}_G \star \text{id}_F = \text{id}_{G \circ F}.$$

notations in this work.

³⁴Further Notation: Also written αF or $\alpha \star F$, although we won't use either of these

4. *Middle Four Exchange.* Let $F_1, F_2, F_3: \mathcal{C} \rightarrow \mathcal{D}$ and $G_1, G_2, G_3: \mathcal{D} \rightarrow \mathcal{E}$ be functors. The diagram

$$\begin{array}{ccc}
& (\text{Nat}(G_2, G_3) \times \text{Nat}(G_1, G_2)) \times (\text{Nat}(F_2, F_3) \times \text{Nat}(F_1, F_2)) \xrightarrow{\mu_4} (\text{Nat}(G_2, G_3) \times \text{Nat}(F_2, F_3)) \times (\text{Nat}(G_1, G_2) \times \text{Nat}(F_1, F_2)) & \\
\downarrow \circ_{G_1, G_2, G_3} \times \circ_{F_1, F_2, F_3} & & \downarrow \star_{F_2, F_3, G_2, G_3} \times \star_{F_1, F_2, G_1, G_2} \\
\text{Nat}(G_1, G_3) \times \text{Nat}(F_1, F_3) & & \text{Nat}(G_2 \circ F_2, G_3 \circ F_3) \times \text{Nat}(G_1 \circ F_1, G_2 \circ F_2) \\
& \searrow \star_{F_1, F_3, G_1, G_3} & \swarrow \circ_{G_1 \circ F_1, G_2 \circ F_2, G_3 \circ F_3} \\
& \text{Nat}(G_1 \circ F_1, G_3 \circ F_3) &
\end{array}$$

commutes, i.e. given a diagram

$$\begin{array}{ccccc}
& F_1 & & G_1 & \\
\text{C} & \xrightarrow{\quad F_2 \quad} & \mathcal{D} & \xrightarrow{\quad G_2 \quad} & \mathcal{E} \\
\alpha \parallel \downarrow & \curvearrowright & \beta \parallel \downarrow & \curvearrowright & \\
\alpha' \parallel \downarrow & \nearrow & \beta' \parallel \downarrow & \nearrow & \\
& F_3 & & G_3 &
\end{array}$$

in \mathbf{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 $A \in \text{Obj}(\mathcal{C})$, showing the desired equality.

notations in this work.

Item 4, Middle Four Exchange: Let $A \in \text{Obj}(\mathcal{C})$ and consider the diagram

$$\begin{array}{ccccc}
 & & G_1(F_3(A)) & & \\
 & G_1(\alpha'_A) \nearrow & \searrow \beta_{F_3(A)} & & \\
 G_1(F_1(A)) \xrightarrow{G_1(\alpha_A)} & G_1(F_2(A)) & (1) & G_2(F_3(A)) \xrightarrow{\beta'_{F_3(A)}} & G_3(F_3(A)). \\
 & \searrow \beta_{F_2(A)} & & \nearrow G_2(\alpha'_A) & \\
 & & G_2(F_2(A)) & &
 \end{array}$$

The top composition

$$\begin{array}{ccccc}
 & & G_1(F_3(A)) & & \\
 & G_1(\alpha'_A) \nearrow & \searrow \beta_{F_3(A)} & & \\
 G_1(F_1(A)) \xrightarrow{G_1(\alpha_A)} & G_1(F_2(A)) & (1) & G_2(F_3(A)) \xrightarrow{\beta'_{F_3(A)}} & G_3(F_3(A)). \\
 & \searrow \beta_{F_2(A)} & & \nearrow G_2(\alpha'_A) & \\
 & & G_2(F_2(A)) & &
 \end{array}$$

is given by $((\beta' \circ \beta) \star (\alpha' \circ \alpha))_A$, while the bottom composition

$$\begin{array}{ccccc}
 & & G_1(F_3(A)) & & \\
 & G_1(\alpha'_A) \nearrow & \searrow \beta_{F_3(A)} & & \\
 G_1(F_1(A)) \xrightarrow{G_1(\alpha_A)} & G_1(F_2(A)) & (1) & G_2(F_3(A)) \xrightarrow{\beta'_{F_3(A)}} & G_3(F_3(A)). \\
 & \searrow \beta_{F_2(A)} & & \nearrow G_2(\alpha'_A) & \\
 & & G_2(F_2(A)) & &
 \end{array}$$

is given by $((\beta' \star \alpha') \circ (\beta \star \alpha))_A$. Now, Subdiagram (1) corresponds to the naturality condition

$$\begin{array}{ccc}
 G_1(F_2(A)) \xrightarrow{G_1(\alpha'_A)} G_1(F_3(A)) & & \\
 \beta_{F_2(A)} \downarrow & & \downarrow \beta_{F_3(A)} \\
 G_2(F_2(A)) \xrightarrow{G_2(\alpha'_A)} G_2(F_3(A)) & &
 \end{array}$$

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 $A \in \text{Obj}(\mathcal{C})$ and therefore

$$(\beta' \star \alpha') \circ (\beta \star \alpha) = (\beta' \circ \beta) \star (\alpha' \circ \alpha).$$

This finishes the proof. \square

8.8.5 Properties of Natural Transformations

Proposition 8.8.5.1.1. Let $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$ be functors. The following data are equivalent.³⁵

1. A natural transformation $\alpha: F \Rightarrow G$.
2. A functor $[\alpha]: \mathcal{C} \rightarrow \mathcal{D}^{\mathbb{1}}$ filling the diagram

$$\begin{array}{ccc} & \mathcal{D} & \\ F \swarrow & \uparrow \text{ev}_0 & \\ \mathcal{C} & \xrightarrow{[\alpha]} & \mathcal{D}^{\mathbb{1}}. \\ \searrow G & \downarrow \text{ev}_1 & \\ & \mathcal{D} & \end{array}$$

3. A functor $[\alpha]: \mathcal{C} \times \mathbb{1} \rightarrow \mathcal{D}$ filling the diagram

$$\begin{array}{ccc} \mathcal{C} & & \\ \uparrow \text{ev}_0 & \searrow F & \\ & \mathcal{C} \times \mathbb{1} & \xrightarrow{[\alpha]} \mathcal{D}. \\ \downarrow \text{ev}_1 & \nearrow G & \\ \mathcal{C} & & \end{array}$$

Proof. From Item 1 to Item 2 and Back: We may identify $\mathcal{D}^{\mathbb{1}}$ with

³⁵Taken from [MO 64365].

$\text{Arr}(\mathcal{D})$. Given a natural transformation $\alpha: F \Rightarrow G$, we have a functor

$$\begin{aligned} [\alpha]: \mathcal{C} &\longrightarrow \mathcal{D}^{\mathbb{I}} \\ A &\longmapsto \alpha_A \\ (f: A \rightarrow B) &\longmapsto \left(\begin{array}{ccc} F_A & \xrightarrow{F_f} & F_B \\ \downarrow \alpha_A & & \downarrow \alpha_B \\ G_A & \xrightarrow{G_f} & G_B \end{array} \right) \end{aligned}$$

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](#). \square

8.8.6 Natural Isomorphisms

Let \mathcal{C} and \mathcal{D} be categories and let $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$ be functors.

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

$$\begin{aligned} \alpha^{-1} \circ \alpha &= \text{id}_F, \\ \alpha \circ \alpha^{-1} &= \text{id}_G. \end{aligned}$$

Proposition 8.8.6.1.2. Let $\alpha: F \Rightarrow G$ be a natural transformation.

1. *Characterisations.* The following conditions are equivalent:
 - (a) The natural transformation α is a natural isomorphism.
 - (b) For each $A \in \text{Obj}(\mathcal{C})$, the morphism $\alpha_A: F_A \rightarrow G_A$ is an isomorphism.
2. *Componentwise Inverses of Natural Transformations Assemble Into Natural Transformations.* Let $\alpha^{-1}: G \Rightarrow F$ be a transformation such that, for each $A \in \text{Obj}(\mathcal{C})$, 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 diagram

$$\begin{array}{ccc} G(A) & \xrightarrow{G(f)} & G(B) \\ \alpha_A^{-1} \downarrow & (1) & \downarrow \alpha_B^{-1} \\ F(A) & \xrightarrow{F(f)} & F(B) \\ \alpha_A \downarrow & (2) & \downarrow \alpha_B \\ G(A) & \xrightarrow{G(f)} & G(B), \end{array}$$

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

8.9 Categories of Categories

8.9.1 Functor Categories

Let C be a category and \mathcal{D} be a small category.

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

$$\text{Hom}_{\text{Fun}(\mathcal{C}, \mathcal{D})}(F, G) \stackrel{\text{def}}{=} \text{Nat}(F, G).$$

- *Identities.* For each $F \in \text{Obj}(\text{Fun}(\mathcal{C}, \mathcal{D}))$, the unit map

$$\mathbb{1}_F^{\text{Fun}(\mathcal{C}, \mathcal{D})}: \text{pt} \rightarrow \text{Nat}(F, F)$$

of $\text{Fun}(\mathcal{C}, \mathcal{D})$ at F is given by

$$\text{id}_F^{\text{Fun}(\mathcal{C}, \mathcal{D})} \stackrel{\text{def}}{=} \text{id}_F,$$

where $\text{id}_F: F \Rightarrow F$ is the identity natural transformation of F of [Example 8.8.2.1.4](#).

- *Composition.* For each $F, G, H \in \text{Obj}(\text{Fun}(\mathcal{C}, \mathcal{D}))$, the composition map

$$\circ_{F, G, H}^{\text{Fun}(\mathcal{C}, \mathcal{D})}: \text{Nat}(G, H) \times \text{Nat}(F, G) \rightarrow \text{Nat}(F, H)$$

of $\text{Fun}(\mathcal{C}, \mathcal{D})$ at (F, G, H) is given by

$$\beta \circ_{F, G, H}^{\text{Fun}(\mathcal{C}, \mathcal{D})} \alpha \stackrel{\text{def}}{=} \beta \circ \alpha,$$

where $\beta \circ \alpha$ is the vertical composition of α and β of [Item 1](#) of [Proposition 8.8.3.1.2](#).

Proposition 8.9.1.1.2. Let \mathcal{C} and \mathcal{D} be categories and let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Functionality.* The assignments $\mathcal{C}, \mathcal{D}, (\mathcal{C}, \mathcal{D}) \mapsto \text{Fun}(\mathcal{C}, \mathcal{D})$ define functors

$$\begin{aligned} \text{Fun}(\mathcal{C}, -_2): \text{Cats} &\rightarrow \text{Cats}, \\ \text{Fun}(-_1, \mathcal{D}): \text{Cats}^{\text{op}} &\rightarrow \text{Cats}, \\ \text{Fun}(-_1, -_2): \text{Cats}^{\text{op}} \times \text{Cats} &\rightarrow \text{Cats}. \end{aligned}$$

2. *2-Functionality.* The assignments $\mathcal{C}, \mathcal{D}, (\mathcal{C}, \mathcal{D}) \mapsto \text{Fun}(\mathcal{C}, \mathcal{D})$ define 2-functors

$$\begin{aligned} \text{Fun}(\mathcal{C}, -_2): \text{Cats}_2 &\rightarrow \text{Cats}_2, \\ \text{Fun}(-_1, \mathcal{D}): \text{Cats}_2^{\text{op}} &\rightarrow \text{Cats}_2, \\ \text{Fun}(-_1, -_2): \text{Cats}_2^{\text{op}} \times \text{Cats}_2 &\rightarrow \text{Cats}_2. \end{aligned}$$

³⁶Further Terminology: Also called the **functor category** $\text{Fun}(\mathcal{C}, \mathcal{D})$.

³⁷Further Notation: Also written $\mathcal{D}^{\mathcal{C}}$ and $[\mathcal{C}, \mathcal{D}]$.

3. *Adjointness.* We have adjunctions

$$(C \times - \dashv \text{Fun}(C, -)): \quad \text{Cats} \begin{array}{c} \xrightarrow{C \times -} \\ \perp \\ \xleftarrow{\text{Fun}(C, -)} \end{array} \text{Cats},$$

$$(- \times \mathcal{D} \dashv \text{Fun}(\mathcal{D}, -)): \quad \text{Cats} \begin{array}{c} \xrightarrow{- \times \mathcal{D}} \\ \perp \\ \xleftarrow{\text{Fun}(\mathcal{D}, -)} \end{array} \text{Cats},$$

witnessed by bijections of sets

$$\text{Hom}_{\text{Cats}}(C \times \mathcal{D}, \mathcal{E}) \cong \text{Hom}_{\text{Cats}}(\mathcal{D}, \text{Fun}(C, \mathcal{E})),$$

$$\text{Hom}_{\text{Cats}}(C \times \mathcal{D}, \mathcal{E}) \cong \text{Hom}_{\text{Cats}}(C, \text{Fun}(\mathcal{D}, \mathcal{E})),$$

natural in $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$.

4. *2-Adjointness.* We have 2-adjunctions

$$(C \times - \dashv \text{Fun}(C, -)): \quad \text{Cats}_2 \begin{array}{c} \xrightarrow{C \times -} \\ \perp_2 \\ \xleftarrow{\text{Fun}(C, -)} \end{array} \text{Cats}_2,$$

$$(- \times \mathcal{D} \dashv \text{Fun}(\mathcal{D}, -)): \quad \text{Cats}_2 \begin{array}{c} \xrightarrow{- \times \mathcal{D}} \\ \perp_2 \\ \xleftarrow{\text{Fun}(\mathcal{D}, -)} \end{array} \text{Cats}_2,$$

witnessed by isomorphisms of categories

$$\text{Fun}(C \times \mathcal{D}, \mathcal{E}) \cong \text{Fun}(\mathcal{D}, \text{Fun}(C, \mathcal{E})),$$

$$\text{Fun}(C \times \mathcal{D}, \mathcal{E}) \cong \text{Fun}(C, \text{Fun}(\mathcal{D}, \mathcal{E})),$$

natural in $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats}_2)$.

5. *Interaction With Punctual Categories.* We have a canonical isomorphism of categories

$$\text{Fun}(\text{pt}, C) \cong C,$$

natural in $C \in \text{Obj}(\text{Cats})$.

6. *Objectwise Computation of Co/Limits.* Let

$$D: \mathcal{I} \rightarrow \text{Fun}(C, \mathcal{D})$$

be a diagram in $\text{Fun}(C, \mathcal{D})$. We have isomorphisms

$$\lim(D)_A \cong \lim_{i \in \mathcal{I}}(D_i(A)),$$

$$\text{colim}(D)_A \cong \text{colim}_{i \in \mathcal{I}}(D_i(A)),$$

naturally in $A \in \text{Obj}(C)$.

7. *Interaction With Co/Completeness.* If \mathcal{E} is co/complete, then so is $\text{Fun}(\mathcal{C}, \mathcal{E})$.
8. *Monomorphisms and Epimorphisms.* Let $\alpha: F \Rightarrow G$ be a morphism of $\text{Fun}(\mathcal{C}, \mathcal{D})$. The following conditions are equivalent:
- The natural transformation

$$\alpha: F \Rightarrow G$$

is a monomorphism (resp. epimorphism) in $\text{Fun}(\mathcal{C}, \mathcal{D})$.

- For each $A \in \text{Obj}(\mathcal{C})$, 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

8.9.2 The Category of Categories and Functors

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 $\mathcal{C}, \mathcal{D} \in \text{Obj}(\text{Cats})$, we have

$$\text{Hom}_{\text{Cats}}(\mathcal{C}, \mathcal{D}) \stackrel{\text{def}}{=} \text{Obj}(\text{Fun}(\mathcal{C}, \mathcal{D})).$$

- *Identities.* For each $\mathcal{C} \in \text{Obj}(\text{Cats})$, the unit map

$$1_C^{\text{Cats}}: \text{pt} \rightarrow \text{Hom}_{\text{Cats}}(\mathcal{C}, \mathcal{C})$$

of Cats at \mathcal{C} is defined by

$$\text{id}_C^{\text{Cats}} \stackrel{\text{def}}{=} \text{id}_{\mathcal{C}},$$

where $\text{id}_{\mathcal{C}}: \mathcal{C} \rightarrow \mathcal{C}$ is the identity functor of \mathcal{C} of Example 8.4.1.1.4.

- *Composition.* For each $\mathcal{C}, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$, the composition map

$$\circ_{\mathcal{C}, \mathcal{D}, \mathcal{E}}^{\text{Cats}} : \text{Hom}_{\text{Cats}}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}}(\mathcal{C}, \mathcal{D}) \rightarrow \text{Hom}_{\text{Cats}}(\mathcal{C}, \mathcal{E})$$

of Cats at $(\mathcal{C}, \mathcal{D}, \mathcal{E})$ is given by

$$G \circ_{\mathcal{C}, \mathcal{D}, \mathcal{E}}^{\text{Cats}} F \stackrel{\text{def}}{=} G \circ F,$$

where $G \circ F : \mathcal{C} \rightarrow \mathcal{E}$ is the composition of F and G of [Definition 8.4.1.1.5](#).

Proposition 8.9.2.1.2. Let \mathcal{C} be a category.

1. *Co/Completeness.* The category Cats is complete and cocomplete.
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

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 $\mathcal{C}, \mathcal{D} \in \text{Obj}(\text{Cats}_2)$, we have

$$\text{Hom}_{\text{Cats}_2}(\mathcal{C}, \mathcal{D}) \stackrel{\text{def}}{=} \text{Fun}(\mathcal{C}, \mathcal{D}).$$

- *Identities.* For each $\mathcal{C} \in \text{Obj}(\text{Cats}_2)$, the unit functor

$$\mathbb{1}_{\mathcal{C}}^{\text{Cats}_2} : \text{pt} \rightarrow \text{Fun}(\mathcal{C}, \mathcal{C})$$

of Cats_2 at \mathcal{C} is the functor picking the identity functor $\text{id}_{\mathcal{C}} : \mathcal{C} \rightarrow \mathcal{C}$ of \mathcal{C} .

- *Composition.* For each $\mathcal{C}, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats}_2)$, the composition bifunctor

$$\circ_{\mathcal{C}, \mathcal{D}, \mathcal{E}}^{\text{Cats}_2} : \text{Hom}_{\text{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}_2}(\mathcal{C}, \mathcal{D}) \rightarrow \text{Hom}_{\text{Cats}_2}(\mathcal{C}, \mathcal{E})$$

of Cats_2 at $(\mathcal{C}, \mathcal{D}, \mathcal{E})$ is the functor where

- *Action on Objects.* For each object $(G, F) \in \text{Obj}(\text{Hom}_{\text{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}_2}(\mathcal{C}, \mathcal{D}))$, we have

$$\circ_{\mathcal{C}, \mathcal{D}, \mathcal{E}}^{\text{Cats}_2}(G, F) \stackrel{\text{def}}{=} G \circ F.$$

- *Action on Morphisms.* For each morphism $(\beta, \alpha): (K, H) \Rightarrow (G, F)$ of $\text{Hom}_{\text{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}_2}(\mathcal{C}, \mathcal{D})$, we have

$$\circ_{\mathcal{C}, \mathcal{D}, \mathcal{E}}^{\text{Cats}_2}(\beta, \alpha) \stackrel{\text{def}}{=} \beta \star \alpha,$$

where $\beta \star \alpha$ is the horizontal composition of α and β of [Definition 8.8.4.1.1](#).

Proposition 8.9.3.1.2. Let \mathcal{C} be a category.

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. \square

8.9.4 The Category of Groupoids

Definition 8.9.4.1.1. The **category of (small) groupoids** is the full subcategory Grpd of Cats spanned by the groupoids.

8.9.5 The 2-Category of Groupoids

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

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| 1. Sets | 7. Equivalence Relations and Apartness Relations |
| 2. Constructions With Sets | |
| 3. Pointed Sets | Category Theory |
| 4. Tensor Products of Pointed Sets | 8. Categories |
| 5. Relations | Bicategories |
| Relations | 9. Types of Morphisms in Bicategories |

Part IV

Bicategories

Chapter 9

Types of Morphisms in Bicategories

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 *pseudomonic 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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9.1 Monomorphisms in Bicategories

9.1.1 Representably Faithful Morphisms

Let C be a bicategory.

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.

Remark 9.1.1.1.2. In detail, f is representably faithful if, for all diagrams in C of the form

$$X \xrightarrow[\psi]{\alpha \parallel \beta} A \xrightarrow{f} B,$$

if we have

$$\text{id}_f * \alpha = \text{id}_f * \beta,$$

then $\alpha = \beta$.

Example 9.1.1.1.3. Here are some examples of representably faithful morphisms.

¹Further Terminology: Also called simply a **faithful morphism**, based on Item 1 of Example 9.1.1.3.

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.
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.

9.1.2 Representably Full Morphisms

Let \mathcal{C} be a bicategory.

Definition 9.1.2.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{C} is **representably full**² if, for each $X \in \text{Obj}(\mathcal{C})$, the functor

$$f_*: \mathbf{Hom}_{\mathcal{C}}(X, A) \rightarrow \mathbf{Hom}_{\mathcal{C}}(X, B)$$

given by postcomposition by f is full.

Remark 9.1.2.1.2. In detail, f is representably full if, for each $X \in \text{Obj}(\mathcal{C})$ and each 2-morphism

$$\beta: f \circ \phi \Rightarrow f \circ \psi, \quad X \xrightarrow[\psi]{\beta} \xrightarrow[\phi]{f \circ \phi} B$$

of \mathcal{C} , there exists a 2-morphism

$$\alpha: \phi \Rightarrow \psi, \quad X \xrightarrow[\psi]{\alpha} \xrightarrow[\phi]{\phi} A$$

of \mathcal{C} such that we have an equality

$$X \xrightarrow[\psi]{\alpha} \xrightarrow[\phi]{\phi} A \xrightarrow{f} B = X \xrightarrow[\psi]{\beta} \xrightarrow[\phi]{f \circ \phi} B$$

of pasting diagrams in \mathcal{C} , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

Example 9.1.2.1.3. Here are some examples of representably full morphisms.

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.
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.

²Further Terminology: Also called simply a **full morphism**, based on Item 1 of

9.1.3 Representably Fully Faithful Morphisms

Let \mathcal{C} be a bicategory.

Definition 9.1.3.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{C} is **representably fully faithful**³ if the following equivalent conditions are satisfied:

1. The 1-morphism f is representably faithful ([Definition 9.1.1.1.1](#)) and representably full ([Definition 9.1.2.1.1](#)).
2. For each $X \in \text{Obj}(\mathcal{C})$, the functor

$$f_*: \mathbf{Hom}_{\mathcal{C}}(X, A) \rightarrow \mathbf{Hom}_{\mathcal{C}}(X, B)$$

given by postcomposition by f is fully faithful.

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 \mathcal{C} of the form

$$X \xrightarrow[\psi]{\alpha \parallel \beta} A \xrightarrow{f} B,$$

if we have

$$\text{id}_f * \alpha = \text{id}_f * \beta,$$

then $\alpha = \beta$.

2. For each $X \in \text{Obj}(\mathcal{C})$ and each 2-morphism

$$\beta: f \circ \phi \Rightarrow f \circ \psi, \quad X \xrightarrow[\psi]{\beta \parallel} B$$

of \mathcal{C} , there exists a 2-morphism

$$\alpha: \phi \Rightarrow \psi, \quad X \xrightarrow[\psi]{\alpha \parallel} A$$

of \mathcal{C} such that we have an equality

$$X \xrightarrow[\psi]{\phi \parallel} A \xrightarrow{f} B = X \xrightarrow[\psi]{\beta \parallel} B$$

[Example 9.1.2.1.3.](#)

³Further Terminology: Also called simply a **fully faithful morphism**, based on

of pasting diagrams in \mathcal{C} , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

Example 9.1.3.1.3. Here are some examples of representably fully faithful morphisms.

1. *Representably Fully Faithful Morphisms in Cats_2 .* The representably fully faithful morphisms in Cats_2 are precisely the fully faithful functors; see Item 5 of Proposition 8.5.3.1.2.
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.

9.1.4 Morphisms Representably Faithful on Cores

Let \mathcal{C} be a bicategory.

Definition 9.1.4.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{C} is **representably faithful on cores** if, for each $X \in \text{Obj}(\mathcal{C})$, the functor

$$f_*: \text{Core}(\text{Hom}_{\mathcal{C}}(X, A)) \rightarrow \text{Core}(\text{Hom}_{\mathcal{C}}(X, B))$$

given by postcomposition by f is faithful.

Remark 9.1.4.1.2. In detail, f is representably faithful on cores if, for all diagrams in \mathcal{C} of the form

$$X \xrightarrow[\psi]{\alpha \parallel \beta} A \xrightarrow{f} B,$$

if α and β are 2-isomorphisms and we have

$$\text{id}_f \star \alpha = \text{id}_f \star \beta,$$

then $\alpha = \beta$.

9.1.5 Morphisms Representably Full on Cores

Let \mathcal{C} be a bicategory.

Definition 9.1.5.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{C} is **representably**

Item 1 of Example 9.1.3.1.3.

full on cores if, for each $X \in \text{Obj}(\mathcal{C})$, 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.

Remark 9.1.5.1.2. In detail, f is representably full on cores if, for each $X \in \text{Obj}(\mathcal{C})$ and each 2-isomorphism

$$\beta: f \circ \phi \xrightarrow{\sim} f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\[-1ex] \beta \Downarrow \\[-1ex] \xrightarrow{f \circ \psi} \end{array} B$$

of \mathcal{C} , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \Downarrow \\[-1ex] \psi \end{array} A$$

of \mathcal{C} such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \Downarrow \\[-1ex] \psi \end{array} A \xrightarrow{f} B = X \begin{array}{c} \xrightarrow{f \circ \phi} \\[-1ex] \beta \Downarrow \\[-1ex] f \circ \psi \end{array} B$$

of pasting diagrams in \mathcal{C} , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

9.1.6 Morphisms Representably Fully Faithful on Cores

Let \mathcal{C} be a bicategory.

Definition 9.1.6.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{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) and representably full on cores (Definition 9.1.4.1.1).
2. For each $X \in \text{Obj}(\mathcal{C})$, 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.

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

$$X \xrightarrow[\psi]{\alpha \parallel \beta} A \xrightarrow{f} B,$$

if α and β are 2-isomorphisms and we have

$$\text{id}_f * \alpha = \text{id}_f * \beta,$$

then $\alpha = \beta$.

2. For each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: f \circ \phi \xrightarrow{\sim} f \circ \psi, \quad X \xrightarrow[\psi]{\beta \parallel} B$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \xrightarrow[\psi]{\alpha \parallel} A$$

of C such that we have an equality

$$X \xrightarrow[\psi]{\alpha \parallel} A \xrightarrow{f} B = X \xrightarrow[\psi]{\beta \parallel} B$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \text{id}_f * \alpha.$$

9.1.7 Representably Essentially Injective Morphisms

Let C be a bicategory.

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.

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) If $f \circ \phi \cong f \circ \psi$, then $\phi \cong \psi$.

9.1.8 Representably Conservative Morphisms

Let C be a bicategory.

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.

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

$$\alpha: \phi \Rightarrow \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \Downarrow \\[-1ex] \xrightarrow{\psi} \end{array} A$$

of C , if the 2-morphism

$$\text{id}_f * \alpha: f \circ \phi \Rightarrow f \circ \psi, \quad X \begin{array}{c} \xrightarrow{f \circ \phi} \\[-1ex] \text{id}_f * \alpha \Downarrow \\[-1ex] \xrightarrow{f \circ \psi} \end{array} B$$

is a 2-isomorphism, then so is α .

9.1.9 Strict Monomorphisms

Let C be a bicategory.

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.

Remark 9.1.9.1.2. In detail, f is a strict monomorphism in C if, for each diagram in C of the form

$$X \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \psi \end{array} A \xrightarrow{f} B,$$

if $f \circ \phi = f \circ \psi$, then $\phi = \psi$.

Example 9.1.9.1.3. Here are some examples of strict monomorphisms.

1. *Strict Monomorphisms in \mathbf{Cats}_2 .* The strict monomorphisms in \mathbf{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.
2. *Strict Monomorphisms in \mathbf{Rel} .* The strict monomorphisms in \mathbf{Rel} are characterised in Proposition 5.3.7.1.1.

9.1.10 Pseudomonic Morphisms

Let C be a bicategory.

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

$$f_*: \mathbf{Hom}_C(X, A) \rightarrow \mathbf{Hom}_C(X, B)$$

given by postcomposition by f is pseudomonic.

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:

1. For all diagrams in C of the form

$$\begin{array}{ccc} & \phi & \\ X & \xrightarrow{\alpha \parallel \beta} & A \xrightarrow{f} B, \\ & \psi & \end{array}$$

if we have

$$\text{id}_f * \alpha = \text{id}_f * \beta,$$

then $\alpha = \beta$.

2. For each $X \in \text{Obj}(C)$ and each 2-isomorphism

$$\beta: f \circ \phi \xrightarrow{\sim} f \circ \psi, \quad X \xrightarrow[\substack{\beta \downarrow \\ f \circ \psi}]{} B$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \xrightarrow[\substack{\alpha \downarrow \\ \psi}]{} A$$

of C such that we have an equality

$$X \xrightarrow[\substack{\phi \downarrow \\ \psi}]{} A \xrightarrow{f} B = X \xrightarrow[\substack{\beta \downarrow \\ f \circ \psi}]{} B$$

of pasting diagrams in \mathcal{C} , i.e. such that we have

$$\beta = \text{id}_f \star \alpha.$$

Proposition 9.1.10.1.3. Let $f: A \rightarrow B$ be a 1-morphism of \mathcal{C} .

1. *Characterisations.* The following conditions are equivalent:

- (a) The morphism f is pseudomonic.
- (b) The morphism f is representably full on cores and representably faithful.
- (c) We have an isocomma square of the form

$$\begin{array}{ccc} A & \xrightarrow{\text{id}_A} & A \\ \text{id}_A \downarrow & \swarrow \text{dashed} & \downarrow F \\ A & \xrightarrow{F} & B \end{array}$$

$A \xrightarrow{\text{eq.}} A \times_B A,$

in \mathcal{C} up to equivalence.

2. *Interaction With Cotensors.* If \mathcal{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

$$\begin{array}{ccc} A & \longrightarrow & \mathbb{1} \pitchfork A \\ F \downarrow & \swarrow \text{dashed} & \downarrow \mathbb{1} \pitchfork F \\ B & \hookrightarrow & \mathbb{1} \pitchfork B \end{array}$$

$A \xrightarrow{\text{eq.}} A \times_{\mathbb{1} \pitchfork F} B,$

in \mathcal{C} up to equivalence.

Proof. Item 1, Characterisations: Omitted.

Item 2, Interaction With Cotensors: Omitted. □

9.2 Epimorphisms in Bicategories

9.2.1 Corepresentably Faithful Morphisms

Let \mathcal{C} be a bicategory.

Definition 9.2.1.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{C} is **corepre-**

sentably 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.

Remark 9.2.1.1.2. In detail, f is corepresentably faithful if, for all diagrams in C of the form

$$A \xrightarrow{f} B \xrightarrow{\phi} X, \quad \begin{array}{c} \alpha \parallel \beta \\ \downarrow \psi \end{array}$$

if we have

$$\alpha \star \text{id}_f = \beta \star \text{id}_f,$$

then $\alpha = \beta$.

Example 9.2.1.1.3. Here are some examples of corepresentably faithful morphisms.

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.
2. *Corepresentably Faithful Morphisms in Rel .* Every morphism of Rel is corepresentably faithful; see Item 1 of Proposition 5.3.10.1.1.

9.2.2 Corepresentably Full Morphisms

Let C be a bicategory.

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.

Remark 9.2.2.1.2. In detail, f is corepresentably full if, for each $X \in \text{Obj}(C)$ and each 2-morphism

$$\beta: \phi \circ f \Rightarrow \psi \circ f, \quad A \xrightarrow{\phi \circ f} X, \quad \begin{array}{c} \beta \parallel \\ \downarrow \psi \circ f \end{array}$$

of C , there exists a 2-morphism

$$\alpha: \phi \Rightarrow \psi, \quad B \xrightarrow{\phi} X, \quad \begin{array}{c} \alpha \parallel \\ \downarrow \psi \end{array}$$

of \mathcal{C} such that we have an equality

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \parallel \\ \psi \end{array} X = A \begin{array}{c} \xrightarrow{\phi \circ f} \\ \beta \parallel \\ \psi \circ f \end{array} X$$

of pasting diagrams in \mathcal{C} , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

Example 9.2.2.1.3. Here are some examples of corepresentably full morphisms.

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.
2. *Corepresentably Full Morphisms in Rel .* The corepresentably full morphisms in Rel are characterised in ?? of Proposition 5.3.8.1.1.

9.2.3 Corepresentably Fully Faithful Morphisms

Let \mathcal{C} be a bicategory.

Definition 9.2.3.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{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 $X \in \text{Obj}(\mathcal{C})$, the functor

$$f^*: \text{Hom}_{\mathcal{C}}(B, X) \rightarrow \text{Hom}_{\mathcal{C}}(A, X)$$

given by precomposition by f is fully faithful.

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 \mathcal{C} of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\ \alpha \parallel \beta \\ \psi \end{array} X,$$

⁴Further Terminology: Corepresentably fully faithful morphisms have also been

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

$$\beta: \phi \circ f \Rightarrow \psi \circ f, \quad A \xrightarrow[\psi \circ f]{\beta} X$$

$\phi \circ f$

of C , there exists a 2-morphism

$$\alpha: \phi \Rightarrow \psi, \quad B \xrightarrow[\psi]{\alpha} X$$

ϕ

of C such that we have an equality

$$A \xrightarrow{f} B \xrightarrow[\psi]{\alpha} X = A \xrightarrow[\psi \circ f]{\beta} X$$

ϕ

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

Example 9.2.3.1.3. Here are some examples of corepresentably fully faithful morphisms.

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.
2. *Corepresentably Fully Faithful Morphisms in Rel .* The corepresentably fully faithful morphisms of Rel coincide (Item 3 of Proposition 5.3.10.1.1) with the corepresentably full morphisms in Rel , which are characterised in Item 2 of Proposition 5.3.10.1.1.

9.2.4 Morphisms Corepresentably Faithful on Cores

Let C be a bicategory.

Definition 9.2.4.1.1. A 1-morphism $f: A \rightarrow B$ of C is **corepre-**

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.

sentably 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.

Remark 9.2.4.1.2. In detail, f is corepresentably faithful on cores if, for all diagrams in C of the form

$$A \xrightarrow{f} B \xrightarrow{\phi} X, \quad \begin{array}{c} \alpha \parallel \beta \\ \psi \end{array}$$

if α and β are 2-isomorphisms and we have

$$\alpha \star \text{id}_f = \beta \star \text{id}_f,$$

then $\alpha = \beta$.

9.2.5 Morphisms Corepresentably Full on Cores

Let C be a bicategory.

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.

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

$$\beta: \phi \circ f \xrightarrow{\sim} \psi \circ f, \quad A \xrightarrow{\phi} X \xrightarrow{\psi} X, \quad \begin{array}{c} \phi \circ f \\ \beta \\ \psi \circ f \end{array}$$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \xrightarrow{\phi} X \xrightarrow{\alpha} X \xrightarrow{\psi} X, \quad \begin{array}{c} \phi \\ \alpha \\ \psi \end{array}$$

of C such that we have an equality

$$A \xrightarrow{f} B \xrightarrow{\phi} X = A \xrightarrow{\phi \circ f} X \xrightarrow{\psi} X, \quad \begin{array}{c} \phi \\ \alpha \\ \psi \end{array} \quad \begin{array}{c} \phi \circ f \\ \beta \\ \psi \circ f \end{array}$$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

9.2.6 Morphisms Corepresentably Fully Faithful on Cores

Let \mathcal{C} be a bicategory.

Definition 9.2.6.1.1. A 1-morphism $f: A \rightarrow B$ of \mathcal{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 $X \in \text{Obj}(\mathcal{C})$, the functor

$$f^*: \text{Core}(\text{Hom}_{\mathcal{C}}(B, X)) \rightarrow \text{Core}(\text{Hom}_{\mathcal{C}}(A, X))$$

given by precomposition by f is fully faithful.

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 \mathcal{C} of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \parallel \beta \\[-1ex] \psi \end{array} X,$$

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 $X \in \text{Obj}(\mathcal{C})$ and each 2-isomorphism

$$\beta: \phi \circ f \xrightarrow{\sim} \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\[-1ex] \beta \parallel \\[-1ex] \psi \circ f \end{array} X$$

of \mathcal{C} , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \parallel \\[-1ex] \psi \end{array} X$$

of \mathcal{C} such that we have an equality

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \parallel \\[-1ex] \psi \end{array} X = A \begin{array}{c} \xrightarrow{\phi \circ f} \\[-1ex] \beta \parallel \\[-1ex] \psi \circ f \end{array} X$$

of pasting diagrams in \mathcal{C} , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

9.2.7 Corepresentably Essentially Injective Morphisms

Let C be a bicategory.

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.

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:

- (*) If $\phi \circ f \cong \psi \circ f$, then $\phi \cong \psi$.

9.2.8 Corepresentably Conservative Morphisms

Let C be a bicategory.

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.

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

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \Downarrow \\[-1ex] \xrightarrow{\psi} \end{array} X$$

of C , if the 2-morphism

$$\alpha \star \text{id}_f: \phi \circ f \Longrightarrow \psi \circ f, \quad A \begin{array}{c} \xrightarrow{\phi \circ f} \\[-1ex] \alpha \Downarrow \\[-1ex] \alpha \star \text{id}_f \\[-1ex] \Downarrow \\[-1ex] \xrightarrow{\psi \circ f} \end{array} X$$

is a 2-isomorphism, then so is α .

9.2.9 Strict Epimorphisms

Let C be a bicategory.

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.

Remark 9.2.9.1.2. In detail, f is a strict epimorphism if, for each diagram in C of the form

$$A \xrightarrow{f} B \xrightarrow[\psi]{\phi} X,$$

if $\phi \circ f = \psi \circ f$, then $\phi = \psi$.

Example 9.2.9.1.3. Here are some examples of strict epimorphisms.

1. *Strict Epimorphisms in Cats_2 .* The strict epimorphisms in Cats_2 are characterised in Item 1 of [Proposition 8.6.3.1.2](#).
2. *Strict Epimorphisms in Rel .* The strict epimorphisms in Rel are characterised in [Proposition 5.3.9.1.1](#).

9.2.10 Pseudoepic Morphisms

Let C be a bicategory.

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.

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:

1. For all diagrams in C of the form

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{\phi} \\[-1ex] \alpha \parallel \beta \\[-1ex] \xrightarrow{\psi} \end{array} X,$$

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-isomorphism

$$\beta: \phi \circ f \xrightarrow{\sim} \psi \circ f, \quad A \xrightarrow[\psi \circ f]{\beta \Downarrow} X$$

$\phi \circ f$
 $\beta \Downarrow$
 $\psi \circ f$

of C , there exists a 2-isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad B \xrightarrow[\psi]{\alpha \Downarrow} X$$

ϕ
 $\alpha \Downarrow$
 ψ

of C such that we have an equality

$$A \xrightarrow{f} B \xrightarrow[\psi]{\alpha \Downarrow} X = A \xrightarrow[\psi \circ f]{\phi \circ f} X$$

f
 ϕ
 $\alpha \Downarrow$
 ψ
 $\phi \circ f$
 $\beta \Downarrow$
 $\psi \circ f$

of pasting diagrams in C , i.e. such that we have

$$\beta = \alpha \star \text{id}_f.$$

Proposition 9.2.10.1.3. Let $f: A \rightarrow B$ be a 1-morphism of C .

1. *Characterisations.* The following conditions are equivalent:

- (a) The morphism f is pseudoepic.
- (b) The morphism f is corepresentably full on cores and corepresentably faithful.
- (c) We have an isococomma square of the form

$$B \cong B \coprod_A B, \quad \begin{array}{ccc} B & \xleftarrow{\text{id}_B} & B \\ \text{id}_B \uparrow & \swarrow \text{dashed} & \uparrow F \\ B & \xleftarrow[F]{} & A \end{array}$$

in C up to equivalence.

Proof. **Item 1, Characterisations:** Omitted. □

Appendices

9.A Other Chapters

Sets

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

Relations

5. Relations

Constructions With Relations

6. Constructions With Relations
7. Equivalence Relations and Apartness Relations

Category Theory

8. Categories

Bicategories

9. Types of Morphisms in Bicategories

Part V

Extra Part

Chapter 10

Miscellaneous Notes

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10.1 To Do List

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.

Remark 10.1.1.1. 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 isocofibrations 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: ??.

10.1.2 Things To Explore/Add

Here we list things to be explored/added to this work in the future.

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

$$\mathfrak{q} \square \mathfrak{p} \stackrel{\text{def}}{=} \int_{A \in C} \mathfrak{p}_A^{-1} \amalg \mathfrak{q}_{-2}^A$$

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/how/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 $\text{Fun}(\mathcal{C}, \mathcal{D})$, e.g. pointwise sections vs. sections in $\text{Fun}(\mathcal{C}, \mathcal{D})$.
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 $C \times_{\mathcal{E}}^{\text{ps}} \mathcal{D} \rightarrow C \times_{\mathcal{E}}^{\leftrightarrow} \mathcal{D}$ 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 $\text{Fun}(\mathcal{C}, \mathcal{D})$ using right Kan extensions instead of left Kan extensions?
3. Similarly, are there skew monoidal category structures on the subcategory of $\text{Rel}(A, B)$ 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

$$\begin{aligned} b &= a_0 y_1, \\ b &= x_m a_{2m} \end{aligned}$$

connected by relations

$$\begin{aligned} a_0 &= x_1 a_1, \\ a_1 y_1 &= a_2 y_2, \\ x_1 a_2 &= x_2 a_3, \\ a_{2m-1} y_m &= a_{2m} \end{aligned}$$

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-whose-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_carteian_to_symmetric_mo.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/> (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>

Appendices

10.A Other Chapters

Sets

1. [Sets](#)
2. [Constructions With Sets](#)
3. [Pointed Sets](#)
4. [Tensor Products of Pointed Sets](#)
5. [Relations](#)

Relations

6. Constructions With Relations

7. [Equivalence Relations and Apartness Relations](#)

Category Theory

8. [Categories](#)

Bicategories

9. [Types of Morphisms in Bicategories](#)

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