

The Gigantic Mess Project

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The Gigantic Mess 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 The Enrichment of Sets in Classical Truth Values

1.1.1 (-2)-Categories

Definition 1.1.1.1. A (-2)-category is the “necessarily true” truth value.^{1,2,3}

1.1.2 (-1)-Categories

Definition 1.1.2.1.1. A (-1)-category is a classical truth value.

Remark 1.1.2.1.2. 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).

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].

Therefore, a (-1) -category \mathcal{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 $\text{Hom}_{\mathcal{C}}(a, b)$ being a (-2) -category (i.e. trivial) for all $a, b \in \text{Obj}(\mathcal{C})$, forcing all objects of \mathcal{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 1.1.2.1.3. The **poset of truth values**⁵ is the poset $(\{\text{true}, \text{false}\}, \leq)^6$ consisting of

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

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

on $\{\text{true}, \text{false}\}$ defined by⁷

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

Proposition 1.1.2.1.4. The poset of truth values $\{\text{t}, \text{f}\}$ is Cartesian closed with product given by⁸

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

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

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

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

⁶Further Notation: Also written $\{\text{t}, \text{f}\}$.

⁷This partial order coincides with logical implication.

⁸Note that \times coincides with the “and” operator, while $\mathbf{Hom}_{\{\text{t}, \text{f}\}}$ coincides with the logical implication

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

$$\begin{array}{cccc} \begin{array}{c} P_1 \\ | \\ \exists! \\ \downarrow \\ t \xleftarrow{\text{pr}_1} \underbrace{t \times t}_{=t} \xrightarrow{\text{pr}_2} t \end{array} & \begin{array}{c} P_2 \\ | \\ \exists! \\ \downarrow \\ t \xleftarrow{\text{pr}_1} \underbrace{t \times f}_{=f} \xrightarrow{\text{pr}_2} f \end{array} & \begin{array}{c} P_3 \\ | \\ \exists! \\ \downarrow \\ f \xleftarrow{\text{pr}_1} \underbrace{f \times t}_{=f} \xrightarrow{\text{pr}_2} t \end{array} & \begin{array}{c} P_4 \\ | \\ \exists! \\ \downarrow \\ f \xleftarrow{\text{pr}_1} \underbrace{f \times f}_{=f} \xrightarrow{\text{pr}_2} f. \end{array} \end{array}$$

Here:

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

Cartesian Closedness: We claim there's a bijection

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

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

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

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

operator.

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\begin{aligned}\text{Hom}_{\{\mathbf{t}, \mathbf{f}\}}(\mathbf{f} \times \mathbf{f}, \mathbf{f}) &\cong \text{Hom}_{\{\mathbf{t}, \mathbf{f}\}}(\mathbf{f}, \mathbf{f}) \\ &= \{\text{id}_{\mathbf{f}\mathbf{a}\mathbf{l}s\mathbf{e}}\} \\ &\cong \text{Hom}_{\{\mathbf{t}, \mathbf{f}\}}(\mathbf{f}, \mathbf{f}) \\ &\cong \text{Hom}_{\{\mathbf{t}, \mathbf{f}\}}(\mathbf{f}, \mathbf{H}\mathbf{o}\mathbf{m}_{\{\mathbf{t}, \mathbf{f}\}}(\mathbf{f}, \mathbf{f})).\end{aligned}$$

The proof of naturality is omitted. \square

1.1.3 0-Categories

Definition 1.1.3.1.1. A **0-category** is a poset.⁹

Definition 1.1.3.1.2. A **0-groupoid** is a 0-category in which every morphism is invertible.¹⁰

1.1.4 Tables of Analogies Between Set Theory and Category Theory

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

Basics:

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

Powersets and categories of presheaves:

⁹Motivation: A 0-category is precisely a category enriched in the poset of (-1) -categories.

¹⁰That is, a set.

SET THEORY	CATEGORY THEORY
Powerset $\mathcal{P}(X)$	Presheaf category $\text{PSh}(\mathcal{C})$
Characteristic function $\chi_{\{x\}}$	Representable presheaf h_X
Characteristic embedding $\chi_{(-)}: X \hookrightarrow \mathcal{P}(X)$	Yoneda embedding $\mathfrak{y}: \mathcal{C}^{\text{op}} \hookrightarrow \text{PSh}(\mathcal{C})$
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 $\chi_U = \text{colim}_{x \in \text{Sets}(U, \{\text{t}, \text{f}\})} (\chi_x)$	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 $\mathcal{P}(X) \cong \text{Sets}(X, \{\text{t}, \text{f}\})$	Assignment $\mathcal{F} \mapsto \int_{\mathcal{C}} \mathcal{F}$ giving an equivalence $\text{PSh}(\mathcal{C}) \xrightarrow{\text{eq}} \text{DFib}(\mathcal{C})$

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

Relations and profunctors:

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

Appendices

1.A Other Chapters

- Sets**
 - 1. Sets
 - 2. Constructions With Sets
 - 3. Pointed Sets
 - 4. Tensor Products of Pointed Sets
 - 5. Relations
 - 6. Spans
 - 7. Posets
- Indexed and Fibred Sets**
 - 7. Indexed Sets
 - 8. Fibred Sets
 - 9. Un/Straightening for Indexed and Fibred Sets
- Category Theory**
 - 11. Categories
 - 12. Types of Morphisms in Categories
 - 13. Adjunctions and the Yoneda Lemma
 - 14. Constructions With Categories
 - 15. Profunctors
- Cartesian Closed Categories**
- Kan Extensions**
- Bicategories**
 - 18. Bicategories
 - 19. Internal Adjunctions
- Internal Category Theory**
 - 20. Internal Categories
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 - 21. The Cycle Category
- Cubical Stuff**
 - 22. The Cube Category
- Globular Stuff**
 - 23. The Globe Category
- Cellular Stuff**
 - 24. The Cell Category
- Monoids**
 - 25. Monoids
 - 26. Constructions With Monoids
- Monoids With Zero**
 - 27. Monoids With Zero

-
28. Constructions With Monoids With Zero 38. Real Analysis in Several Variables

Groups

29. Groups
30. Constructions With Groups

Hyper Algebra

31. Hypermonoids
32. Hypergroups
33. Hypersemirings and Hyperrings
34. Quantales

Near-Rings

35. Near-Semirings
36. Near-Rings
37. Real Analysis in One Variable

Real Analysis**Measure Theory**

39. Measurable Spaces
40. Measures and Integration

Probability Theory

40. Probability Theory

Stochastic Analysis

41. Stochastic Processes, Martingales, and Brownian Motion
42. Itô Calculus
43. Stochastic Differential Equations

Differential Geometry

44. Topological and Smooth Manifolds

Schemes

45. Schemes

1.2 Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets
5. Relations
6. Spans
7. Posets

Indexed and Fibred Sets

7. Indexed Sets
8. Fibred Sets

9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories
12. Types of Morphisms in Categories
13. Adjunctions and the Yoneda Lemma
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16. Cartesian Closed Categories
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Bicategories

- 18. Bicategories
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- Differential Geometry
- 44. Topological and Smooth Manifolds
- Schemes
- 45. Schemes

Chapter 2

Constructions With Sets

This chapter contains some material relating to constructions with sets. Notably, it contains:

1. Explicit descriptions of the major types of co/limits in Sets, including in particular pushouts and coequalisers (see [Definitions 2.2.3.1.1](#) and [2.2.4.1.1](#) and [Remarks 2.2.3.1.2](#) and [2.2.4.1.2](#));
2. A discussion of powersets as decategorifications of categories of presheaves ([Remarks 2.4.1.1.2](#) and [2.4.3.1.2](#));
3. A lengthy discussion of the adjoint triple

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

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 $f_!$.

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2.1 Limits of Sets

2.1.1 Products of Families of Sets

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

Definition 2.1.1.1. The **product¹** 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

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

- *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 $(a_i)_{i \in I}$ with $a_i \in A_i$ for

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 $\phi: P \rightarrow \prod_{i \in I} A_i$, uniquely determined by the condition $\text{pr}_i \circ \phi = p_i$ for each $i \in I$, being necessarily given by

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

for each $x \in P$. □

Proposition 2.1.1.1.2. Let $\{A_i\}_{i \in I}$ be a family of sets.

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

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

where

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

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

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

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

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

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

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

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

defined by

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

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

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

2.1.2 Binary Products of Sets

Let A and B be sets.

Definition 2.1.2.1.1. The **product**³ of A and B is the pair $(A \times B, \{\text{pr}_1, \text{pr}_2\})$ consisting of

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

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

- *The Cone.* The maps

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

defined by

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

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

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

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

in **Sets**. Then there exists a unique map $\phi: P \rightarrow A \times B$, uniquely determined by the conditions

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

being necessarily given by

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

for each $x \in P$. □

each $i \in I$.

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 $a \in A$ and $b \in B$ as in

Proposition 2.1.2.1.2. Let A, B, C , and X be sets.

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

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

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

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

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

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

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

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

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

defined by

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

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

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

2. *Adjointness.* We have adjunctions

$$\begin{aligned} (A \times - \dashv \text{Sets}(A, -)): \text{Sets} &\xrightleftharpoons[\text{Sets}(A, -)]{A \times -} \text{Sets}, \\ (- \times B \dashv \text{Sets}(B, -)): \text{Sets} &\xrightleftharpoons[\text{Sets}(B, -)]{- \times B} \text{Sets}, \end{aligned}$$

witnessed by bijections

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

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

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

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

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

4. *Unitality.* We have isomorphisms of sets

$$\text{pt} \times A \cong A,$$

$$A \times \text{pt} \cong A,$$

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

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

$$A \times \emptyset \cong \emptyset,$$

$$\emptyset \times A \cong \emptyset,$$

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

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

$$A \times (B \cup C) = (A \times B) \cup (A \times C),$$

$$(A \cup B) \times C = (A \times C) \cup (B \times C).$$

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

$$A \times (B \cap C) = (A \times B) \cap (A \times C),$$

$$(A \cap B) \times C = (A \times C) \cap (B \times C).$$

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

$$A \times (B \setminus C) = (A \times B) \setminus (A \times C),$$

$$(A \setminus B) \times C = (A \times C) \setminus (B \times C),$$

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 $(\text{Sets}, \coprod, \emptyset, \times, \text{pt})$ is a symmetric bimonoidal category.

Proof. **Item 1, Functoriality:** This follows by applying associativity and unitality componentwise.

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

$$\text{Hom}_{\text{Sets}}(X \times Y, Z) \cong \text{Hom}_{\text{Sets}}(X, \text{Hom}_{\text{Sets}}(Y, Z)),$$

natural in $Y, Z \in \text{Obj}(\text{Sets})$, as the proof of the existence of the adjunction $- \times Y \dashv \text{Hom}_{\text{Sets}}(-, Z)$ follows almost exactly in the same way.⁵

- *Map I.* We define a map

$$\Phi_{Y,Z}: \text{Hom}_{\text{Sets}}(X \times Y, Z) \rightarrow \text{Hom}_{\text{Sets}}(X, \text{Hom}_{\text{Sets}}(Y, Z)),$$

by sending a morphism $\xi: X \times Y \rightarrow Z$ to the morphism

$$\xi^\dagger: X \rightarrow \text{Hom}_{\text{Sets}}(Y, Z)$$

defined by

$$\xi^\dagger(x) \stackrel{\text{def}}{=} \xi_x$$

for each $x \in X$, where $\xi_x: Y \rightarrow Z$ is the map defined by

$$\xi_x(y) \stackrel{\text{def}}{=} \xi(x, y)$$

for each $y \in Y$.

- *Map II.* We define a map

$$\Psi_{Y,Z}: \text{Hom}_{\text{Sets}}(X, \text{Hom}_{\text{Sets}}(Y, Z)) \rightarrow \text{Hom}_{\text{Sets}}(X \times Y, Z)$$

given by sending a map $\xi: X \rightarrow \text{Hom}_{\text{Sets}}(Y, Z)$ to the map

$$\xi^\dagger: X \times Y \rightarrow Z$$

defined by

$$\xi^\dagger(x, y) \stackrel{\text{def}}{=} [\xi(x)](y)$$

for each $(x, y) \in X \times Y$.

⁵Here we sometimes denote a map $f: X \rightarrow Y$ by $[x \mapsto f(x)]$, similar to the lambda notation $\lambda x. f(x)$.

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

$$\begin{array}{ccc} \text{Hom}_{\text{Sets}}(X \times Y', Z) & \xrightarrow{\Phi_{Y',Z}} & \text{Hom}_{\text{Sets}}(X, \text{Hom}_{\text{Sets}}(Y', Z)), \\ \downarrow \text{id}_X \times g^* & & \downarrow (g^*)_* \\ \text{Hom}_{\text{Sets}}(X \times Y, Z) & \xrightarrow{\Phi_{Y,Z}} & \text{Hom}_{\text{Sets}}(X, \text{Hom}_{\text{Sets}}(Y, Z)), \end{array}$$

commutes. Indeed, given a morphism $\xi: X' \times Y \rightarrow Z$, we have

$$\begin{aligned} [\Phi_{Y,Z} \circ (g^* \times \text{id}_Y)](\xi) &\stackrel{\text{def}}{=} (\xi(-_1, g(-_2)))^\dagger \\ &\stackrel{\text{def}}{=} \xi_{-1}(g(-_2)) \\ &\stackrel{\text{def}}{=} (g_*)^*(\xi_{-1}(-_2)) \\ &\stackrel{\text{def}}{=} (g_*)^*(\xi^\dagger) \\ &\stackrel{\text{def}}{=} [(g_*)^* \circ \Phi_{Y',Z}](\xi). \end{aligned}$$

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

$$\begin{array}{ccc} \text{Hom}_{\text{Sets}}(X \times Y, Z) & \xrightarrow{\Phi_{Y,Z}} & \text{Hom}_{\text{Sets}}(X, \text{Hom}_{\text{Sets}}(Y, Z)), \\ \downarrow h_* & & \downarrow (h_*)_* \\ \text{Hom}_{\text{Sets}}(X \times Y, Z') & \xrightarrow{\Phi_{Y,Z'}} & \text{Hom}_{\text{Sets}}(X, \text{Hom}_{\text{Sets}}(Y, Z')), \end{array}$$

commutes. Indeed, given a morphism $\xi: X \times Y \rightarrow Z$, we have

$$\begin{aligned} [\Phi_{Y,Z} \circ h_*](\xi) &\stackrel{\text{def}}{=} (h(\xi(-_1, -_2)))^\dagger \\ &\stackrel{\text{def}}{=} [x \mapsto [y \mapsto h(\xi(x, y))]] \\ &\stackrel{\text{def}}{=} [x \mapsto h_*([y \mapsto \xi(x, y)])] \\ &\stackrel{\text{def}}{=} [x \mapsto h_*(\xi^\dagger(x))] \\ &\stackrel{\text{def}}{=} h_*(\xi^\dagger) \\ &\stackrel{\text{def}}{=} [(h_*)_* \circ \Phi_{Y,Z}](\xi). \end{aligned}$$

- *Invertibility I.* We claim that

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

Indeed, given a morphism $\xi: X \times Y \rightarrow Z$, we have

$$\begin{aligned} [\Psi_{X,Y} \circ \Phi_{X,Y}](\xi) &\stackrel{\text{def}}{=} \Psi_{X,Y}(\Phi_{X,Y}(\xi)) \\ &\stackrel{\text{def}}{=} \Psi_{X,Y}([x \mapsto [y \mapsto \xi(x, y)]]) \\ &\stackrel{\text{def}}{=} [(x, y) \mapsto \text{ev}_x([x \mapsto \text{ev}_y([y \mapsto \xi(x, y)])])] \\ &\stackrel{\text{def}}{=} [(x, y) \mapsto \text{ev}_x([x \mapsto \xi(x, y)])] \\ &\stackrel{\text{def}}{=} [(x, y) \mapsto \xi(x, y)] \\ &\stackrel{\text{def}}{=} \xi. \end{aligned}$$

- *Invertibility II.* We claim that

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

Indeed, given a morphism $\xi: X \rightarrow \text{Hom}_{\text{Sets}}(Y, Z)$, we have

$$\begin{aligned} [\Phi_{X,Y} \circ \Psi_{X,Y}](\xi) &\stackrel{\text{def}}{=} \Phi_{X,Y}(\Psi_{X,Y}(\xi)) \\ &\stackrel{\text{def}}{=} \Phi_{X,Y}(\Psi_{X,Y}([x \mapsto \xi(x)])) \\ &\stackrel{\text{def}}{=} \Phi_{X,Y}([(x, y) \mapsto \text{ev}_x([x \mapsto \text{ev}_y(\xi(x))])]) \\ &\stackrel{\text{def}}{=} \Phi_{X,Y}([(x, y) \mapsto \xi(x, y)]) \\ &\stackrel{\text{def}}{=} [x \mapsto [y \mapsto \xi(x, y)]] \\ &\stackrel{\text{def}}{=} \xi. \end{aligned}$$

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. □

2.1.3 Pullbacks

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

Definition 2.1.3.1.1. The **pullback of A and B over C along f and g** ⁶ is the pair⁷ $(A \times_C B, \{\text{pr}_1, \text{pr}_2\})$ consisting of

⁶Further Terminology: Also called the **fibre product of A and B over C along f and g** .

⁷Further Notation: Also written $A \times_{f,C,g} B$.

- *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

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

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

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

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

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

in Sets. Then there exists a unique map $\phi: P \rightarrow A \times_C B$, uniquely determined by the conditions

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

being necessarily given by

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

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 2.1.3.1.2. Here are some examples of pullbacks of sets.

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

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

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 2.1.3.1.3. 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

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

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

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

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

phism

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

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

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

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

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

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

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

where these pullbacks are built as in the diagrams

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

3. *Unitarity.* We have isomorphisms of sets

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

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

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

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

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

6. *Interaction With Products.* We have

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

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. □

2.1.4 Equalisers

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

Definition 2.1.4.1.1. 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

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

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

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

which gives

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

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

Proposition 2.1.4.1.2. Let A, B , and C be sets.

1. *Associativity.* We have an isomorphism of sets⁸

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

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

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

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

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

⁸That 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

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

in Sets.

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

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

and then take the equaliser of the composition

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

obtaining a subset

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

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

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

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

and then take the equaliser of the composition

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

obtaining a subset

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

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

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

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

6. *Interaction With Composition.* Let

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

be functions. We have an inclusion of sets

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

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

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

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

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

Indeed, suppose we have a diagram of the form

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

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

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

being necessarily given by

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

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

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

which gives

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

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

We now check the equalities

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

Indeed, we have

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

Similarly, we have

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

Item 4, Unitality: Clear.

Item 5, Commutativity: Clear.

Item 6, Interaction With Composition: Indeed, we have

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

and

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

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

2.2 Colimits of Sets

2.2.1 Coproducts of Families of Sets

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

Definition 2.2.1.1.1. The **disjoint union of the family** $\{A_i\}_{i \in I}$ is the pair $(\coprod_{i \in I} A_i, \{\text{inj}_i\}_{i \in I})$ consisting of

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

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

- *The Cocone.* The collection

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

of maps given by

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

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

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

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

in Sets. Then there exists a unique map $\phi: \coprod_{i \in I} A_i \rightarrow C$, uniquely determined by the condition $\phi \circ \text{inj}_i = i_i$ for each $i \in I$, being necessarily given by

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

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

Proposition 2.2.1.1.2. 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

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

where

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

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

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

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

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

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

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

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

defined by

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

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

Proof. **Item 1, Functoriality:** Clear. □

2.2.2 Binary Coproducts

Let A and B be sets.

Definition 2.2.2.1.1. The **coproduct**⁹ 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 Sets. Indeed, suppose we have a diagram of the form

$$\begin{array}{ccccc} & & C & & \\ & i_A \nearrow & & \swarrow i_B & \\ A & \xrightarrow{\text{inj}_A} & A \coprod B & \xleftarrow{\text{inj}_B} & B \end{array}$$

in Sets. Then there exists a unique map $\phi : A \coprod B \rightarrow C$, uniquely determined by the conditions

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

being necessarily given by

$$\phi(x) = \begin{cases} i_A(x) & \text{if } x \in A, \\ i_B(x) & \text{if } x \in B \end{cases}$$

for each $x \in C$. □

⁹Further Terminology: Also called the **disjoint union of A and B** , or the **binary disjoint union of A and B** ,

Proposition 2.2.2.1.2. Let A, B, C , and X be sets.

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

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

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

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

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

$$[f \coprod g](x) \stackrel{\text{def}}{=} \begin{cases} f(x) & \text{if } x \in A, \\ g(x) & \text{if } x \in B \end{cases}$$

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

for emphasis.

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:** Clear.

Item 2, Associativity: Clear.

Item 3, Unitality: Clear.

Item 4, Commutativity: Clear.

Item 5, Symmetric Monoidality: Omitted. \square

2.2.3 Pushouts

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

Definition 2.2.3.1.1. The **pushout of A and B over C along f and g** ¹⁰ is the pair $(A \coprod_C B, \{\text{inj}_1, \text{inj}_2\})$ 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

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

¹⁰Further Terminology: Also called the **fibre coproduct of A and B over C along f and g** .

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

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

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

$$\begin{array}{ccccc} & & P & & \\ & \swarrow i_2 & & \downarrow & \\ A \coprod_C B & \xleftarrow{\text{inj}_2} & B & & \\ \uparrow i_1 & & \uparrow g & & \\ A & \xleftarrow{f} & C & & \end{array}$$

in Sets. Then there exists a unique map $\phi : A \coprod_C B \rightarrow P$, uniquely determined by the conditions

$$\begin{aligned} \phi \circ \text{inj}_1 &= i_1, \\ \phi \circ \text{inj}_2 &= i_2, \end{aligned}$$

being necessarily given by

$$\phi(x) = \begin{cases} i_1(a) & \text{if } x = [(0, a)], \\ i_2(b) & \text{if } x = [(1, b)] \end{cases}$$

for each $x \in A \coprod_C B$, where the well-definedness of ϕ is guaranteed by the equality $i_1 \circ f = i_2 \circ g$ and the definition of the relation \sim on $A \coprod_C B$ as follows.

1. *Case 1:* Suppose we have $x = [(0, a)] = [(0, a')]$ for some $a, a' \in A$. Then, by Remark 2.2.3.1.2, 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 2.2.3.1.2, 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 2.2.3.1.2, 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 $i_1 \circ f = i_2 \circ g$ gives

$$\begin{aligned} \phi([x]) &= \phi([(0, f(c))]) \\ &\stackrel{\text{def}}{=} i_1(f(c)) \\ &= i_2(g(c)) \\ &\stackrel{\text{def}}{=} \phi([(1, g(c))]) \\ &= \phi([y]), \end{aligned}$$

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 2.2.3.1.2. In detail, by ??, the relation \sim of Definition 2.2.3.1.1 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:

- (★) 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 2.2.3.1.3. Here are some examples of pushouts of sets.

1. *Wedge Sums of Pointed Sets.* The wedge sum of two pointed sets of ?? is an example of a pushout of sets.
2. *Intersections via Unions.* Let $A, B \subset X$. We have a bijection of sets

$$\begin{array}{ccc} A \cup B & \xleftarrow{\quad} & B \\ \uparrow & \lrcorner & \uparrow \\ A \amalg_{A \cap B} B & & A \cap B. \\ \uparrow & & \downarrow \\ A & \xleftarrow{\quad} & A \cap B. \end{array}$$

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

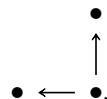
Item 2, Intersections via Unions: Indeed, $A \amalg_{A \cap B} B$ is the quotient of $A \coprod B$ by the equivalence relation obtained by declaring $(0, a) \sim (1, b)$ iff $a = b \in A \cap B$, which is in bijection with $A \cup B$ via the map with $[(0, a)] \mapsto a$ and $[(1, b)] \mapsto b$. \square

Proposition 2.2.3.1.4. Let A, B, C , and X be sets.

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

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

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



In particular, the action on morphisms of $-_1 \amalg_{-_3} -_1$ is given by sending a mor-

phism

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

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

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

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

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

where these pullbacks are built as in the diagrams

$$\begin{array}{ccc}
 \begin{array}{c} (A \sqcup_X B) \sqcup_Y C \\ \swarrow \quad \searrow \\ A \sqcup_X B \end{array} & \begin{array}{c} (A \sqcup_X B) \sqcup_B (B \sqcup_Y C) \\ \swarrow \quad \searrow \\ A \sqcup_X B \quad B \sqcup_Y C \end{array} & \begin{array}{c} A \sqcup_X (B \sqcup_Y C) \\ \swarrow \quad \searrow \\ A \quad B \sqcup_Y C \end{array} \\
 \begin{array}{ccccc} & f & g & h & k \\ A & \nearrow & \searrow & \nearrow & \searrow \\ X & & Y & & C \end{array} & \begin{array}{ccccc} & f & g & h & k \\ A & \nearrow & \searrow & \nearrow & \searrow \\ X & & Y & & C \end{array} & \begin{array}{ccccc} & f & g & h & k \\ A & \nearrow & \searrow & \nearrow & \searrow \\ X & & Y & & C \end{array}
 \end{array}$$

3. *Unitality.* We have isomorphisms of sets

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

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

$$\begin{array}{ccc}
 \begin{array}{c} A \sqcup_X B \leftarrow B \\ \uparrow \lrcorner \qquad \uparrow g \\ A \xleftarrow{f} X, \end{array} & \begin{array}{c} A \sqcup_X B \cong B \sqcup_X A \end{array} & \begin{array}{c} B \sqcup_X A \leftarrow A \\ \uparrow \lrcorner \qquad \uparrow f \\ B \xleftarrow{g} X. \end{array}
 \end{array}$$

5. *Interaction With Coproducts.* We have

$$\begin{array}{c}
 \begin{array}{c} A \sqcup B \leftarrow B \\ \uparrow \lrcorner \qquad \uparrow \iota_B \\ A \xleftarrow{\iota_A} \emptyset. \end{array} \\
 A \sqcup_{\emptyset} B \cong A \sqcup B,
 \end{array}$$

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

Proof. **Item 1, Functoriality:** This is a special case of functoriality of colimits, ?? 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. □

2.2.4 Coequalisers

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

Definition 2.2.4.1.1. 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

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

in Sets. Then, since $c(f(a)) = c(g(a))$ for each $a \in A$, it follows from **????** of **??** that there exists a unique map $\text{CoEq}(f, g) \xrightarrow{\exists!} C$ making the diagram

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

commutes. □

Remark 2.2.4.1.2. In detail, by ??, 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 $a = b$;
- 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 2.2.4.1.3. 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 [Pro24z]. □

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

1. *Associativity.* We have an isomorphism of sets¹¹

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

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

$$A \xrightarrow[\substack{g \\ h}]{} B$$

in Sets .

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

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

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

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

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

in Sets .

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

$$A \xrightarrow[\substack{f \\ g}]{} B \xrightarrow{\text{coeq}(f, g)} \text{CoEq}(f, g)$$

and then take the coequaliser of the composition

$$A \xrightarrow[\substack{f \\ h}]{} B \xrightarrow{\text{coeq}(f, g)} \text{CoEq}(f, g),$$

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

$$A \xrightarrow[\substack{g \\ h}]{} B \xrightarrow{\text{coeq}(g, h)} \text{CoEq}(g, h)$$

and then take the coequaliser of the composition

$$A \xrightarrow[\substack{f \\ g}]{} B \xrightarrow{\text{coeq}(g, h)} \text{CoEq}(g, h),$$

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

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. 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 Unions of Families

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

Definition 2.3.5.1.1. 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 ??.

2.3.6 Binary Unions

Let A and B be sets.

Definition 2.3.6.1.1. The **union¹² 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 2.3.6.1.2. 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

¹²*Further Terminology:* Also called the **binary union of A and B** , for emphasis.

- *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

$$(\star) \quad \text{If } U \subset U' \text{ and } V \subset V', \text{ then } U \cup V \subset U' \cup V';$$

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, *Functionality:* See [Pro24an].

Item 2, *Via Intersections and Symmetric Differences:* See [Pro24ay].

Item 3, *Associativity:* See [Pro24ba].

Item 4, *Unitality:* This follows from [Pro24bd] and Item 5.

Item 5, *Commutativity:* See [Pro24bb].

Item 6, *Idempotency:* See [Pro24am].

Item 7, *Distributivity Over Intersections:* See [Pro24az].

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 2.3.8.1.2. \square

2.3.7 Intersections of Families

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

Definition 2.3.7.1.1. The **intersection of a family \mathcal{F} of sets** is the set $\bigcap_{X \in \mathcal{F}} X$ defined by

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

2.3.8 Binary Intersections

Let X and Y be sets.

Definition 2.3.8.1.1. The **intersection**¹³ 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 2.3.8.1.2. Let X be a set.

1. *Functionality.* 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

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

¹³Further Terminology: Also called the **binary intersection of X and Y** , for emphasis.

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 by¹⁴

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

witnessed by bijections

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

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

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

(a) The following conditions are equivalent:

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

(b) The following conditions are equivalent:

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

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

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

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

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

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

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

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

¹⁴ *Intuition:* Since intersections are the products in $\mathcal{P}(X)$, the left adjoint $\mathbf{Hom}_{\mathcal{P}(X)}(U, V)$ works as a function type $U \rightarrow V$.

Now, under the Curry–Howard correspondence, the function type $U \rightarrow V$ corresponds to implication $U \implies V$, which is logically equivalent to the statement $\neg U \vee V$, which in turn corresponds to the set $U^c \vee V \stackrel{\text{def}}{=} (X \setminus U) \cup V$.

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

$$U \cap U = U$$

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

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 [Pro24al].

Item 2, Adjointness: See [MSE 267469].

Item 3, Associativity: See [Pro24t].

Item 4, Unitality: This follows from [Pro24x] and Item 5.

Item 5, Commutativity: See [Pro24u].

Item 6, Idempotency: See [Pro24ak].

Item 7, Distributivity Over Unions: See [Pro24aj].

Item 8, Annihilation With the Empty Set: This follows from [Pro24v] 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 2.3.8.1.2. □

2.3.9 Differences

Let X and Y be sets.

Definition 2.3.9.1.1. 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 2.3.9.1.2. Let X be a set.

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

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

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

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

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

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

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

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

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

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

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

i.e. where we have

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

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

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 [Pro24ad] and [Pro24ah].

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 [Pro24ai].

Item 6, Interaction With Unions IV: See [Pro24ac].

Item 7, Interaction With Intersections: See [Pro24w].

Item 8, Interaction With Complements: See [Pro24aa].

Item 9, Interaction With Symmetric Differences: See [Pro24ab].

Item 10, Triple Differences: See [Pro24ag].

Item 11, Left Annihilation: Clear.

Item 12, Right Unitality: See [Pro24ae].

Item 13, Invertibility: See [Pro24af].

Item 14, Interaction With Containment: Omitted.

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

□

2.3.10 Complements

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

Definition 2.3.10.1.1. 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 2.3.10.1.2. 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 $V^c \subset U^c$.

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 2.3.9.1.2.

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

Item 3, *Involutority:* See [Pro24l].

Item 4, *Interaction With Characteristic Functions:* Clear. □

2.3.11 Symmetric Differences

Let A and B be sets.

Definition 2.3.11.1.1. The **symmetric difference of A and B** is the set $A \Delta B$ defined by

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

Proposition 2.3.11.1.2. Let X be a set.

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

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

2. *Via Unions and Intersections.* We have¹⁵

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

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

3. *Associativity.* We have¹⁶

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

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

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

$$\emptyset \Delta U = U$$

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

¹⁵ Illustration:



¹⁶ Illustration:



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

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

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

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.¹⁷
- (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 ??;

¹⁷Here 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 $\mathbb{Z}/2 \times \mathbb{Z}/2$:

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

- 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:

- (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.¹⁸

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

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

[Item 3, Associativity](#): See [[Pro24ao](#)].

[Item 4, Commutativity](#): See [[Pro24ap](#)].

[Item 5, Unitality](#): This follows from [Item 4](#) and [[Pro24at](#)].

[Item 6, Invertibility](#): See [[Pro24av](#)].

[Item 7, Interaction With Unions](#): See [[Pro24bc](#)].

[Item 8, Interaction With Complements I](#): See [[Pro24as](#)].

[Item 9, Interaction With Complements II](#): This follows from [Item 4](#) and [[Pro24ax](#)].

[Item 10, Interaction With Complements III](#): See [[Pro24aq](#)].

[Item 11, "Transitivity"](#): We have

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

[Item 12, The Triangle Inequality for Symmetric Differences](#): This follows from [Items 2](#) and [11](#).

[Item 13, Distributivity Over Intersections](#): See [[Pro24s](#)].

[Item 14, Interaction With Characteristic Functions](#): See [[Pro24j](#)].

[Item 15, Bijectivity](#): Clear.

[Item 16, Interaction With Powersets and Groups](#): [Item 16a](#) follows from¹⁹ [Items 3](#) to [6](#), while [Item 3b](#) follows from [Item 6](#).

¹⁸ 

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 [[Pro24aw](#)] for a proof.

END TEXTDBEND

¹⁹ Reference: [[Pro24ar](#)].

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 2.3.8.1.2](#) and [Items 13](#) and [16](#).²⁰ \square

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** ²¹ is the function²²

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

defined by

$$\chi_U(x) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x \in U, \\ \text{false} & \text{if } x \notin U \end{cases}$$

for each $x \in X$.

2. The **characteristic function of x** is the function²³

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

defined by

$$\chi_x \stackrel{\text{def}}{=} \chi_{\{x\}},$$

i.e. by

$$\chi_x(y) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x = y, \\ \text{false} & \text{if } x \neq y \end{cases}$$

for each $y \in X$.

3. The **characteristic relation on X** ²⁴ is the relation²⁵

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

²⁰Reference: [Pro24au].

²¹Further Terminology: Also called the **indicator function of U** .

²²Further Notation: Also written $\chi_X(U, -)$ or $\chi_X(-, U)$.

²³Further Notation: Also written χ_x , $\chi_X(x, -)$, or $\chi_X(-, x)$.

²⁴Further Terminology: Also called the **identity relation on X** .

²⁵Further Notation: Also written χ^{-1}_{-2} , or \sim_{id} in the context of relations.

on X defined by²⁶

$$\chi_X(x, y) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } x = y, \\ \text{false} & \text{if } x \neq y \end{cases}$$

for each $x, y \in X$.

4. The **characteristic embedding**²⁷ 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:²⁸

1. A function

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

²⁶As a subset of $X \times X$, the relation χ_X corresponds to the diagonal $\Delta_X \subset X \times X$ of X .

²⁷The 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 $x, y \in X$.

²⁸These 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 $y \in \text{Obj}(X_{\text{disc}})$.

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.

2. The characteristic function

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

of an *element* x of X is a decategorification of the representable presheaf

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

of an *object* x of a category \mathcal{C} .

3. The characteristic relation

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

of X is a decategorification of the Hom profunctor

$$\text{Hom}_{\mathcal{C}}(-_1, -_2): \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \text{Sets}$$

of a category \mathcal{C} .

4. The characteristic embedding

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

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

$$\mathfrak{J}: \mathcal{C}^{\text{op}} \hookrightarrow \text{PSh}(\mathcal{C})$$

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

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

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 inclusion²⁹

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

2. *Interaction With Unions I.* We have

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

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

3. *Interaction With Unions II.* We have

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

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

4. *Interaction With Intersections I.* We have

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

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

5. *Interaction With Intersections II.* We have

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

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

6. *Interaction With Differences.* We have

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

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

7. *Interaction With Complements.* We have

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

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

8. *Interaction With Symmetric Differences.* We have

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

and thus, in particular, we have

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

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

²⁹This is the 0-categorical version of ??.

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 2.3.6.1.2](#) and is proved there.

Item 3, Interaction With Unions II: This is a repetition of **Item 9** of [Proposition 2.3.6.1.2](#) and is proved there.

Item 4, Interaction With Intersections I: This is a repetition of **Item 9** of [Proposition 2.3.8.1.2](#) and is proved there.

Item 5, Interaction With Intersections II: This is a repetition of **Item 10** of [Proposition 2.3.8.1.2](#) and is proved there.

Item 6, Interaction With Differences: This is a repetition of **Item 15** of [Proposition 2.3.9.1.2](#) and is proved there.

Item 7, Interaction With Complements: This is a repetition of **Item 4** of [Proposition 2.3.10.1.2](#) and is proved there.

Item 8, Interaction With Symmetric Differences: This is a repetition of **Item 14** of [Proposition 2.3.11.1.2](#) and is proved there. \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: while³⁰

- The powerset of a set X is equivalently (Item 6 of Proposition 2.4.3.1.3) the set

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

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

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

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

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

Proposition 2.4.3.1.3. Let X be a set.

1. *Functionality.* The assignment $X \mapsto \mathcal{P}(X)$ defines functors

$$\begin{aligned} \mathcal{P}_*: \text{Sets} &\rightarrow \text{Sets}, \\ \mathcal{P}^{-1}: \text{Sets}^{\text{op}} &\rightarrow \text{Sets}, \\ \mathcal{P}_!: \text{Sets} &\rightarrow \text{Sets} \end{aligned}$$

where

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

$$\begin{aligned} \mathcal{P}_*(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}^{-1}(A) &\stackrel{\text{def}}{=} \mathcal{P}(A), \\ \mathcal{P}_!(A) &\stackrel{\text{def}}{=} \mathcal{P}(A); \end{aligned}$$

- *Action on Morphisms.* For each morphism $f: A \rightarrow B$ of Sets, the images

$$\begin{aligned} \mathcal{P}_*(f): \mathcal{P}(A) &\rightarrow \mathcal{P}(B), \\ \mathcal{P}^{-1}(f): \mathcal{P}(B) &\rightarrow \mathcal{P}(A), \\ \mathcal{P}_!(f): \mathcal{P}(A) &\rightarrow \mathcal{P}(B) \end{aligned}$$

³⁰This parallel is based on the following comparison:

- A category is enriched over the category

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

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

- A set is enriched over the set

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

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

of f by \mathcal{P}_* , \mathcal{P}^{-1} , and $\mathcal{P}_!$ are defined by

$$\begin{aligned}\mathcal{P}_*(f) &\stackrel{\text{def}}{=} f_*, \\ \mathcal{P}^{-1}(f) &\stackrel{\text{def}}{=} f^{-1}, \\ \mathcal{P}_!(f) &\stackrel{\text{def}}{=} f_!,\end{aligned}$$

as in [Definitions 2.4.4.1.1](#), [2.4.5.1.1](#) and [2.4.6.1.1](#).

2. *Adjointness I.* We have an adjunction

$$(\mathcal{P}^{-1} \dashv \mathcal{P}^{-1,\text{op}}): \quad \text{Sets}^{\text{op}} \begin{array}{c} \xrightarrow{\mathcal{P}^{-1}} \\ \perp \\ \xleftarrow{\mathcal{P}^{-1,\text{op}}} \end{array} \text{Sets},$$

witnessed by a bijection

$$\underbrace{\text{Sets}^{\text{op}}(\mathcal{P}(X), Y)}_{\stackrel{\text{def}}{=} \text{Sets}(Y, \mathcal{P}(X))} \cong \text{Sets}(X, \mathcal{P}(Y)),$$

natural in $X \in \text{Obj}(\text{Sets})$ and $Y \in \text{Obj}(\text{Sets}^{\text{op}})$.

3. *Adjointness II.* We have an adjunction

$$(\text{Gr} \dashv \mathcal{P}_*): \quad \text{Sets} \begin{array}{c} \xrightarrow{\text{Gr}} \\ \perp \\ \xleftarrow{\mathcal{P}_*} \end{array} \text{Rel},$$

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 ?? of ??.

4. *Symmetric Strong Monoidality With Respect to Coproducts.* The powerset functor \mathcal{P}_* of [Item 1](#) has a symmetric strong monoidal structure

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

being equipped with isomorphisms

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

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

5. *Symmetric Lax Monoidality With Respect to Products.* The powerset functor \mathcal{P}_* of [Item 1](#) 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 isomorphisms

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

natural in $X, Y \in \text{Obj}(\text{Sets})$, where $\mathcal{P}_{*|X,Y}^\otimes$ is given by

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

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

6. *Powersets as Sets of Functions.* The assignment $U \mapsto \chi_U$ defines a bijection³¹

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

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

7. *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 $X \in \text{Obj}(\text{Sets})$.

8. *As a Free Cocompletion: 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, \leq) ;
 - A function $f : X \rightarrow Y$;

³¹This bijection is a decategorified form of the equivalence

$$\text{PSh}(\mathcal{C}) \xrightarrow{\text{eq.}} \text{DFib}(\mathcal{C})$$

of ?? of ??, with $\chi_{(-)}$ being a decategorified version of the category of elements construction of ??.
See also ?? of ??.

there exists a unique cocontinuous morphism of posets $(\mathcal{P}(X), \subset) \xrightarrow{\exists!} (Y, \leq)$ making the diagram

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

commute.

9. *As a Free Cocompletion: Adjointness.* We have an adjunction³²

$$(\chi_{(-)} \dashv \text{忘}): \text{Sets} \begin{array}{c} \xrightarrow{\chi_{(-)}} \\ \perp \\ \xleftarrow{\text{忘}} \end{array} \text{Pos}^{\text{cocomp.}},$$

witnessed by a bijection

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

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

- We have a natural map

$$\chi_X^*: \text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \leq)) \rightarrow \text{Sets}(X, Y)$$

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

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

- We have a natural map

$$\text{Lan}_{\chi_X}: \text{Sets}(X, Y) \rightarrow \text{Pos}^{\text{cocomp.}}((\mathcal{P}(X), \subset), (Y, \leq))$$

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:

³²In this sense, $\mathcal{P}(A)$ is the free cocompletion of A . (Note that, despite its name, however, this is not an

- \vee is the join in (Y, \leq) ;
- 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, \leq) .

Proof. **Item 1, Functoriality:** This follows from [Items 3 and 4 of Proposition 2.4.4.1.4](#), [Items 3 and 4 of Proposition 2.4.5.1.4](#), and [Items 3 and 4 of Proposition 2.4.6.1.6](#).

Item 2, Adjointness I: Omitted.

Item 3, Adjointness II: We have

$$\begin{aligned} \text{Rel}(\text{Gr}(A), B) &= \mathcal{P}(A \times B) \\ &= \text{Sets}(A \times B, \{\text{t}, \text{f}\}) && (\text{by Item 6}) \\ &= \text{Sets}(A, \text{Sets}(B, \{\text{t}, \text{f}\})) && (\text{by Item 2 of Proposition 2.1.2.1.2}) \\ &= \text{Sets}(A, \mathcal{P}(B)) && (\text{by Item 6}) \end{aligned}$$

with all bijections natural in A and B .

Item 4, Symmetric Strong Monoidality With Respect to Coproducts: Omitted.

Item 5, Symmetric Lax Monoidality With Respect to Products: Omitted.

Item 6, Powersets as Sets of Functions: Omitted.

Item 7, Powersets as Sets of Relations: Omitted.

Item 8, As a Free Cocompletion: Universal Property: This is a rephrasing of [??](#).

Item 9, As a Free Cocompletion: Adjointness: Omitted. □

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 function³³

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

idempotent operation, as we have $\mathcal{P}(\mathcal{P}(A)) \neq \mathcal{P}(A)$.)

³³Further Notation: Also written $\exists_f: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$. This notation comes from the fact that the following statements are equivalent, where $b \in B$ and $U \in \mathcal{P}(A)$:

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

defined by^{34,35}

$$\begin{aligned} f_*(U) &\stackrel{\text{def}}{=} f(U) \\ &= \left\{ b \in B \mid \begin{array}{l} \text{there exists some } a \in U \\ \text{such that } b = f(a) \end{array} \right\} \\ &= \{f(a) \in B \mid a \in U\} \end{aligned}$$

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

Remark 2.4.4.1.2. Identifying subsets of A with functions from A to $\{\text{true}, \text{false}\}$ via Item 6 of Proposition 2.4.3.1.3, we see that the direct image function associated to f is equivalently the function

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

defined by

$$\begin{aligned} f_*(\chi_U) &\stackrel{\text{def}}{=} \text{Lan}_f(\chi_U) \\ &= \text{colim} \left(\left(f \xrightarrow{\vec{\times}} \underline{(-_1)} \right) \xrightarrow{\text{pr}} A \xrightarrow{\chi_U} \{\text{t}, \text{f}\} \right) \\ &= \underset{\substack{a \in A \\ f(a) = -1}}{\text{colim}} (\chi_U(a)) \\ &= \bigvee_{\substack{a \in A \\ f(a) = -1}} (\chi_U(a)). \end{aligned}$$

So, in other words, we have

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

for each $b \in B$.

Proposition 2.4.4.1.3. Let $f: A \rightarrow B$ be a function.

³⁴Further Terminology: The set $f(U)$ is called the **direct image of U by f** .

³⁵We also have

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

see Item 7 of Proposition 2.4.4.1.3.

1. *Functionality.* The assignment $U \mapsto f_*(U)$ defines a functor

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

where

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

$$[f_*](U) \stackrel{\text{def}}{=} f_*(U);$$

- *Action on Morphisms.* For each $U, V \in \mathcal{P}(A)$:

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

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

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

witnessed by bijections of sets

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

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. *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

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

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

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

being equipped with equalities

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

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

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

being equipped with inclusions

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

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

7. *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 ?? 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 7, Relation to Direct Images With Compact Support: Applying ?? of ?? 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 2.4.4.1.4. Let $f: A \rightarrow B$ be a function.

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

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

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

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

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

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

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

Item 2, Functionality II: Clear.

Item 3, Interaction With Identities: This follows from ?? of ??.

Item 4, Interaction With Composition: This follows from ?? of ??.

\square

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 function³⁶

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

defined by³⁷

$$f^{-1}(V) \stackrel{\text{def}}{=} \{a \in A \mid \text{we have } f(a) \in V\}$$

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 Item 6 of Proposition 2.4.3.1.3, 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.

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

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

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

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

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

³⁶Further Notation: Also written $f^*: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$.

³⁷Further Terminology: The set $f^{-1}(V)$ is called the **inverse image of V by f** .

witnessed by bijections of sets

$$\begin{aligned}\text{Hom}_{\mathcal{P}(B)}(f_*(U), V) &\cong \text{Hom}_{\mathcal{P}(A)}\left(U, f^{-1}(V)\right), \\ \text{Hom}_{\mathcal{P}(A)}\left(f^{-1}(U), V\right) &\cong \text{Hom}_{\mathcal{P}(B)}(U, f_!(V)),\end{aligned}$$

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. *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

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

being equipped with equalities

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

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

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

being equipped with equalities

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

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

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

[Item 2](#), *Triple Adjunctions:* This follows from ?? of ??.

[Item 3](#), *Preservation of Colimits:* This follows from [Item 2](#) and ?? of ??.

[Item 4](#), *Preservation of Limits:* This follows from [Item 2](#) and ?? of ??.

[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](#).

□

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

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

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

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

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 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 ?? of ??.

Item 4, Interaction With Composition: This follows from ?? of ??.

□

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 function³⁸

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

defined by^{39,40}

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

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

Remark 2.4.6.1.2. Identifying subsets of A with functions from A to {true, false} via Item 6 of Proposition 2.4.3.1.3, 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

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

³⁸Further Notation: Also written $\forall_f: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$. 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 $a \in U$.

³⁹Further Terminology: The set $f_!(U)$ is called the **direct image with compact support of U by f** .

⁴⁰We also have

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

see Item 7 of Proposition 2.4.6.1.5.

So, 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 2.4.6.1.3. Let U be a subset of A .^{41,42}

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

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

⁴¹Note that we have

$$f_!(U) = f_{!,\text{im}}(U) \cup f_{!,\text{cp}}(U),$$

as

$$\begin{aligned} f_!(U) &= f_!(U) \cap B \\ &= f_!(U) \cap (\text{Im}(f) \cup (B \setminus \text{Im}(f))) \\ &= (f_!(U) \cap \text{Im}(f)) \cup (f_!(U) \cap (B \setminus \text{Im}(f))) \\ &\stackrel{\text{def}}{=} f_{!,\text{im}}(U) \cup f_{!,\text{cp}}(U). \end{aligned}$$

⁴²In terms of the meet computation of $f_!(U)$ of Remark 2.4.6.1.2, namely

$$f_!(\chi_U) = \bigwedge_{\substack{a \in A \\ f(a)=-1}} (\chi_U(a)),$$

Example 2.4.6.1.4. 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

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

for any $U \subset \mathbb{N}$.

2. *Parabolas.* Consider the function $f: \mathbb{R} \rightarrow \mathbb{R}$ given by

$$f(x) \stackrel{\text{def}}{=} x^2$$

for each $x \in \mathbb{R}$. We have

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

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

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

3. *Circles.* Consider the function $f: \mathbb{R}^2 \rightarrow \mathbb{R}$ given by

$$f(x, y) \stackrel{\text{def}}{=} x^2 + y^2$$

for each $(x, y) \in \mathbb{R}^2$. We have

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

for any $U \subset \mathbb{R}^2$, and since

$$f^{-1}(r) = \begin{cases} \text{a circle of radius } r \text{ about the origin} & \text{if } r > 0, \\ \{(0, 0)\} & \text{if } r = 0, \\ \emptyset & \text{if } r < 0, \end{cases}$$

we have e.g.:

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

Proposition 2.4.6.1.5. Let $f: A \rightarrow B$ be a function.

1. *Functionality.* The assignment $U \mapsto f_!(U)$ defines a functor

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

where

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

$$[f_!](U) \stackrel{\text{def}}{=} f_!(U);$$

• *Action on Morphisms.* For each $U, V \in \mathcal{P}(A)$:

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

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

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

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\mathcal{P}(B)}(f_*(U), V) &\cong \text{Hom}_{\mathcal{P}(A)}\left(U, f^{-1}(V)\right), \\ \text{Hom}_{\mathcal{P}(A)}\left(f^{-1}(U), V\right) &\cong \text{Hom}_{\mathcal{P}(B)}(U, f_!(V)), \end{aligned}$$

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

$$\bigcup_{i \in I} f_!(U_i) \subset f_!\left(\bigcup_{i \in I} U_i\right),$$

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.

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

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

being equipped with inclusions

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

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

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

being equipped with equalities

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

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

7. *Relation to Direct Images.* We have

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

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

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

9. *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 ?? of ??.

Item 3, Lax Preservation of Colimits: Omitted.

Item 4, Preservation of Limits: Omitted. This follows from Item 2 and ?? of ??.

Item 5, Symmetric Lax Monoidality With Respect to Unions: This follows from ??.

Item 6, Symmetric Strict Monoidality With Respect to Intersections: This follows from Item 4.

Item 7, 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 7](#).

[Item 8, Interaction With Injections:](#) Clear.

[Item 9, Interaction With Surjections:](#) Clear. \square

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

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

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

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

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

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

[Item 4, Interaction With Composition:](#) This follows from ?? of ??.

\square

Appendices

2.A Other Chapters

Sets

1. [Sets](#)
2. [Constructions With Sets](#)
3. [Pointed Sets](#)
4. [Tensor Products of Pointed Sets](#)

Relations

5. [Relations](#)
6. [Spans](#)
7. [Posets](#)

Indexed and Fibred Sets

7. [Indexed Sets](#)

8. Fibred Sets

9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories

12. Types of Morphisms in Categories

13. Adjunctions and the Yoneda Lemma

14. Constructions With Categories

15. Profunctors

16. Cartesian Closed Categories

17. Kan Extensions

Bicategories

18. Bicategories

19. Internal Adjunctions

Internal Category Theory

20. Internal Categories

Cyclic Stuff

21. The Cycle Category

Cubical Stuff

22. The Cube Category

Globular Stuff

23. The Globe Category

Cellular Stuff

24. The Cell Category

Monoids

25. Monoids

26. Constructions With Monoids

Monoids With Zero

27. Monoids With Zero

28. Constructions With Monoids With Zero

Groups

29. Groups

30. Constructions With Groups

Hyper Algebra

31. Hypermonoids

32. Hypergroups

33. Hypersemirings and Hyperrings

34. Quantales

Near-Rings

35. Near-Semirings

36. Near-Rings

Real Analysis

37. Real Analysis in One Variable

38. Real Analysis in Several Variables

Measure Theory

39. Measurable Spaces

40. Measures and Integration

Probability Theory

40. Probability Theory

Stochastic Analysis

41. Stochastic Processes, Martingales, and Brownian Motion

42. Itô Calculus

43. Stochastic Differential Equations

Differential Geometry

44. Topological and Smooth Manifolds

Schemes

45. Schemes

2.2 Other Chapters

Sets	Cyclic Stuff
1. Sets	21. The Cycle Category
2. Constructions With Sets	Cubical Stuff
3. Pointed Sets	22. The Cube Category
4. Tensor Products of Pointed Sets	Globular Stuff
5. Relations	23. The Globe Category
6. Spans	Cellular Stuff
7. Posets	24. The Cell Category
Indexed and Fibred Sets	Monoids
7. Indexed Sets	25. Monoids
8. Fibred Sets	26. Constructions With Monoids
9. Un/Straightening for Indexed and Fibred Sets	Monoids With Zero
Category Theory	27. Monoids With Zero
11. Categories	28. Constructions With Monoids With Zero
12. Types of Morphisms in Categories	Groups
13. Adjunctions and the Yoneda Lemma	29. Groups
14. Constructions With Categories	30. Constructions With Groups
15. Profunctors	Hyper Algebra
16. Cartesian Closed Categories	31. Hypermonoids
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Internal Category Theory	35. Near-Semirings
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- 41. Stochastic Processes, Martingales, and Brownian Motion
- 42. Itô Calculus
- 43. Stochastic Differential Equations
- Differential Geometry
- 44. Topological and Smooth Manifolds
- Schemes
- 45. Schemes

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 $(M, 0_M)$.

3.1.2 Morphisms of Pointed Sets

Definition 3.1.2.1.1. A **morphism of pointed sets**⁴ is equivalently

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

¹Further Terminology: Also called an \mathbb{F}_1 -module.

²Further Terminology: Also called the underlying pointed set of the field with one element.

³Further Notation: Also denoted $(\mathbb{F}_1, 0)$.

⁴Further Terminology: Also called a pointed function or a morphism of \mathbb{F}_1 -modules.

- 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

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

of Sets_* at (X, x_0) is defined by⁵

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

- *Composition.* For each $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\text{Sets}_*)$, the composition map

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

of Sets_* at $((X, x_0), (Y, y_0), (Z, z_0))$ is defined by⁶

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

⁵Note that id_X is indeed a morphism of pointed sets, as we have $\text{id}_X(x_0) = x_0$.

⁶Note that the composition of two morphisms of pointed sets is indeed a morphism of pointed sets, as

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 Sets_* of pointed sets and morphisms between them is complete, having in particular products (Definition 3.2.1.1.1), pullbacks (Definition 3.2.3.1.1), and equalisers (Definition 3.2.2.1.1).
2. *Cocompleteness.* The category Sets_* of pointed sets and morphisms between them is cocomplete, having in particular coproducts (Definition 3.3.1.1.1), pushouts (Definition 3.2.2.1.1), and coequalisers (Definition 3.3.3.1.1).
3. *Failure To Be Cartesian Closed.* The category Sets_* is not Cartesian closed.
4. *Relation to Partial Functions.* We have an equivalence of categories⁷

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

between the category of pointed sets and pointed functions between them and the category of sets and partial functions between them.

Proof. Item 1, Completeness: Omitted.

Item 2, Cocompleteness: Omitted.

Item 3, Failure To Be Cartesian Closed: See [MSE2855868].

Item 4, Relation to Partial Functions: Omitted. □

3.2 Limits of Pointed Sets

3.2.1 Products

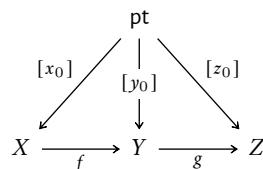
Let (X, x_0) and (Y, y_0) be pointed sets.

Definition 3.2.1.1.1. The **product** of (X, x_0) and (Y, y_0) is the pointed set $(X \times Y, (x_0, y_0))$.

we have

$$\begin{aligned} g(f(x_0)) &= g(y_0) \\ &= z_0, \end{aligned}$$

or



in terms of diagrams.



Warning: This is not an isomorphism of categories, only an equivalence.
END TEXTDBEND

3.2.2 Equalisers

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

Definition 3.2.2.1.1. The **equaliser of** (f, g) is the pointed set $(\text{Eq}_*(f, g), x_0)$ consisting of

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

$$\text{Eq}_*(f, g) \stackrel{\text{def}}{=} \{x \in X \mid f(x) = y_0 = g(x)\};$$

- *The Basepoint.* The element x_0 of $\text{Eq}_*(f, g)$.

3.2.3 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 3.2.3.1.1. The **pullback of** (X, x_0) and (Y, y_0) over (Z, z_0) **along** (f, g) is the pointed set $((X, x_0) \times_{(z, z_0)} (Y, y_0), p_0)$ consisting of

- *The Underlying Set.* The set $(X, x_0) \times_{(z, z_0)} (Y, y_0)$ defined by

$$(X, x_0) \times_{(z, z_0)} (Y, y_0) \stackrel{\text{def}}{=} \{(x, y) \in X \times Y \mid f(x) = z_0 = g(y)\};$$

- *The Basepoint.* The element (x_0, y_0) of $(X, x_0) \times_{(z, z_0)} (Y, y_0)$.

3.3 Colimits of Pointed Sets

3.3.1 Coproducts

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

Definition 3.3.1.1.1. The **coproduct of** (X, x_0) and (Y, y_0) is their wedge sum $(X \vee Y, p_0)$ of [Definition 3.4.3.1.1](#).

3.3.2 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 3.3.2.1.1. The **pushout of** (X, x_0) and (Y, y_0) over (Z, z_0) **along** (f, g) is the pointed set $(X \coprod_{f, Z, g} Y, p_0)$, where $p_0 = [x_0] = [y_0]$.

3.3.3 Coequalisers

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

Definition 3.3.3.1.1. The **coequaliser of** (f, g) is the pointed set $(\text{CoEq}(f, g), x_0)$.

3.4 Constructions With Pointed Sets

3.4.1 Internal Homs

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

Definition 3.4.1.1.1. The **pointed set of morphisms of pointed sets from** (X, x_0) **to** (Y, y_0) is the pointed set $\mathbf{Sets}_*((X, x_0), (Y, y_0))$ consisting of

- *The Underlying Set.* The set $\mathbf{Sets}_*((X, x_0), (Y, y_0))$ of morphisms of pointed sets from (X, x_0) to (Y, y_0) ;
- *The Basepoint.* The element

$$\Delta_{y_0}: (X, x_0) \rightarrow (Y, y_0)$$

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

3.4.2 Free Pointed Sets

Let X be a set.

Definition 3.4.2.1.1. The **free pointed set on** X is the pointed set X^+ consisting of

- *The Underlying Set.* The set X^+ defined by

$$X^+ \stackrel{\text{def}}{=} X \coprod \text{pt};$$

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

Proposition 3.4.2.1.2. Let X be a set.

1. *Functoriality.* The assignment $X \mapsto X^+$ defines a functor

$$(-)^+: \mathbf{Sets} \rightarrow \mathbf{Sets}_*,$$

where

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

$$[(-)^+](X) \stackrel{\text{def}}{=} X_+,$$

where X_+ is the pointed set of [Definition 3.4.2.1.1](#);

- *Action on Morphisms.* For each morphism $f: X \rightarrow Y$ of \mathbf{Sets} , the image

$$f_+: X_+ \rightarrow Y_+$$

of f by $(-)^+$ is the map of pointed sets defined by

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

2. *Adjointness.* We have an adjunction

$$((-)^+ \dashv \overline{\text{忘}}) : \text{Sets} \begin{array}{c} \xrightarrow{(-)^+} \\[-1ex] \perp \\[-1ex] \xleftarrow{\text{忘}} \end{array} \text{Sets}_*,$$

witnessed by a bijection of sets

$$\text{Sets}_*((X_+, \star), (Y, y_0)) \cong \text{Sets}(X, Y),$$

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

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

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

being equipped with isomorphisms of pointed sets

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

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

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

being equipped with isomorphisms of pointed sets

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

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

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

[Item 2](#), *Adjointness:* Clear.

[Item 3](#), *Symmetric Strong Monoidality With Respect to Wedge Sums:* Omitted.

[Item 4](#), *Symmetric Strong Monoidality With Respect to Smash Products:* Omitted. \square

3.4.3 Wedge Sums of Pointed Sets

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

Definition 3.4.3.1.1. The **wedge sum of X and Y** is the pointed set $(X \vee Y, p_0)$ consisting of

- *The Underlying Set.* The set $X \vee Y$ defined by⁸

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

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

where \sim is the equivalence relation on $X \coprod Y$ given by $x_0 \sim y_0$;

- *The Basepoint.* The element p_0 of $X \vee Y$ defined by

$$\begin{aligned} p_0 &\stackrel{\text{def}}{=} [x_0] \\ &= [y_0]. \end{aligned}$$

Proposition 3.4.3.1.2. Let (X, x_0) and (Y, y_0) be pointed sets.

1. *Functionality.* The assignments $(X, x_0), (Y, y_0), ((X, x_0), (Y, y_0)) \mapsto (X \vee Y, p_0)$ define functors

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

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

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

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

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

$$\begin{aligned} \text{pt} \vee X &\cong X, \\ X \vee \text{pt} &\cong X, \end{aligned}$$

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

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

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

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

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

⁸Here $(X, x_0) \coprod (Y, y_0)$ is the coproduct of (X, x_0) and (Y, y_0) in Sets_* .

6. *Symmetric Strong Monoidality With Respect to Free Pointed Sets.* The free pointed set functor of [Item 1](#) of [Proposition 3.4.2.1.2](#) has a symmetric strong monoidal structure

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

being equipped with isomorphisms of pointed sets

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

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

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

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

```

    \begin{CD}
    Sets_* \times Sets_* @>>> Sets_*, \\
    @V \Delta_{Sets_*}^{\text{Cats}} VV @VV V \\
    Sets_* @>>> Sets_*, \\
    @V \text{id}_{Sets_*} VV
    \end{CD}
  
```

called the **fold map**, whose component

$$\nabla_X: X \vee X \rightarrow X$$

at X is given by the composition

$$\begin{aligned} X &\xrightarrow{\Delta_X} X \times X \\ &\longrightarrow X \times X / \sim \\ &\xrightarrow{\text{def}} X \vee X. \end{aligned}$$

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

[Item 2, Associativity:](#) Omitted.

[Item 3, Unitality:](#) Omitted.

[Item 4, Commutativity:](#) Omitted.

[Item 5, Symmetric Monoidality:](#) Omitted.

[Item 6, Symmetric Strong Monoidality With Respect to Free Pointed Sets:](#) Omitted.

[Item 7, The Fold Map:](#) Omitted. □

Appendices

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3. Pointed Sets
4. Tensor Products of Pointed Sets
5. Relations
6. Spans
7. Posets

Indexed and Fibred Sets

7. Indexed Sets
8. Fibred Sets
9. Un/Straightening for Indexed and Fibred Sets

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12. Types of Morphisms in Categories
13. Adjunctions and the Yoneda Lemma
14. Constructions With Categories
15. Profunctors
16. Cartesian Closed Categories
17. Kan Extensions

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18. Bicategories
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22. The Cube Category

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Chapter 4

Tensor Products of Pointed Sets

This chapter contains some material on tensor products of pointed sets.

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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. A **left bilinear morphism of pointed sets from** $(X \times Y, (x_0, y_0))$ **to** (Z, z_0) is a map of sets

$$f: (X \times Y, (x_0, y_0)) \rightarrow (Z, z_0)$$

satisfying the following condition:^{1,2}

(★) *Left Unital Bilinearity.* The diagram

$$\begin{array}{ccc} & \text{pt} \times \text{pt} & \\ \text{id}_{\text{pt} \times \epsilon_Y} \nearrow & \swarrow \text{pt} & \\ \text{pt} \times Y & & \text{pt} \\ \downarrow [x_0] \times \text{id}_Y & & \downarrow [z_0] \\ X \times Y & \xrightarrow{f} & Z \end{array}$$

commutes, i.e. for each $y \in Y$, we have

$$f(x_0, y) = z_0.$$

Definition 4.1.1.2. 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

$$\text{Hom}_{\text{Sets}_*}^{\otimes, L}(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Sets}_*(A \times B, C) \mid f \text{ is left bilinear}\}.$$

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

$$f: (X \times Y, (x_0, y_0)) \rightarrow (Z, z_0)$$

satisfying the following condition:^{3,4}

¹Slogan: f is left bilinear if it preserves basepoints in its first argument.

²Succinctly, f is bilinear if we have

$$f(x_0, y) = z_0$$

for each $y \in Y$.

³Slogan: f is right bilinear if it preserves basepoints in its second argument.

⁴Succinctly, f is bilinear if we have

$$f(x, y_0) = z_0$$

(★) *Right Unital Bilinearity.* The diagram

$$\begin{array}{ccc}
 & \text{pt} \times \text{pt} & \\
 \swarrow_{\epsilon_X \times \text{id}_{\text{pt}}} & & \searrow \text{pt} \\
 X \times \text{pt} & & \text{pt} \\
 \downarrow \text{id}_X \times [y_0] & & \downarrow [z_0] \\
 X \times Y & \xrightarrow{f} & Z
 \end{array}$$

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

$$\text{Hom}_{\text{Sets}_*}^{\otimes, R}(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Sets}_*(A \times B, C) \mid f \text{ is right bilinear}\}.$$

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

$$f: (X \times Y, (x_0, y_0)) \rightarrow (Z, z_0)$$

that is both left bilinear and right bilinear.

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}

for each $x \in X$.

⁵Slogan: f is bilinear if it preserves basepoints in each argument.

⁶Succinctly, f is bilinear if we have

$$\begin{aligned}
 f(x_0, y) &= z_0, \\
 f(x, y_0) &= z_0
 \end{aligned}$$

for each $x \in X$ and each $y \in Y$.

1. *Left Unital Bilinearity.* The diagram

$$\begin{array}{ccc}
 & \text{pt} \times \text{pt} & \\
 \text{id}_{\text{pt}} \times \epsilon_Y \nearrow & \searrow \curvearrowright & \\
 \text{pt} \times Y & & \text{pt} \\
 \downarrow [x_0] \times \text{id}_Y & & \downarrow [z_0] \\
 X \times Y & \xrightarrow{f} & Z
 \end{array}$$

commutes, i.e. for each $y \in Y$, we have

$$f(x_0, y) = z_0.$$

2. *Right Unital Bilinearity.* The diagram

$$\begin{array}{ccc}
 & \text{pt} \times \text{pt} & \\
 \epsilon_X \times \text{id}_{\text{pt}} \nearrow & \searrow \curvearrowright & \\
 X \times \text{pt} & & \text{pt} \\
 \downarrow \text{id}_X \times [y_0] & & \downarrow [z_0] \\
 X \times Y & \xrightarrow{f} & Z
 \end{array}$$

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

$$\text{Hom}_{\text{Sets}_*}^\otimes(X \times Y, Z) \stackrel{\text{def}}{=} \{f \in \text{Sets}_*(A \times B, C) \mid f \text{ is bilinear}\}.$$

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 is the pointed set $A \odot (X, x_0)$ 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 tensor of (X, x_0) by A satisfies the following universal property:

$$\text{Sets}_*(A \odot X, K) \cong \text{Sets}_{\mathbb{B}_0}^\otimes(A \times X, K),$$

where $\text{Sets}_{\mathbb{B}_0}^\otimes(A \times X, K)$ is the set defined by

$$\text{Sets}_{\mathbb{B}_0}^\otimes(A \times X, K) \stackrel{\text{def}}{=} \left\{ f \in \text{Sets}(A \times X, K) \mid \begin{array}{l} \text{for each } a \in A, \text{ we have} \\ f(a, x_0) = k_0 \end{array} \right\}.$$

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

$$A \odot X \cong \bigvee_{a \in A} (X, x_0);$$

- *The Basepoint.* The point $[x_0]$ of $\bigvee_{a \in A} (X, x_0)$.

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 is the pointed set $A \pitchfork (X, x_0)$ 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 cotensor of (X, x_0) by A satisfies the following universal property:

$$\text{Sets}_*(K, A \pitchfork X) \cong \text{Sets}_{\mathbb{B}_0}^\otimes(A \times K, X),$$

where $\text{Sets}_{\mathbb{B}_0}^\otimes(A \times K, X)$ is the set defined by

$$\text{Sets}_{\mathbb{B}_0}^\otimes(A \times K, X) \stackrel{\text{def}}{=} \left\{ f \in \text{Sets}(A \times K, X) \mid \begin{array}{l} \text{for each } a \in A, \text{ we have} \\ f(a, k_0) = x_0 \end{array} \right\}.$$

Construction 4.2.2.1.3. Concretely, the **cotensor of** (X, x_0) **by** A is the pointed set $A \pitchfork (X, x_0)$ consisting of

- *The Underlying Set.* The set $A \pitchfork X$ given by

$$A \pitchfork X \cong \bigwedge_{a \in A} (X, x_0);$$

- *The Basepoint.* The point $[(x_0, x_0, x_0, \dots)]$ of $\bigwedge_{a \in A} (X, x_0)$.

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 functor

$$\triangleleft_{\text{Sets}_*} : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

defined as the composition

$$\text{Sets}_* \times \text{Sets}_* \xrightarrow{\text{id} \times \beta} \text{Sets}_* \times \text{Sets} \xrightarrow{\beta_{\text{Sets}_*, \text{Sets}}^{\text{Cats}_2}} \text{Sets} \times \text{Sets}_* \xrightarrow{\odot} \text{Sets}_*.$$

Remark 4.3.1.1.2. The left tensor product of pointed sets satisfies the following universal property:⁷

$$\text{Sets}_*(X \triangleleft_{\text{Sets}_*} Y, Z) \cong \text{Hom}_{\text{Sets}_*}^{\otimes, L}(X \times Y, Z).$$

Remark 4.3.1.1.3. In detail, the **left tensor product of** (X, x_0) **and** (Y, y_0) is the pointed set $(X \triangleleft_{\text{Sets}_*} Y, [x_0])$ consisting of⁸

- *The Underlying Set.* The set $X \triangleleft_{\text{Sets}_*} Y$ defined by

$$\begin{aligned} X \triangleleft_{\text{Sets}_*} Y &\stackrel{\text{def}}{=} |Y| \odot X \\ &\cong \bigvee_{y \in Y} (X, x_0); \end{aligned}$$

- *The Underlying Basepoint.* The point $[x_0]$ of $\bigvee_{y \in Y} (X, x_0)$.

Proposition 4.3.1.1.4. Let (X, x_0) and (Y, y_0) be pointed sets.

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

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

Proof. **Item 1, Functionality:** Omitted. □

⁷Namely, a pointed map $f : X \triangleleft_{\text{Sets}_*} Y \rightarrow Z$ is the same as a map $f^\dagger : X \times Y \rightarrow Z$ such that

$$f^\dagger(x_0, y) = z_0$$

for each $y \in Y$.

⁸Further Notation: We write $x \triangleleft_{\text{Sets}_*} y$ for the image of (x, y) under the map

$$\begin{aligned} X \times Y \rightarrow & \underbrace{X \triangleleft_{\text{Sets}_*} Y}_{\cong \bigvee_{y \in Y} (X, x_0)}. \end{aligned}$$

4.3.2 The Skew Associator

Definition 4.3.2.1.1. The **skew associator of the left tensor product of pointed sets** is the natural isomorphism

$$\alpha^{\text{Sets}_*, \triangleleft} : \triangleleft_{\text{Sets}_*} \circ (\triangleleft_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\cong} \triangleleft_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \triangleleft_{\text{Sets}_*}),$$

whose component

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft} : (X \triangleleft_{\text{Sets}_*} Y) \triangleleft_{\text{Sets}_*} Z \xrightarrow{\cong} X \triangleleft_{\text{Sets}_*} (Y \triangleleft_{\text{Sets}_*} Z)$$

at (X, Y, Z) is given by the composition⁹

$$\begin{aligned} (X \triangleleft_{\text{Sets}_*} Y) \triangleleft_{\text{Sets}_*} Z &\stackrel{\text{def}}{=} |Z| \odot (X \triangleleft_{\text{Sets}_*} Y) \\ &\stackrel{\text{def}}{=} |Z| \odot (|Y| \odot X) \\ &\cong \bigvee_{z \in Z} (|Y| \odot X, [x_0]) \\ &\stackrel{\text{def}}{=} \bigvee_{z \in Z} \left(\bigvee_{y \in Y} (X, x_0) \right) \\ &\cong \bigvee_{(z,y) \in \bigvee_{z \in Z} (Y, y_0)} (X, x_0) \\ &\stackrel{\text{def}}{=} \bigvee_{(z,y) \in |Z| \odot Y} (X, x_0) \\ &\cong |Z| \odot Y \odot X \\ &\stackrel{\text{def}}{=} |Y \triangleleft_{\text{Sets}_*} Z| \odot X \\ &\stackrel{\text{def}}{=} X \triangleleft_{\text{Sets}_*} (Y \triangleleft_{\text{Sets}_*} Z), \end{aligned}$$

where the isomorphism

$$\bigvee_{z \in Z} \left(\bigvee_{y \in Y} (X, x_0) \right) \cong \bigvee_{(y,z) \in \bigvee_{z \in Z} (Y, y_0)} (X, x_0)$$

is given by $[(z, (y, x))] \mapsto [(z, y), x]$.

sending (x, y) to the element $x \in X$ in the y th copy of X in $\bigvee_{y \in Y} (X, x_0)$. Note that we have

$$x_0 \triangleleft_{\text{Sets}_*} y = x_0 \triangleleft_{\text{Sets}_*} y',$$

for each $y, y' \in Y$.

⁹In other words, $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft}$ acts on elements as

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleleft} ((x \triangleleft_{\text{Sets}_*} y) \triangleleft_{\text{Sets}_*} z) \stackrel{\text{def}}{=} x \triangleleft_{\text{Sets}_*} (y \triangleleft_{\text{Sets}_*} z)$$

for each $(x \triangleleft_{\text{Sets}_*} y) \triangleleft_{\text{Sets}_*} z \in (X \triangleleft_{\text{Sets}_*} Y) \triangleleft_{\text{Sets}_*} Z$.

4.3.3 The Skew Left Unit

Definition 4.3.3.1.1. The **skew left unit** of the left tensor product of pointed sets is the natural transformation

$$\lambda^{\text{Sets}_*, \triangleleft} : \triangleleft_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \Rightarrow \text{id}_{\text{Sets}_*},$$

whose component

$$\lambda_X^{\text{Sets}_*, \triangleleft} : S^0 \triangleleft_{\text{Sets}_*} X \rightarrow X$$

at X is given by the composition¹⁰

$$\begin{aligned} S^0 \triangleleft_{\text{Sets}_*} X &\cong |X| \odot S^0 \\ &\cong \bigvee_{x \in X} S^0 \\ &\rightarrow X \end{aligned}$$

where $\bigvee_{x \in X} S^0 \rightarrow X$ is the map given by

$$\begin{aligned} (x, 0) &\mapsto x, \\ (x, 1) &\mapsto x. \end{aligned}$$

4.3.4 The Skew Right Unit

Definition 4.3.4.1.1. The **skew right unit** of the left tensor product of pointed sets is the natural transformation

$$\rho^{\text{Sets}_*, \triangleleft} : \text{id}_{\text{Sets}_*} \Rightarrow \triangleleft_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}),$$

whose component

$$\rho_X^{\text{Sets}_*, \triangleleft} : X \rightarrow X \triangleleft_{\text{Sets}_*} S^0$$

at X is given by the composition¹¹

$$\begin{aligned} X &\rightarrow X \vee X \\ &\cong |S^0| \odot X \\ &\cong S^0 \triangleleft_{\text{Sets}_*} X, \end{aligned}$$

where $X \rightarrow X \vee X$ is the map sending X to the first factor of X in $X \vee X$.

¹⁰In other words, $\lambda_X^{\text{Sets}_*, \triangleleft}$ acts on elements as

$$\begin{aligned} \lambda_X^{\text{Sets}_*, \triangleleft}(x \triangleleft_{\text{Sets}_*} 0) &\stackrel{\text{def}}{=} x, \\ \lambda_X^{\text{Sets}_*, \triangleleft}(x \triangleleft_{\text{Sets}_*} 1) &\stackrel{\text{def}}{=} x, \end{aligned}$$

for each $x \in X$.

¹¹In other words, $\rho_X^{\text{Sets}_*, \triangleleft}$ acts on elements as

$$\rho_X^{\text{Sets}_*, \triangleleft}(x) \stackrel{\text{def}}{=} x \triangleleft_{\text{Sets}_*} 0$$

4.3.5 The Left-Skew Monoidal Category Structure on Pointed Sets

Proposition 4.3.5.1.1. The category Sets_* admits a left-skew monoidal category structure consisting of¹²

- *The Skew Monoidal Product.* The left tensor product functor

$$\triangleleft_{\text{Sets}_*} : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*,$$

of [Proposition 4.3.1.1.4](#);

- *The Skew Monoidal Unit.* The functor

$$\mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*} : \text{pt} \rightarrow \text{Sets}_*$$

defined by

$$\mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*} \stackrel{\text{def}}{=} S^0;$$

- *The Skew Associators.* The natural isomorphism

$$\alpha^{\text{Sets}_*, \triangleleft} : \triangleleft_{\text{Sets}_*} \circ (\triangleleft_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\cong} \triangleleft_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \triangleleft_{\text{Sets}_*}),$$

of [Definition 4.3.2.1.1](#);

- *The Skew Left Unitors.* The natural transformation

$$\lambda^{\text{Sets}_*, \triangleleft} : \triangleleft_{\text{Sets}_*} \circ (\mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \Rightarrow \text{id}_{\text{Sets}_*},$$

of [Definition 4.3.3.1.1](#);

- *The Skew Right Unitors.* The natural transformation

$$\rho^{\text{Sets}_*, \triangleleft} : \text{id}_{\text{Sets}_*} \Rightarrow \triangleleft_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*}),$$

of [Definition 4.3.4.1.1](#).

Proof. Omitted. □

4.4 The Right Tensor Product of Pointed Sets

4.4.1 Foundations

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

for each $x \in X$.

¹²Note in particular that, differently from general left-skew monoidal categories, the skew associator of $(\text{Sets}_*, \triangleleft_{\text{Sets}_*}, S^0)$ is a natural isomorphism.

Definition 4.4.1.1.1. The **right tensor product of pointed sets** is the functor

$$\triangleright_{\text{Sets}_*} : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*$$

defined as the composition

$$\text{Sets}_* \times \text{Sets}_* \xrightarrow{\text{忘} \times \text{id}} \text{Sets} \times \text{Sets}_* \xrightarrow{\odot} \text{Sets}_*.$$

Remark 4.4.1.1.2. The right tensor product of pointed sets satisfies the following universal property.¹³

$$\text{Sets}_*(X \triangleright_{\text{Sets}_*} Y, Z) \cong \text{Hom}_{\text{Sets}_*}^{\otimes, R}(X \times Y, Z).$$

Remark 4.4.1.1.3. In detail, the **right tensor product of** (X, x_0) **and** (Y, y_0) is the pointed set $(X \triangleright_{\text{Sets}_*} Y, [y_0])$ consisting of¹⁴

- *The Underlying Set.* The set $X \triangleright_{\text{Sets}_*} Y$ defined by

$$\begin{aligned} X \triangleright_{\text{Sets}_*} Y &\stackrel{\text{def}}{=} |X| \odot Y \\ &\cong \bigvee_{x \in X} (Y, y_0); \end{aligned}$$

- *The Underlying Basepoint.* The point $[y_0]$ of $\bigvee_{x \in X} (Y, y_0)$.

Proposition 4.4.1.1.4. Let (X, x_0) and (Y, y_0) be pointed sets.

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

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

Proof. **Item 1, Functionality:** Omitted. □

¹³Namely, a pointed map $f: X \triangleleft_{\text{Sets}_*} Y \rightarrow Z$ is the same as a map $f^\dagger: X \times Y \rightarrow Z$ such that

$$f^\dagger(x, y_0) = z_0$$

for each $y \in Y$.

¹⁴Further Notation: We write $x \triangleright_{\text{Sets}_*} y$ for the image of (x, y) under the map

$$\begin{aligned} X \times Y &\rightarrow \underbrace{X \triangleright_{\text{Sets}_*} Y}_{\cong \bigvee_{x \in X} (Y, y_0)}. \end{aligned}$$

sending (x, y) to the element $y \in Y$ in the x th copy of Y in $\bigvee_{x \in X} (Y, y_0)$. Note that we have

$$x \triangleright_{\text{Sets}_*} y_0 = x' \triangleright_{\text{Sets}_*} y_0,$$

for each $x, x' \in X$.

4.4.2 The Skew Associator

Definition 4.4.2.1.1. The **skew associator of the right tensor product of pointed sets** is the natural isomorphism

$$\alpha^{\text{Sets}_*, \triangleright} : \triangleright_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \triangleright_{\text{Sets}_*}) \xrightarrow{\cong} \triangleright_{\text{Sets}_*} \circ (\triangleright_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}),$$

whose component

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright} : X \triangleright_{\text{Sets}_*} (Y \triangleright_{\text{Sets}_*} Z) \xrightarrow{\cong} (X \triangleright_{\text{Sets}_*} Y) \triangleright_{\text{Sets}_*} Z$$

at (X, Y, Z) is given by the composition¹⁵

$$\begin{aligned} X \triangleright_{\text{Sets}_*} (Y \triangleright_{\text{Sets}_*} Z) &\stackrel{\text{def}}{=} |X| \odot (Y \triangleright_{\text{Sets}_*} Z) \\ &\stackrel{\text{def}}{=} |X| \odot (|Y| \odot Z) \\ &\cong |X| \odot \left(\bigvee_{y \in Y} (Z, z_0) \right) \\ &\cong \bigvee_{x \in X} \left(\bigvee_{y \in Y} (Z, z_0) \right) \\ &\cong \bigvee_{(x,y) \in \bigvee_{x \in X} (Y, y_0)} (Z, z_0) \\ &\cong \left| \bigvee_{x \in X} (Y, y_0) \right| \odot Z \\ &\stackrel{\text{def}}{=} |X \odot Y| \odot Z \\ &\stackrel{\text{def}}{=} |X \triangleright_{\text{Sets}_*} Y| \odot Z \\ &\stackrel{\text{def}}{=} (X \triangleright_{\text{Sets}_*} Y) \triangleright_{\text{Sets}_*} Z \end{aligned}$$

where the isomorphism

$$\bigvee_{x \in X} \left(\bigvee_{y \in Y} (Z, z_0) \right) \cong \bigvee_{(x,y) \in \bigvee_{x \in X} (Y, y_0)} (Z, z_0)$$

is given by $[(x, (y, z))] \mapsto [(x, y), z]$.

¹⁵In other words, $\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright}$ acts on elements as

$$\alpha_{X,Y,Z}^{\text{Sets}_*, \triangleright} (x \triangleright_{\text{Sets}_*} (y \triangleright_{\text{Sets}_*} z)) \stackrel{\text{def}}{=} (x \triangleright_{\text{Sets}_*} y) \triangleright_{\text{Sets}_*} z$$

for each $x \triangleright_{\text{Sets}_*} (y \triangleright_{\text{Sets}_*} z) \in X \triangleright_{\text{Sets}_*} (Y \triangleright_{\text{Sets}_*} Z)$.

4.4.3 The Skew Left Unitor

Definition 4.4.3.1.1. The **skew left unitor of the right tensor product of pointed sets** is the natural transformation

$$\lambda^{\text{Sets}_*, \triangleright} : \text{id}_{\text{Sets}_*} \Longrightarrow \triangleright_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}),$$

whose component

$$\lambda_X^{\text{Sets}_*, \triangleright} : X \rightarrow S^0 \triangleright_{\text{Sets}_*} X$$

at X is given by the composition¹⁶

$$\begin{aligned} X &\rightarrow X \vee X \\ &\cong |S^0| \odot X \\ &\cong S^0 \triangleright_{\text{Sets}_*} X, \end{aligned}$$

where $X \rightarrow X \vee X$ is the map sending X to the first factor of X in $X \vee X$.

4.4.4 The Skew Right Unitor

Definition 4.4.4.1.1. The **skew right unitor of the right tensor product of pointed sets** is the natural transformation

$$\rho^{\text{Sets}_*, \triangleright} : \triangleright_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \Longrightarrow \text{id}_{\text{Sets}_*},$$

whose component¹⁷

$$\rho_X^{\text{Sets}_*, \triangleright} : X \triangleright_{\text{Sets}_*} S^0 \rightarrow X$$

at X is given by the composition

$$\begin{aligned} X \triangleright_{\text{Sets}_*} S^0 &\cong |X| \odot S^0 \\ &\cong \bigvee_{x \in X} S^0 \\ &\rightarrow X \end{aligned}$$

where $\bigvee_{x \in X} S^0 \rightarrow X$ is the map given by

$$\begin{aligned} (x, 0) &\mapsto x, \\ (x, 1) &\mapsto x. \end{aligned}$$

¹⁶In other words, $\lambda_X^{\text{Sets}_*, \triangleright}$ acts on elements as

$$\lambda_X^{\text{Sets}_*, \triangleright}(x) \stackrel{\text{def}}{=} 0 \triangleright_{\text{Sets}_*} x$$

for each $x \in X$.

¹⁷In other words, $\rho_X^{\text{Sets}_*, \triangleright}$ acts on elements as

$$\begin{aligned} \rho_X^{\text{Sets}_*, \triangleright}(x \triangleright_{\text{Sets}_*} 0) &\stackrel{\text{def}}{=} x, \\ \rho_X^{\text{Sets}_*, \triangleright}(x \triangleright_{\text{Sets}_*} 1) &\stackrel{\text{def}}{=} x \end{aligned}$$

4.4.5 The Right-Skew Monoidal Category Structure on Pointed Sets

Proposition 4.4.5.1.1. The category Sets_* admits a right-skew monoidal category structure consisting of¹⁸

- *The Skew Monoidal Product.* The right tensor product functor

$$\triangleright_{\text{Sets}_*} : \text{Sets}_* \times \text{Sets}_* \rightarrow \text{Sets}_*,$$

of [Item 1](#);

- *The Skew Monoidal Unit.* The functor

$$\mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*} : \text{pt} \rightarrow \text{Sets}_*$$

defined by

$$\mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*} \stackrel{\text{def}}{=} S^0;$$

- *The Skew Associators.* The natural isomorphism

$$\alpha^{\text{Sets}_*, \triangleright} : \triangleright_{\text{Sets}_*} \circ (\triangleright_{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}) \xrightarrow{\cong} \triangleright_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \triangleright_{\text{Sets}_*}),$$

of [Definition 4.4.2.1.1](#);

- *The Skew Left Unitors.* The natural transformation

$$\lambda^{\text{Sets}_*, \triangleright} : \text{id}_{\text{Sets}_*} \Longrightarrow \triangleright_{\text{Sets}_*} \circ (\mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*} \times \text{id}_{\text{Sets}_*}),$$

of [Definition 4.3.3.1.1](#);

- *The Skew Right Unitors.* The natural transformation

$$\rho^{\text{Sets}_*, \triangleright} : \triangleright_{\text{Sets}_*} \circ (\text{id}_{\text{Sets}_*} \times \mathbb{1}_{\text{Sets}_*}^{\text{Sets}_*}) \Longrightarrow \text{id}_{\text{Sets}_*},$$

of [Definition 4.3.4.1.1](#).

Proof. Omitted. □

4.5 Smash Products of Pointed Sets

4.5.1 Foundations

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

for each $x \in X$.

¹⁸Note in particular that, differently from general right-skew monoidal categories, the skew associator of $(\text{Sets}_*, \triangleright_{\text{Sets}_*}, S^0)$ is a natural isomorphism.

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 such that we have a bijection

$$\text{Sets}_*(X \wedge Y, Z) \cong \text{Hom}_{\text{Sets}_*}^{\otimes}(X \times Y, Z),$$

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

Remark 4.5.1.1.2. In detail, the **smash product of** (X, x_0) **and** (Y, y_0) is the pair $((X \wedge Y, [(x_0, y_0)]), \iota)$ consisting of

- A pointed set $(X \wedge Y, [(x_0, y_0)])$;
- 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 $f: (X \times Y, (x_0, y_0)) \rightarrow Z$;

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 4.5.1.1.3. Concretely, the **smash product of** (X, x_0) **and** (Y, y_0) is the pointed set $(X \wedge Y, [(x_0, y_0)])$ consisting of²¹

¹⁹Further Terminology: 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: Also written $X \otimes_{\mathbb{F}_1} Y$.

²¹Further Notation: We write $x \wedge y$ for the image of (x, y) under the quotient map

$$X \times Y \twoheadrightarrow \frac{X \times Y}{\underbrace{X \vee Y}_{\stackrel{\text{def}}{=} X \wedge Y}}$$

Note that we have

$$\begin{aligned} x \wedge y_0 &= x' \wedge y_0, \\ x_0 \wedge y &= x_0 \wedge y' \end{aligned}$$

for each $x, x' \in X$ and each $y, y' \in Y$.

- *The Underlying Set.* The set $X \wedge Y$ defined by

$$\begin{aligned} X \wedge Y &\cong \text{pt} \coprod_{X \vee Y} (X \times Y) \\ &\stackrel{\text{def}}{=} \frac{X \times Y}{X \vee Y} \\ &\cong X \times Y / \sim, \end{aligned} \quad \begin{array}{ccc} X \wedge Y & \leftarrow & X \times Y \\ \uparrow \lrcorner & & \downarrow \\ \text{pt} & \xleftarrow[!]{} & X \vee Y, \end{array}$$

where \sim is the equivalence relation of $X \times Y$ obtained by declaring $(x, y) \sim (x', y')$ iff $(x, y), (x', y') \in X \vee Y$, i.e. by declaring

$$\begin{aligned} (x_0, y) &\sim (x_0, y'), \\ (x, y_0) &\sim (x', y_0) \end{aligned}$$

for all $x \in X$ and all $y \in Y$;

- *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. Clear. □

Example 4.5.1.1.4. Here are some examples of smash products of pointed sets.

1. *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 4.5.1.1.5. Let (X, x_0) and (Y, y_0) be pointed sets.

1. *Functionality.* The assignments $(X, x_0), (Y, y_0), ((X, x_0), (Y, y_0)) \mapsto X \wedge Y$ define functors

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

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

$$\begin{aligned}\mathbf{Sets}_*(X \wedge Y, Z) &\cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(Y, Z)), \\ \mathbf{Sets}_*(X \wedge Y, Z) &\cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(A, Z)),\end{aligned}$$

natural in $(X, x_0), (Y, y_0), (Z, z_0) \in \text{Obj}(\mathbf{Sets}_*)$, which internalise to isomorphisms of pointed sets

$$\begin{aligned}\mathbf{Sets}_*(X \wedge Y, Z) &\cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(Y, Z)), \\ \mathbf{Sets}_*(X \wedge Y, Z) &\cong \mathbf{Sets}_*(X, \mathbf{Sets}_*(A, Z)),\end{aligned}$$

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

3. *Closed Symmetric Monoidality.* The quadruple $(\mathbf{Sets}_*, \wedge, S^0, \mathbf{Sets}_*)$ is a closed symmetric monoidal category.

4. *Morphisms From the Monoidal Unit.* We have a bijection of sets²²

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

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. *Symmetric Strong Monoidality With Respect to Free Pointed Sets.* The free pointed set functor of ?? of ?? has a symmetric strong monoidal structure

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

being equipped with isomorphisms of pointed sets

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

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

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

²²In other words, the forgetful functor

$$\mathfrak{U}: \mathbf{Sets}_* \rightarrow \mathbf{Sets}$$

7. *Universal Property I.* The symmetric monoidal structure on the category Sets_* is uniquely determined by the following requirements:

(a) *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.

(b) *The Unit Object Is S^0 .* We have $\mathbb{1}_{\text{Sets}_*} = S^0$.

8. *Universal Property II.* 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.

9. *Existence of Monoidal Diagonals.* The triple $(\text{Sets}_*, \wedge, S^0)$ is a monoidal category with diagonals:

(a) *Monoidal Diagonals.* The natural transformation

$$\Delta : \text{id}_{\text{Sets}_*} \Longrightarrow \wedge \circ \Delta_{\text{Sets}_*}^{\text{Cats}_2},$$

whose component

$$\Delta_X : (X, x_0) \rightarrow (X \wedge X, [(x_0, x_0)])$$

at $(X, x_0) \in \text{Obj}(\text{Sets}_*)$ is given by the composition

$$\begin{aligned} (X, x_0) &\xrightarrow{\Delta_X} (X \times X, (x_0, x_0)) \\ &\longrightarrow (\frac{X \times X}{X \vee X}, [(x_0, x_0)]) \\ &\xrightarrow{\text{def}} (X \wedge X, [(x_0, x_0)]) \end{aligned}$$

in Sets_* , is a monoidal natural transformation:

i. *Naturality.* For each morphism $f : X \rightarrow Y$ of pointed sets, the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \Delta_X \downarrow & & \downarrow \Delta_Y \\ X \wedge X & \xrightarrow{f \wedge f} & Y \wedge Y \end{array}$$

commutes.

- ii. *Compatibility With Strong Monoidality Constraints.* For each $(X, x_0), (Y, y_0) \in \text{Obj}(\text{Sets}_*)$, the diagram

$$\begin{array}{ccc} X \wedge Y & \xrightarrow{\Delta_X \wedge \Delta_Y} & (X \wedge X) \wedge (Y \wedge Y) \\ \parallel & & \downarrow \text{?} \\ X \wedge Y & \xrightarrow{\Delta_{X \wedge Y}} & (X \wedge Y) \wedge (X \wedge Y) \end{array}$$

commutes.

- iii. *Compatibility With Strong Unitality Constraints.* The diagram

$$\begin{array}{ccc} S^0 & & (\lambda_{S^0}^{\text{Sets}_*})^{-1} = (\rho_{S^0}^{\text{Sets}_*})^{-1} \\ \parallel & \searrow & \\ S^0 & \xrightarrow{\Delta_{S^0}} & S^0 \wedge S^0 \end{array}$$

commutes.

- (b) *The Diagonal of the Unit.* The component

$$\Delta_{S^0}^{\text{Sets}_*} : S^0 \xrightarrow{\cong} S^0 \wedge S^0$$

of the diagonal natural transformation of Sets_* at S^0 is an isomorphism.

10. *Comonoids in Sets_* .* The symmetric monoidal functor

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

of ?? of ?? lifts to an equivalence of categories

$$\begin{aligned} \text{CoMon}(\text{Sets}_*, \wedge, S^0) &\stackrel{\text{eq.}}{\cong} \text{CoMon}(\text{Sets}, \times, \text{pt}) \\ &\cong \text{Sets}. \end{aligned}$$

Proof. **Item 1, Functoriality:** Omitted.

Item 2, Adjointness: Omitted.

Item 3, Closed Symmetric Monoidality: Omitted.

Item 4, Morphisms From the Monoidal Unit: Omitted.

Item 5, Symmetric Strong Monoidality With Respect to Free Pointed Sets: Omitted.

Item 6, Distributivity Over Wedge Sums: This follows from **Item 3**, ?? of ??, and the fact that \vee is the coproduct in Sets_* .

Item 7, Universal Property I: Omitted.

Item 8, Universal Property II: See [GGN15, Theorem 5.1].

Item 9, Existence of Monoidal Diagonals: Omitted.

Item 10, Comonoids in Sets_* : See [PS19, Lemma 2.4].

□

Appendices

4.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets
5. Relations
6. Spans
7. Posets

Indexed and Fibred Sets

7. Indexed Sets
8. Fibred Sets
9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories
12. Types of Morphisms in Categories
13. Adjunctions and the Yoneda Lemma
14. Constructions With Categories
15. Profunctors
16. Cartesian Closed Categories
17. Kan Extensions

Bicategories

18. Bicategories
19. Internal Adjunctions

Internal Category Theory

defined on objects by sending a pointed set to its underlying set is corepresentable by S^0 .

20. Internal Categories

33. Hypersemirings and Hyperrings

Cyclic Stuff

21. The Cycle Category

34. Quantales

Cubical Stuff

22. The Cube Category

Near-Rings

Globular Stuff

23. The Globe Category

35. Near-Semirings

Cellular Stuff

24. The Cell Category

Real Analysis

Monoids

25. Monoids

37. Real Analysis in One Variable

26. Constructions With Monoids

38. Real Analysis in Several Variables

Monoids With Zero

27. Monoids With Zero

Measure Theory

28. Constructions With Monoids With
Zero

39. Measurable Spaces

Groups

29. Groups

40. Measures and Integration

30. Constructions With Groups

Probability Theory

Hyper Algebra

31. Hypermonoids

40. Probability Theory

32. Hypergroups

Stochastic Analysis

41. Stochastic Processes, Martingales,
and Brownian Motion

42. Itô Calculus

Differential Geometry

43. Stochastic Differential Equations

44. Topological and Smooth Manifolds

Schemes

45. Schemes

4.2 Other Chapters

Sets	Cyclic Stuff
1. Sets	21. The Cycle Category
2. Constructions With Sets	Cubical Stuff
3. Pointed Sets	22. The Cube Category
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Chapter 5

Relations

This chapter contains some material about relations and constructions with them. 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](#)), and
 - (d) A double category ([Section 5.2.4](#)).
4. The various categorical properties of the 2-category of relations, including ([Section 5.2.5](#)):
 - (a) The self-duality of **Rel** and **Rel** ([Items 1 and 2 of Proposition 5.2.5.1.1](#));
 - (b) Identifications of equivalences and isomorphisms in **Rel** with bijections ([Item 3 of Proposition 5.2.5.1.1](#));
 - (c) Identifications of adjunctions in **Rel** with functions ([Item 4 of Proposition 5.2.5.1.1](#));
 - (d) Identifications of monads in **Rel** with preorders ([Item 5 of Proposition 5.2.5.1.1](#));
 - (e) Identifications of comonads in **Rel** with subsets ([Item 6 of Proposition 5.2.5.1.1](#));
 - (f) Characterisations of monomorphisms in **Rel** ([Item 7 of Proposition 5.2.5.1.1](#));
 - (g) Characterisations of epimorphisms in **Rel** ([Item 8 of Proposition 5.2.5.1.1](#));
 - (h) The partial co/completeness of **Rel** ([Item 10 of Proposition 5.2.5.1.1](#));
 - (i) The existence of right Kan extensions and right Kan lifts in **Rel** ([Items 11 and 12 of Proposition 5.2.5.1.1](#));
 - (j) The closedness of **Rel** ([Item 13 of Proposition 5.2.5.1.1](#)).

-
5. The various kinds of constructions involving relations, such as graphs, domains, ranges, unions, intersections, products, inverse relations, composition of relations, and collages ([Section 5.3](#)).
 6. Equivalence relations ([Section 5.4](#)) and quotient sets ([Section 5.4.5](#)).
 7. The adjoint pairs

$$\begin{aligned} R_* \dashv R_{-1} : \mathcal{P}(A) \rightleftarrows \mathcal{P}(B), \\ R^{-1} \dashv R_! : \mathcal{P}(B) \rightleftarrows \mathcal{P}(A) \end{aligned}$$

of functors (morphisms of posets) between $\mathcal{P}(A)$ and $\mathcal{P}(B)$ induced by a relation $R : A \rightarrow B$, as well as the properties of R_* , R_{-1} , R^{-1} , and $R_!$ ([Section 5.5](#)).

Here we also note that:

- (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 [??](#);
- (b) We have $R_{-1} = R^{-1}$ iff R is total and functional ([Item 8 of Proposition 5.5.2.1.3](#)).
- (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 before.

- (d) The pairs $R_* \dashv R_{-1}$ and $R^{-1} \dashv R_!$ later make an appearance in the context of continuous, open, and closed relations between topological spaces ([??](#)).

8. A notion of *relative preorder* that is to that of a preorder as relative monads are to monads, extending the identifications of monads in Rel with preorders of [Item 5](#) of [Proposition 5.2.5.1.1](#) to “relative monads in Rel”.

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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** $R: A \rightarrow B$ from A to B ^{1,2} is a subset R of $A \times B$.³

Definition 5.1.1.1.2. 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

$$\subset: \text{Rel}(A, B) \times \text{Rel}(A, B) \rightarrow \{\text{true}, \text{false}\}$$

on $\text{Rel}(A, B)$ given by inclusion of relations.

Remark 5.1.1.3. A relation from A to B is equivalently:⁴

1. A subset of $A \times B$;
2. A function from $A \times B$ to $\{\text{true}, \text{false}\}$;
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 $(\mathcal{P}(B), \subset)$.

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** .

³Further Notation: Given elements $a \in A$ and $b \in B$, we write $a \sim_R b$ to mean $(a, b) \in R$.

⁴Intuition: 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

$$\begin{aligned}\text{Rel}(A, B) &\stackrel{\text{def}}{=} \mathcal{P}(A \times B), \\ &\cong \text{Sets}(A \times B, \{\text{true}, \text{false}\}), \\ &\cong \text{Sets}(A, \mathcal{P}(B)), \\ &\cong \text{Sets}(B, \mathcal{P}(A)), \\ &\cong \text{Hom}_{\text{Pos}}^{\text{cocont}}(\mathcal{P}(A), \mathcal{P}(B)),\end{aligned}$$

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 ?? of ??.
- **Item 2** \iff **Item 3**: This is an instance of currying, following from the bijections

$$\begin{aligned}\text{Sets}(A \times B, \{\text{true}, \text{false}\}) &\cong \text{Sets}(A, \text{Sets}(B, \{\text{true}, \text{false}\})) \\ &\cong \text{Sets}(A, \mathcal{P}(B)),\end{aligned}$$

where the last bijection is from ?? of ??.

- **Item 2** \iff **Item 4**: This is also an instance of currying, following from the bijections

$$\begin{aligned}\text{Sets}(A \times B, \{\text{true}, \text{false}\}) &\cong \text{Sets}(B, \text{Sets}(B, \{\text{true}, \text{false}\})) \\ &\cong \text{Sets}(B, \mathcal{P}(A)),\end{aligned}$$

where again the last bijection is from ?? of ??.

- **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 $\mathcal{P}(X)$ (?? of ??).

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 $R: A \rightarrow B$, 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 ??.

This finishes the proof. □

Proposition 5.1.1.4. Let A and B be sets.

1. *End Formula for The Poset of Relations.* Let $R, S : A \rightarrow B$ be relations. We have

$$\text{Hom}_{\mathbf{Rel}(A,B)}(R, S) \cong \int_{a \in A} \int_{b \in B} \text{Hom}_{\{\text{t,f}\}}(R_b^a, S_b^a).$$

Proof. **Item 1, End Formula for The Poset of Relations:** Unwinding the expression inside the end on the right hand side, we have

$$\int_{a \in A} \int_{b \in B} \text{Hom}_{\{\text{t,f}\}}(R_b^a, S_b^a) \cong \begin{cases} \text{pt} & \text{if for each } (a, b) \in A \times B, \\ & \text{if } a \sim_R b, \text{ then } a \sim_S b, \\ \emptyset & \text{otherwise.} \end{cases}$$

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 are equivalent, implying that those two sets are isomorphic, finishing the proof. \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 \mathcal{D} is a functor

$$p : \mathcal{D}^{\text{op}} \times C \rightarrow \text{Sets}.$$

2. A relation on sets A and B is a function

$$R : A \times B \rightarrow \{\text{true, false}\}.$$

Here we notice that:

- The opposite X^{op} of a set X is itself, as $(-)^\text{op} : \text{Cats} \rightarrow \text{Cats}$ restricts to the identity endofunctor on Sets ;
- The values that profunctors and relations take are directly related in relation to decategorification:
 - A category is enriched over the category

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

of sets, with profunctors taking values on it;

- A set is enriched over the set

$$\{\text{true}, \text{false}\} \stackrel{\text{def}}{=} \text{Cats}_{-1}$$

of classical truth values, with relations taking values on it;

Remark 5.1.2.1.2. Extending Remark 5.1.2.1.1, the equivalent definitions of relations in Remark 5.1.1.1.3 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 $\mathbf{p}: \mathcal{D}^{\text{op}} \times \mathcal{C} \rightarrow \text{Sets}$;
2. A functor $\mathbf{p}: \mathcal{C} \rightarrow \text{PSh}(\mathcal{D})$;
3. A functor $\mathbf{p}: \mathcal{D}^{\text{op}} \rightarrow \text{Fun}(\mathcal{C}, \text{Sets})$;
4. A colimit-preserving functor $\mathbf{p}: \text{PSh}(\mathcal{C}) \rightarrow \text{PSh}(\mathcal{D})$.

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

$$\begin{aligned} \text{Sets}(A \times B, \{\text{true}, \text{false}\}) &\cong \text{Sets}(A, \text{Sets}(B, \{\text{true}, \text{false}\})) \\ &\cong \text{Sets}(A, \mathcal{P}(B)), \\ \text{Fun}(\mathcal{D}^{\text{op}} \times \mathcal{D}, \text{Sets}) &\cong \text{Fun}(\mathcal{C}, \text{Fun}(\mathcal{D}^{\text{op}}, \text{Sets})) \\ &\cong \text{Fun}(\mathcal{C}, \text{PSh}(\mathcal{D})). \end{aligned}$$

- 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 $\mathcal{P}(X)$ (?? of ??);

- The category $\text{PSh}(\mathcal{C})$ of presheaves on a category \mathcal{C} as the free cocompletion of \mathcal{C} via the Yoneda embedding

$$\mathbb{Y}: \mathcal{C} \hookrightarrow \text{PSh}(\mathcal{C})$$

of \mathcal{C} into $\text{PSh}(\mathcal{C})$ (?? 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 by^{5,6,7}

$$\sim_{\text{triv}} \stackrel{\text{def}}{=} A \times A.$$

Example 5.1.3.1.2. The **cotrivial relation on A and B** is the relation \sim_{cotriv} defined by^{8,9,10}

$$\sim_{\text{cotriv}} \stackrel{\text{def}}{=} \emptyset.$$

Example 5.1.3.1.3. The characteristic relation on A of ?? of ?? is another example of a relation. It is in fact the unique relation on A making the following conditions equivalent, for each $a, b \in A$:

1. We have $a \sim_{\text{id}} b$.
2. We have $a = b$.

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

$$\sqrt{x} \stackrel{\text{def}}{=} \begin{cases} 0 & \text{if } x = 0, \\ \{-\sqrt{|x|}, \sqrt{|x|}\} & \text{if } x \neq 0. \end{cases}$$

⁵This is the unique relation R on A and B such that we have $a \sim_R b$ for all $a \in A$ and all $b \in B$.

⁶As a function from $A \times A$ to $\{\text{true, false}\}$, the relation \sim_{triv} is the constant function

$$\Delta_{\text{true}} : A \times B \rightarrow \{\text{true, false}\}$$

from $A \times B$ to $\{\text{true, false}\}$ taking value true.

⁷As 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 $a \in A$.

⁸This is the unique relation R on A and B such that we have $a \sim_R b$ for no $a \in A$ and no $b \in B$.

⁹As a function from $A \times B$ to $\{\text{true, false}\}$, the relation \sim_{cotriv} is the constant function

$$\Delta_{\text{false}} : A \times B \rightarrow \{\text{true, false}\}$$

from $A \times B$ to $\{\text{true, false}\}$ taking value false.

¹⁰As a function from A to $\mathcal{P}(A)$, the relation \sim_{cotriv} is the function

$$\Delta_{\text{false}} : A \rightarrow \mathcal{P}(A)$$

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

$$\log(a + bi) \stackrel{\text{def}}{=} \left\{ \log\left(\sqrt{a^2 + b^2}\right) + i \arg(a + bi) + (2\pi i)k \mid k \in \mathbb{Z} \right\}$$

for each $a + bi \in \mathbb{C}$.

Example 5.1.3.1.6. See [wikipedia:multivalued-functions] 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 $R : A \rightarrow B$ 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 $R : A \rightarrow B$ 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

$$[R \diamond R^\dagger](b, b') \leq_{\{\text{t,f}\}} \chi_B(b, b'),$$

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 $b = b'$:

defined by

$$\Delta_{\text{true}}(a) \stackrel{\text{def}}{=} \emptyset$$

1. Since $a \sim_R b$, we have $b \sim_{R^\dagger} a$.
2. Since $R \diamond R^\dagger \subset \chi_B$, we have

$$[R \diamond R^\dagger](b, b') \leq_{\{\text{t,f}\}} \chi_B(b, b'),$$

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

$$\chi_A(a, a') \leq_{\{\text{t,f}\}} [R^\dagger \diamond R](a, a'),$$

i.e. that if $a = a'$, then there exists some $b \in B$ such that $a \sim_R b$ and $b \sim_{R^\dagger} a'$ (i.e. $a \sim_R b$ again), which follows from the totality of R .

- **Item 1b** \implies **Item 1a**: Given $a \in A$, since $\chi_A \subset R^\dagger \diamond R$, we must have

$$\{a\} \subset [R^\dagger \diamond R](a),$$

implying that there must exist some $b \in B$ such that $a \sim_R b$ and $b \sim_{R^\dagger} a$ (i.e. $a \sim_R b$) and thus $R(a) \neq \emptyset$, as $b \in R(a)$.

This finishes the proof. □

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 ?? of ??;

- *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 5.3.12.1.1](#).

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.* We have

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

where $A \times B$ is the Cartesian product of sets of ??;

- *Action on Morphisms.* For each $(A, C), (B, D) \in \text{Obj}(\text{Rel} \times \text{Rel})$, the action on

for each $a \in A$.

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

$$\begin{aligned} R &: A \dashrightarrow B, \\ S &: C \dashrightarrow D \end{aligned}$$

to the relation

$$R \times S : A \times C \dashrightarrow B \times D$$

of [Definition 5.3.9.1.1](#).

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

$$\begin{array}{ccc} \alpha^{\text{Rel}} : \times \circ ((\times) \times \text{id}) & \xrightarrow{\cong} & \times \circ (\text{id} \times (\times)), \\ \downarrow (\times) \times \text{id} & \nearrow \alpha^{\text{Rel}} & \downarrow \times \\ \text{Rel} \times \text{Rel} & \xrightarrow{\times} & \text{Rel}, \end{array}$$

$\xrightarrow{\text{id} \times (\times)}$

whose component

$$\alpha_{A,B,C}^{\text{Rel}} : (A \times B) \times C \dashrightarrow A \times (B \times C)$$

at (A, B, C) is 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

$$\begin{array}{ccc} \text{pt} \times \text{Rel} & \xrightarrow{\mathbb{1}^{\text{Rel}} \times \text{id}} & \text{Rel} \times \text{Rel} \\ \lambda^{\text{Rel}} : \times \circ (\mathbb{1}^{\text{Rel}} \times \text{id}) \xrightarrow{\cong} \lambda_{\text{Rel}}^{\text{Cats}_2}, & \swarrow \lambda_{\text{Rel}}^{\text{Cats}_2} & \downarrow \times \\ & \searrow \lambda^{\text{Rel}} & \\ & \dashrightarrow & \text{Rel}, \end{array}$$

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

$$\begin{array}{ccc} \text{Rel} \times \text{pt} & \xrightarrow{\text{id} \times \mathbb{1}^{\text{Rel}}} & \text{Rel} \times \text{Rel} \\ \rho^{\text{Rel}} : \times \circ (\text{id} \times \mathbb{1}^{\text{Rel}}) \xrightarrow{\cong} \rho_{\text{Rel}}^{\text{Cats}_2}, & \swarrow \rho_{\text{Rel}}^{\text{Cats}_2} & \downarrow \times \\ & \searrow \rho^{\text{Rel}} & \\ & \dashrightarrow & \text{Rel}, \end{array}$$

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

$$\begin{array}{ccc} \text{Rel} \times \text{Rel} & \xrightarrow{\times} & \text{Rel}, \\ \sigma^{\text{Rel}} : \times \Longrightarrow \times \circ \sigma_{\text{Rel}, \text{Rel}}^{\text{Cats}_2}, & \swarrow \sigma_{\text{Rel}, \text{Rel}}^{\text{Cats}_2} & \downarrow \sigma^{\text{Rel}} \\ & \searrow & \nearrow \times \\ & \text{Rel} \times \text{Rel} & \end{array}$$

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

$$\mathbf{Hom}_{\text{Rel}}: \text{Rel}^{\text{op}} \times \text{Rel} \rightarrow \text{Rel}$$

defined by

$$\mathbf{Hom}_{\text{Rel}}(A, B) \stackrel{\text{def}}{=} A \times B$$

for each $A, B \in \text{Obj}(\text{Rel})$.

Proposition 5.2.2.7.2. Let $A, B, C \in \text{Obj}(\text{Rel})$.

1. *Via Self-Duality.* The internal Hom $\mathbf{Hom}_{\text{Rel}}$ of Rel is given by the composition

$$\text{Rel}^{\text{op}} \times \text{Rel} \xrightarrow{\cong} \text{Rel} \times \text{Rel} \xrightarrow{\times} \text{Rel},$$

where the self-duality equivalence $\text{Rel}^{\text{op}} \cong \text{Rel}$ comes from Item 1 of Proposition 5.2.5.1.1.

2. *Adjointness.* We have adjunctions

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

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

witnessed by bijections

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

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

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

Proof. **Item 1, Via Self-Duality:** Omitted.

Item 2, Adjointness: Indeed, we have

$$\begin{aligned}\text{Rel}(A \times B, C) &\stackrel{\text{def}}{=} \text{Sets}(A \times B \times C, \{\text{true}, \text{false}\}) \\ &\stackrel{\text{def}}{=} \text{Rel}(A, B \times C) \\ &\stackrel{\text{def}}{=} \text{Rel}(A, \mathbf{Hom}_{\text{Rel}}(B, C)),\end{aligned}$$

and similarly for the bijection $\text{Rel}(A \times B, C) \cong \text{Rel}(B, \mathbf{Hom}_{\text{Rel}}(A, C))$. \square

5.2.2.8 The Closed Symmetric Monoidal Category of Relations

Definition 5.2.2.8.1. The **closed symmetric monoidal category of relations** is the closed symmetric monoidal category

$$(\text{Rel}, \times, \mathbb{1}_{\text{Rel}}, \alpha^{\text{Rel}}, \lambda^{\text{Rel}}, \rho^{\text{Rel}}, \sigma^{\text{Rel}}, \mathbf{Hom}_{\text{Rel}})$$

consisting of

- *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 Monoidal Unit.* The functor $\mathbb{1}^{\text{Rel}}$ of [Definition 5.2.2.2.1](#);
- *The Associator.* The natural isomorphism α^{Rel} of [Definition 5.2.2.3.1](#);
- *The Left Unitor.* The natural isomorphism λ^{Rel} of [Definition 5.2.2.4.1](#);
- *The Right Unitor.* The natural isomorphism ρ^{Rel} of [Definition 5.2.2.5.1](#);
- *The Symmetry.* The natural isomorphism σ^{Rel} of [Definition 5.2.2.6.1](#);
- *The Internal Hom.* The functor

$$\mathbf{Hom}_{\text{Rel}}: \text{Rel}^{\text{op}} \times \text{Rel} \rightarrow \text{Rel}$$

of [Definition 5.2.2.7.1](#).

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 \mathbf{Rel} where

- *Objects.* The objects of \mathbf{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

$$\sharp_A^{\mathbf{Rel}} : \text{pt} \rightarrow \mathbf{Rel}(A, A)$$

of \mathbf{Rel} at A is defined by

$$\text{id}_A^{\mathbf{Rel}} \stackrel{\text{def}}{=} \chi_A(-_1, -_2),$$

where $\chi_A(-_1, -_2)$ is the characteristic relation of A of ?? of ??;

- **Composition.** For each $A, B, C \in \text{Obj}(\mathbf{Rel})$, the composition map¹¹

$$\circ_{A,B,C}^{\mathbf{Rel}} : \mathbf{Rel}(B, C) \times \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(A, C)$$

of \mathbf{Rel} at (A, B, C) is defined by

$$S \circ_{A,B,C}^{\mathbf{Rel}} R \stackrel{\text{def}}{=} S \diamond R$$

for each $(S, R) \in \mathbf{Rel}(B, C) \times \mathbf{Rel}(A, B)$, where $S \diamond R$ is the composition of S and R of [Definition 5.3.12.1.1](#).

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;
- **Vertical Morphisms.** The vertical morphisms of $\mathbf{Rel}^{\text{dbl}}$ are maps of sets $f : A \rightarrow B$;
- **Horizontal Morphisms.** The horizontal morphisms of $\mathbf{Rel}^{\text{dbl}}$ are relations $R : A \rightarrow X$;

¹¹Note 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

$$\begin{aligned}R_1 &\subset R_2, \\ S_1 &\subset S_2,\end{aligned}$$

we have also $S_1 \diamond R_1 \subset S_2 \diamond R_2$.

- *2-Morphisms.* A 2-cell

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ f \downarrow & \parallel \alpha \downarrow & \downarrow g \\ X & \xrightarrow{s} & Y \end{array}$$

of Rel^{dbl} is either non-existent or an inclusion of relations of the form

$$\begin{array}{ccc} A \times B & \xrightarrow{R} & \{\text{true, false}\} \\ R \subset S \circ (f \times g), \quad f \times g \downarrow & \hookrightarrow & \downarrow \text{id}_{\{\text{true, false}\}} \\ X \times Y & \xrightarrow{s} & \{\text{true, false}\}; \end{array}$$

- *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 $R: A \dashrightarrow B$ of Rel^{dbl} , the identity 2-morphism

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ \text{id}_A \downarrow & \parallel \text{id}_R \downarrow & \downarrow \text{id}_B \\ A & \xrightarrow{R} & B \end{array}$$

of R is the identity inclusion

$$\begin{array}{ccc} B \times A & \xrightarrow{R} & \{\text{true, false}\} \\ R \subset R, \quad \text{id}_B \times \text{id}_A \downarrow & \hookrightarrow & \downarrow \text{id}_{\{\text{true, false}\}} \\ B \times A & \xrightarrow{R} & \{\text{true, false}\}; \end{array}$$

- *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

$$\begin{array}{ccc} A & \xrightarrow{\mathbb{1}_A} & A \\ f \downarrow & \parallel & \downarrow f \\ B & \xrightarrow{\mathbb{1}_B} & B \end{array}$$

of f is the inclusion

$$\begin{array}{ccc} A \times A & \xrightarrow{\chi_A(-_1, -_2)} & \{\text{true}, \text{false}\} \\ \chi_B \circ (f \times f) \subset \chi_A, & f \times f \downarrow & \curvearrowleft \qquad \downarrow \text{id}_{\{\text{true}, \text{false}\}} \\ B \times B & \xrightarrow{\chi_B(-_1, -_2)} & \{\text{true}, \text{false}\} \end{array}$$

of ?? of ??.

5.2.4.3 Horizontal Composition

Definition 5.2.4.3.1. The **horizontal composition functor** of Rel^{dbl} is the functor

$$\odot^{\text{Rel}^{\text{dbl}}} : \text{Rel}_1^{\text{dbl}} \underset{\text{Rel}_0^{\text{dbl}}}{\times} \text{Rel}_1^{\text{dbl}} \rightarrow \text{Rel}_1^{\text{dbl}}$$

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 5.3.12.1.1](#);

- *Action on Morphisms.* For each horizontally composable pair

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ f \downarrow & \Downarrow \alpha & \downarrow g \\ X & \xrightarrow{T} & Y \end{array} \quad \begin{array}{ccc} B & \xrightarrow{S} & C \\ g \downarrow & \Downarrow \beta & \downarrow h \\ Y & \xrightarrow{U} & Z \end{array}$$

of 2-morphisms of Rel^{dbl} , i.e. for each pair

$$\begin{array}{ccc} A \times B & \xrightarrow{R} & \{\text{true, false}\} \\ f \times g \downarrow & \curvearrowright & \downarrow \text{id}_{\{\text{true, false}\}} \\ X \times Y & \xrightarrow{T} & \{\text{true, false}\} \end{array} \quad \begin{array}{ccc} B \times C & \xrightarrow{S} & \{\text{true, false}\} \\ g \times h \downarrow & \curvearrowright & \downarrow \text{id}_{\{\text{true, false}\}} \\ Y \times Z & \xrightarrow{U} & \{\text{true, false}\} \end{array}$$

of inclusions of relations, the horizontal composition

$$\begin{array}{ccc} A & \xrightarrow{S \odot R} & C \\ f \downarrow & \Downarrow \beta \circ \alpha & \downarrow h \\ X & \xrightarrow{U \odot T} & Z \end{array}$$

of α and β is the inclusion of relations¹²

$$\begin{array}{ccc} A \times C & \xrightarrow{S \diamond R} & \{\text{true, false}\} \\ (U \diamond T) \circ (f \times h) \subset (S \diamond R) \quad f \times h \downarrow & \curvearrowright & \downarrow \text{id}_{\{\text{true, false}\}} \\ X \times Z & \xrightarrow{U \diamond T} & \{\text{true, false}\}. \end{array}$$

¹²This 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

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

$$\begin{array}{ccc} A & \xrightarrow{R} & X \\ f \downarrow & \parallel \alpha \downarrow & g \downarrow \\ B & \xrightarrow{S} & Y \end{array} \quad \begin{array}{ccc} B & \xrightarrow{S} & Y \\ h \downarrow & \parallel \beta \downarrow & k \downarrow \\ C & \xrightarrow{T} & Z \end{array}$$

of 2-morphisms of Rel^{dbl} , i.e. for each each pair

$$\begin{array}{ccc} A \times X & \xrightarrow{R} & \{\text{true, false}\} \\ f \times g \downarrow & \curvearrowright & \downarrow \text{id}_{\{\text{true, false}\}} \\ B \times Y & \xrightarrow{S} & \{\text{true, false}\} \end{array} \quad \begin{array}{ccc} B \times Y & \xrightarrow{S} & \{\text{true, false}\} \\ h \times k \downarrow & \curvearrowright & \downarrow \text{id}_{\{\text{true, false}\}} \\ C \times Z & \xrightarrow{T} & \{\text{true, false}\} \end{array}$$

of inclusions of relations, we define the vertical composition

$$\begin{array}{ccc} A & \xrightarrow{R} & X \\ h \circ f \downarrow & \parallel \beta \circ \alpha \downarrow & k \circ g \downarrow \\ C & \xrightarrow{T} & Z \end{array}$$

of α and β as the inclusion of relations

$$T \circ [(h \circ f) \times (k \circ g)] \subset R, \quad \begin{array}{ccc} A \times X & \xrightarrow{R} & \{\text{true, false}\} \\ (h \circ f) \times (k \circ g) \downarrow & \curvearrowright & \downarrow \text{id}_{\{\text{true, false}\}} \\ C \times Z & \xrightarrow{T} & \{\text{true, false}\} \end{array}$$

- We have $a \sim_{S \circ R} c$, i.e. there exists some $b \in B$ such that:

1. We have $a \sim_R b$;
2. We have $b \sim_S c$;

since:

- If $a \sim_R b$, then $f(a) \sim_T g(b)$, as $T \circ (f \times g) \subset R$;
- If $b \sim_S c$, then $g(b) \sim_U h(c)$, as $U \circ (g \times h) \subset S$;

given by the pasting of inclusions¹³

$$\begin{array}{ccc}
 A \times X & \xrightarrow{R} & \{\text{true, false}\} \\
 f \times g \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} \\
 B \times Y & \xrightarrow{s} & \{\text{true, false}\} \\
 h \times k \downarrow & \curvearrowleft & \downarrow \text{id}_{\{\text{true, false}\}} \\
 C \times Z & \xrightarrow[T]{} & \{\text{true, false}\}.
 \end{array}$$

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

$$\begin{array}{ccccc}
 & & A & \xrightarrow{R} & B \xrightarrow{S} C \xrightarrow{T} D \\
 \alpha_{T,S,R}^{\text{Rel}^{\text{dbl}}} : (T \odot S) \odot R & \xrightarrow{\cong} & & \downarrow \text{id}_A & \downarrow \text{id}_D \\
 & & & \alpha_{T,S,R}^{\text{Rel}^{\text{dbl}}} & \downarrow \text{id}_D \\
 & & A & \xrightarrow[R]{\quad} & B \xrightarrow[S]{\quad} C \xrightarrow[T]{\quad} D
 \end{array}$$

of the associator of Rel^{dbl} at (R, S, T) is the identity inclusion¹⁴

$$\begin{array}{ccc}
 A \times B & \xrightarrow{(T \odot S) \diamond R} & \{\text{true, false}\} \\
 \parallel & \equiv & \downarrow \text{id}_{\{\text{true, false}\}} \\
 A \times B & \xrightarrow[T \diamond (S \diamond R)]{} & \{\text{true, false}\}.
 \end{array}$$

¹³This is justified by noting that, given $(a, x) \in A \times X$, the statement

- We have $h(f(a)) \sim_T k(g(x))$;

is implied by the statement

- We have $a \sim_R x$;

since

- If $a \sim_R x$, then $f(a) \sim_S g(x)$, as $S \circ (f \times g) \subset R$;
- If $b \sim_S y$, then $h(b) \sim_T k(y)$, as $T \circ (h \times k) \subset S$, and thus, in particular:
 - If $f(a) \sim_S g(x)$, then $h(f(a)) \sim_T k(g(x))$;

¹⁴This is justified by Item 2 of Proposition 5.3.12.1.3.

5.2.4.6 The Left Unitors

Definition 5.2.4.6.1. For each horizontal morphism $R: A \rightarrow B$ of Rel^{dbl} , the component

$$\lambda_R^{\text{Rel}^{\text{dbl}}}: \mathbb{1}_B \odot R \xrightarrow{\cong} R, \quad \begin{array}{ccccc} A & \xrightarrow{R} & B & \xrightarrow{\mathbb{1}_B} & B \\ \downarrow \text{id}_A & & \downarrow \lambda_R^{\text{Rel}^{\text{dbl}}} & \parallel & \downarrow \text{id}_B \\ A & \xrightarrow{R} & B & & \end{array}$$

of the left unitor of Rel^{dbl} at R is the identity inclusion¹⁵

$$R = \chi_B \diamond R, \quad \begin{array}{ccc} A \times B & \xrightarrow{\chi_B \diamond R} & \{\text{true, false}\} \\ \parallel & \equiv & \downarrow \text{id}_{\{\text{true, false}\}} \\ A \times B & \xrightarrow{R} & \{\text{true, false}\}. \end{array}$$

5.2.4.7 The Right Unitors

Definition 5.2.4.7.1. For each horizontal morphism $R: A \rightarrow B$ of Rel^{dbl} , the component

$$\rho_R^{\text{Rel}^{\text{dbl}}}: R \odot \mathbb{1}_A \xrightarrow{\cong} R, \quad \begin{array}{ccccc} A & \xrightarrow{\mathbb{1}_A} & A & \xrightarrow{R} & B \\ \downarrow \text{id}_A & & \downarrow \rho_R^{\text{Rel}^{\text{dbl}}} & \parallel & \downarrow \text{id}_B \\ A & \xrightarrow{R} & B & & \end{array}$$

of the right unitor of Rel^{dbl} at R is the identity inclusion¹⁶

$$R = R \diamond \chi_A, \quad \begin{array}{ccc} A \times B & \xrightarrow{R \diamond \chi_A} & \{\text{true, false}\} \\ \parallel & \equiv & \downarrow \text{id}_{\{\text{true, false}\}} \\ A \times B & \xrightarrow{R} & \{\text{true, false}\}. \end{array}$$

5.2.5 Properties of the Category of Relations

Proposition 5.2.5.1.1. Let A and B be sets.

¹⁵This is justified by Item 3 of Proposition 5.3.12.1.3.

¹⁶This is justified by Item 3 of Proposition 5.3.12.1.3.

1. *Self-Duality I.* The category **Rel** is self-dual, i.e. we have an equivalence

$$\mathbf{Rel}^{\text{op}} \xrightarrow{\text{eq.}} \mathbf{Rel}$$

of categories.

2. *Self-Duality II.* The bicategory **Rel** is self-dual, i.e. we have a biequivalence

$$\mathbf{Rel}^{\text{op}} \xrightarrow{\text{eq.}} \mathbf{Rel}$$

of bicategories.

3. *Equivalences and Isomorphisms in Rel.* Let $R: A \nrightarrow B$ be a relation from A to B . The following conditions are equivalent:

- (a) The relation $R: A \nrightarrow B$ is an equivalence in **Rel**, i.e. there exists a relation $R^{-1}: B \nrightarrow A$ from B to A together with isomorphisms

$$\begin{aligned} R^{-1} \diamond R &\cong \chi_A, \\ R \diamond R^{-1} &\cong \chi_B. \end{aligned}$$

- (b) The relation $R: A \nrightarrow B$ is an isomorphism in **Rel**, i.e. there exists a relation $R^{-1}: B \nrightarrow A$ from B to A such that we have

$$\begin{aligned} R^{-1} \diamond R &= \chi_A, \\ R \diamond R^{-1} &= \chi_B. \end{aligned}$$

- (c) There exists a bijection $f: A \xrightarrow{\cong} B$ with $R = \text{Gr}(f)$.

4. *Adjunctions in Rel.* We have a natural bijection

$$\left\{ \begin{array}{l} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\} \cong \left\{ \begin{array}{l} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\},$$

with every adjunction in **Rel** being of the form $\text{Gr}(f) \dashv f^{-1}$ for some function f .

5. *Monads in Rel.* We have a natural bijection¹⁷

$$\left\{ \begin{array}{l} \text{Monads in} \\ \mathbf{Rel} \text{ on } A \end{array} \right\} \cong \{ \text{Preorders on } A \}.$$

6. *Comonads in Rel.* We have a natural bijection

$$\left\{ \begin{array}{l} \text{Comonads in} \\ \mathbf{Rel} \text{ on } A \end{array} \right\} \cong \{ \text{Subsets of } A \}.$$

¹⁷See also [Section 5.6](#) for an extension of this correspondence to “relative monads on **Rel**”.

7. *Characterisations of Monomorphisms in Rel.* Let $R: A \rightarrow B$ be a relation. The following conditions are equivalent:

- (a) The relation R is a monomorphism in Rel.
- (b) The direct image function

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

associated to R is injective.

- (c) 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 $a \sim_R b$ and $a' \sim_R b$, then $a = a'$.

8. *Epimorphisms in Rel.* Let $R: A \rightarrow B$ be a relation. The following conditions are equivalent:

- (a) The relation R is an epimorphism in Rel.
- (b) The weak inverse image function

$$R^{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

associated to R is injective.

- (c) The strong inverse image function

$$R_{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

associated to R is injective.

- (d) The function $R: A \rightarrow \mathcal{P}(B)$ is “surjective on singletons”:

- (★) For each $b \in B$, there exists some $a \in A$ such that $R(a) = \{b\}$.

9. *As a Kleisli Category.* We have an isomorphism of categories

$$\text{Rel} \cong \text{FreeAlg}_{\mathcal{P}},$$

where \mathcal{P} is the powerset monad of ??.

10. *Co/Completeness (Or Lack Thereof).* The category Rel is not co/complete, but admits some co/limits:

- (a) *Zero Objects.* The category \mathbf{Rel} has a zero object, the empty set \emptyset .
- (b) *Co/Products.* The category \mathbf{Rel} has co/products, both given by disjoint union of sets.
- (c) *Lack of Co/Equalisers.* The category \mathbf{Rel} does not have co/equalisers.
- (d) *Limits of Graphs of Functions.* The category \mathbf{Rel} has limits whose arrows are all graphs of functions.
- (e) *Colimits of Graphs of Functions.* The category \mathbf{Rel} has colimits whose arrows are all graphs of functions, and these agree with the corresponding limits in \mathbf{Sets} .

11. *Existence of Right Kan Extensions.* The right Kan extension

$$\text{Ran}_R : \mathbf{Rel}(A, X) \rightarrow \mathbf{Rel}(B, X)$$

along a relation $R : A \rightarrow B$ in \mathbf{Rel} exists and is given by

$$\text{Ran}_R(S) \stackrel{\text{def}}{=} \int_{a \in A} \mathbf{Hom}_{\{\text{t,f}\}}(R_{-1}^a, S_{-2}^a)$$

for each $S \in \mathbf{Rel}(A, X)$, so that the following conditions are equivalent:

- (a) We have $b \sim_{\text{Ran}_R(S)} x$.
- (b) For each $a \in A$, if $a \sim_R b$, then $a \sim_S x$.

12. *Existence of Right Kan Lifts.* The right Kan lift

$$\text{Rift}_R : \mathbf{Rel}(X, B) \rightarrow \mathbf{Rel}(X, A)$$

along a relation $R : A \rightarrow B$ in \mathbf{Rel} exists and is given by

$$\text{Rift}_R(S) \stackrel{\text{def}}{=} \int_{b \in B} \mathbf{Hom}_{\{\text{t,f}\}}(R_b^{-2}, S_b^{-1})$$

for each $S \in \mathbf{Rel}(X, B)$, so that the following conditions are equivalent:

- (a) We have $x \sim_{\text{Rift}_R(S)} a$.
- (b) For each $b \in B$, if $a \sim_R b$, then $x \sim_S b$.

13. *Closedness.* The bicategory \mathbf{Rel} is a closed bicategory, there being, for each $R : A \rightarrow B$ and set X , a pair of adjunctions

$$(R^* \dashv \text{Ran}_R) : \quad \mathbf{Rel}(B, X) \begin{array}{c} \xrightarrow{R^*} \\ \perp \\ \xleftarrow{\text{Ran}_R} \end{array} \mathbf{Rel}(A, X),$$

$$(R_* \dashv \text{Rift}_R) : \quad \mathbf{Rel}(X, A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{\text{Rift}_R} \end{array} \mathbf{Rel}(X, B),$$

witnessed by bijections

$$\begin{aligned}\mathbf{Rel}(S \diamond R, T) &\cong \mathbf{Rel}(S, \text{Ran}_R(T)), \\ \mathbf{Rel}(R \diamond U, V) &\cong \mathbf{Rel}(U, \text{Rift}_R(V)),\end{aligned}$$

natural in $S \in \mathbf{Rel}(B, X)$, $T \in \mathbf{Rel}(A, X)$, $U \in \mathbf{Rel}(X, A)$, and $V \in \mathbf{Rel}(X, B)$.

Proof. **Item 1**, Self-Duality I: Omitted.

Item 2, Self-Duality II: Omitted.

Item 3, Equivalences and Isomorphisms in \mathbf{Rel} : We claim that **Items 3a** to **3c** are indeed equivalent:

- **Item 3a** \iff **Item 3b**: This follows from the fact that \mathbf{Rel} is locally posetal, so that natural isomorphisms and equalities of 1-cells in \mathbf{Rel} coincide.
- **Item 3b** \implies **Item 3c**: The equalities in **Item 3b** imply $R \dashv R^{-1}$, and thus by **Item 4**, 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 5.3.2.1.1**). The conditions from **Item 3b** 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 3c** \implies **Item 3b**: By **Item 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 .

Item 4, Adjunctions in **Rel:** 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

$$\begin{aligned} R: A &\rightarrow B, \\ S: B &\rightarrow A, \end{aligned}$$

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 **Rel**.* By Item 2 of Proposition 5.3.1.1.2, every function $f: A \rightarrow B$ gives rise to an adjunction $\text{Gr}(f) \dashv f^{-1}$ in **Rel**, giving a map

$$\left\{ \begin{array}{l} \text{Functions} \\ \text{from } A \text{ to } B \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{Adjunctions in } \mathbf{Rel} \\ \text{from } A \text{ to } B \end{array} \right\}.$$

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.

Item 5, Monads in Rel: 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

$$\begin{array}{ccccc}
 & \chi_A \diamond R & & R \diamond (R \diamond R) & R \diamond \chi_A \\
 \eta_R \diamond \text{id}_R \nearrow & \longrightarrow & & \alpha_{R,R,R} \parallel & \text{id}_R \diamond \mu_R \nearrow \\
 R \diamond R & & (R \diamond R) \diamond R & & R \diamond R \\
 \downarrow \mu_R & & \mu_R \diamond \text{id}_R \swarrow & & \downarrow \mu_R \\
 R & & R \diamond R & & R \\
 & & \mu_R \nearrow & & \downarrow \mu_R \\
 & & R \diamond R & \longrightarrow & R
 \end{array}$$

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 \leq gives rise to a pair of maps μ_\leq and η_\leq , forming a monad on A .

Item 6, Comonads in Rel: A comonad in **Rel** on A consists of a relation $R: A \rightarrow A$ together with maps

$$\begin{aligned}
 \Delta_R: R &\subset R \diamond R, \\
 \epsilon_R: R &\subset \chi_A
 \end{aligned}$$

making the diagrams

$$\begin{array}{ccccc}
 R & \xrightarrow{\Delta_R} & R \diamond R & \xrightarrow{\text{id}_R \diamond \Delta_R} & R \diamond R \\
 \lambda_R^{\text{Rel}(A,B),-1} \parallel & \nearrow & \downarrow \epsilon_R \diamond \text{id}_R & \parallel & \lambda_R^{\text{Rel}(A,B),-1} \\
 & & \chi_A \diamond R & & R \diamond \chi_A \\
 & & \Delta_R \swarrow & & \downarrow \text{id}_R \diamond \epsilon_R \\
 & & R & \xrightarrow{\alpha_{R,R,R}} & R \diamond (R \diamond R) \\
 & & \Delta_R \swarrow & & \mu_R \parallel \alpha_{R,R,R}^{\text{Rel}(A,B),-1} \\
 & & R \diamond R & \xrightarrow{\Delta_R \diamond \text{id}_R} & (R \diamond R) \diamond R
 \end{array}$$

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 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.

Item 7, Monomorphisms in Rel: Firstly note that **Items 7b** and **7c** are equivalent by **Item 7 of Proposition 5.5.1.1.3**. We then claim that **Items 7a** and **7b** are also equivalent:

- **Item 7a \implies Item 7b:** Let $U, V \in \mathcal{P}(A)$ and consider the diagram

$$\text{pt} \xrightarrow[U]{\quad} A \xrightarrow[R]{\quad} B.$$

By **Remark 5.5.1.1.2**, 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 7b \implies Item 7a:** Conversely, suppose that R_* is injective, consider the diagram

$$K \xrightarrow[S]{\quad} A \xrightarrow[R]{\quad} B,$$

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 $k \in K$, we may consider the diagram

$$\text{pt} \xrightarrow[k]{\quad} K \xrightarrow[S]{\quad} A \xrightarrow[R]{\quad} B,$$

for which we have $R \diamond S \diamond [k] = R \diamond T \diamond [k]$, implying that we have

$$S(k) = S \diamond [k] = T \diamond [k] = T(k)$$

for each $k \in K$, implying $S = T$, and thus R is a monomorphism.

We can also prove this in a more abstract way, following [[MSE 350788](#)]:

- **Item 7a \implies Item 7b:** 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 5.5.1.1.2**.

- 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 7b* \implies *Item 7a*: 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 5.5.1.1.2**.
 - Since the monomorphisms in Sets are precisely the injections (?? of ??), it follows that R_* is a monomorphism.
 - Since $\text{Rel}(\text{pt}, -)$ is faithful, it follows by ?? of ?? that $\text{Rel}(\text{pt}, -)$ reflects monomorphisms.
 - Since R_* is a monomorphism and $\text{Rel}(\text{pt}, -)$ maps R to R_* , it follows that R is also a monomorphism.

Finally, we prove the second part of the statement. Assume that R is a monomorphism, let $a, a' \in A$ such that $a \sim_R b$ and $a' \sim_R b$ for some $b \in B$, and consider the diagram

$$\begin{array}{ccc} & [a] & \\ \text{pt} & \not\rightarrow \not\rightarrow & A \xrightarrow{R} B \\ & [a'] & \end{array}$$

Since $\star \sim_{[a]} a$ and $a \sim_R b$, we have $\star \sim_{R \diamond [a]} b$. Similarly, $\star \sim_{R \diamond [a']} b$. Thus $R \diamond [a] = R \diamond [a']$, and since R is a monomorphism, we have $[a] = [a']$, i.e. $a = a'$.

Conversely, assume the condition

- (★) For each $a, a' \in A$, if there exists some $b \in B$ such that $a \sim_R b$ and $a' \sim_R b$, then $a = a'$,

consider the diagram

$$\begin{array}{ccc} & S & \\ K & \not\rightarrow \not\rightarrow & A \xrightarrow{R} B \\ & T & \end{array}$$

and let $(k, a) \in S$. 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 $k \sim_{R \diamond S} b$, and since $R \diamond S = R \diamond T$, we have also $k \sim_{R \diamond T} b$. Thus there must exist some $a' \in A$ such that $k \sim_T a'$ and $a' \sim_R b$. However, since $a, a' \sim_R b$, we must have $a = a'$, and thus $(k, a) \in T$ as well.

A similar argument shows that if $(k, a) \in T$, then $(k, a) \in S$, and thus $S = T$ and R is a monomorphism.

Item 8, Epimorphisms in Rel: Firstly note that *Items 8b* and *8c* are equivalent by *Item 7* of **Proposition 5.5.2.1.3**. We then claim that *Items 8a* and *8b* are also equivalent:

- *Item 8a* \implies *Item 8b*: Let $U, V \in \mathcal{P}(A)$ and consider the diagram

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ & \dashrightarrow & \dashrightarrow \\ & & \text{pt.} \end{array}$$

By Remark 5.5.1.1.2, 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 8b* \implies *Item 8a*: Conversely, suppose that R^{-1} is injective, consider the diagram

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ & \dashrightarrow & \dashrightarrow \\ & & K \\ & & \downarrow T \end{array}$$

and suppose that $S \diamond R = T \diamond R$. Note that, since R^{-1} is injective, given a diagram of the form

$$\begin{array}{ccc} A & \xrightarrow{R} & B \\ & \dashrightarrow & \dashrightarrow \\ & & \text{pt.} \end{array}$$

if $R^{-1}(U) = U \diamond R = V \diamond R = R^{-1}(V)$, then $U = V$. In particular, for each $k \in K$, we may consider the diagram

$$\begin{array}{ccccc} A & \xrightarrow{R} & B & \xrightarrow[S]{\quad} & K \\ & \dashrightarrow & \dashrightarrow & & \downarrow [k] \\ & & & & \text{pt.} \end{array}$$

for which we have $[k] \diamond S \diamond R = [k] \diamond T \diamond R$, implying that we have

$$S^{-1}(k) = [k] \diamond S = [k] \diamond T = T^{-1}(k)$$

for each $k \in K$, implying $S = T$, and thus R is an epimorphism.

We can also prove this in a more abstract way, following [MSE 350788]:

- *Item 8a* \implies *Item 8b*: 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 5.5.3.1.2.
 - 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 8b \implies Item 8a:** 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 5.5.3.1.2.
 - 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.

Finally, we claim that Items 8b and 8d are also equivalent, following [MO 350788]:

- **Item 8b \implies Item 8d:** Since $B \setminus \{b\} \subset B$ and R^{-1} is injective, we have $R^{-1}(B \setminus \{b\}) \subseteq R^{-1}(B)$. So taking some $a \in R^{-1}(B) \setminus R^{-1}(B \setminus \{b\})$ we get an element of A such that $R(a) = \{b\}$.
- **Item 8d \implies Item 8b:** 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.

Item 9, As a Kleisli Category: Omitted.

Item 10, Co/Completeness (Or Lack Thereof): Omitted.

Item 11, Existence of Right Kan Extensions: We have

$$\begin{aligned}
 \text{Hom}_{\mathbf{Rel}(A,X)}(S \diamond R, T) &\cong \int_{a \in A} \int_{x \in X} \mathbf{Hom}_{\{\text{t},\text{f}\}}((S \diamond R)_x^a, T_x^a) \\
 &\cong \int_{a \in A} \int_{x \in X} \mathbf{Hom}_{\{\text{t},\text{f}\}}\left(\left(\int^{b \in B} S_x^b \times R_b^a\right), T_x^a\right) \\
 &\cong \int_{a \in A} \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t},\text{f}\}}(S_x^b \times R_b^a, T_x^a) \\
 &\cong \int_{a \in A} \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t},\text{f}\}}(S_x^b, \mathbf{Hom}_{\{\text{t},\text{f}\}}(R_b^a, T_x^a)) \\
 &\cong \int_{b \in B} \int_{x \in X} \int_{a \in A} \mathbf{Hom}_{\{\text{t},\text{f}\}}(S_x^b, \mathbf{Hom}_{\{\text{t},\text{f}\}}(R_b^a, T_x^a)) \\
 &\cong \int_{b \in B} \int_{x \in X} \mathbf{Hom}_{\{\text{t},\text{f}\}}\left(S_x^b, \int_{a \in A} \mathbf{Hom}_{\{\text{t},\text{f}\}}(R_b^a, T_x^a)\right) \\
 &\cong \text{Hom}_{\mathbf{Rel}(B,X)}\left(S, \int_{a \in A} \mathbf{Hom}_{\{\text{t},\text{f}\}}(R_{-1}^a, T_{-2}^a)\right)
 \end{aligned}$$

naturally in each $S \in \mathbf{Rel}(B, X)$ and each $T \in \mathbf{Rel}(A, X)$, showing that

$$\int_{a \in A} \mathbf{Hom}_{\{\text{t},\text{f}\}}(R_{-1}^a, T_{-2}^a)$$

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 5.1.1.4](#);
2. [Definition 5.3.12.1.1](#);
3. ?? of ??;
4. ??;
5. ?? of ??;
6. ?? of ??;
7. [Item 1 of Proposition 5.1.1.4](#).

Item 12, Existence of Right Kan Lifts: We have

$$\begin{aligned}
 \text{Hom}_{\mathbf{Rel}(X,B)}(R \diamond S, T) &\cong \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t,f}\}}((R \diamond S)_b^x, T_b^x) \\
 &\cong \int_{x \in X} \int_{b \in B} \mathbf{Hom}_{\{\text{t,f}\}}\left(\left(\int^{a \in A} R_b^a \times S_a^x\right), T_b^x\right) \\
 &\cong \int_{x \in X} \int_{b \in B} \int_{a \in A} \mathbf{Hom}_{\{\text{t,f}\}}(R_b^a \times S_a^x, T_b^x) \\
 &\cong \int_{x \in X} \int_{b \in B} \int_{a \in A} \mathbf{Hom}_{\{\text{t,f}\}}(S_a^x, \mathbf{Hom}_{\{\text{t,f}\}}(R_b^a, T_b^x)) \\
 &\cong \int_{x \in X} \int_{a \in A} \int_{b \in B} \mathbf{Hom}_{\{\text{t,f}\}}(S_a^x, \mathbf{Hom}_{\{\text{t,f}\}}(R_b^a, T_b^x)) \\
 &\cong \int_{x \in X} \int_{a \in A} \mathbf{Hom}_{\{\text{t,f}\}}\left(S_a^x, \int_{b \in B} \mathbf{Hom}_{\{\text{t,f}\}}(R_b^a, T_b^x)\right) \\
 &\cong \text{Hom}_{\mathbf{Rel}(X,A)}\left(S, \int_{b \in B} \mathbf{Hom}_{\{\text{t,f}\}}(R_b^{-2}, T_b^{-1})\right)
 \end{aligned}$$

naturally in each $S \in \mathbf{Rel}(X, A)$ and each $T \in \mathbf{Rel}(X, B)$, showing that

$$\int_{b \in B} \mathbf{Hom}_{\{\text{t,f}\}}(R_b^{-2}, T_b^{-1})$$

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 5.1.1.4;
2. Definition 5.3.12.1.1;
3. ?? of ??;
4. ??;
5. ?? of ??;
6. ?? of ??;
7. Item 1 of Proposition 5.1.1.4.

Item 13, Closedness: This has been proved as part of the proof of Items 11 and 12. \square

5.3 Constructions With Relations

5.3.1 The Graph of a Function

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

Definition 5.3.1.1. The **graph of** f is the relation $\text{Gr}(f) : A \rightarrow B$ defined as follows:¹⁸

- 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 5.3.1.2. Let $f : A \rightarrow B$ be a function.

- Functionality.* The assignment $A \mapsto \text{Gr}(A)$ defines a functor

$$\text{Gr} : \text{Sets} \rightarrow \text{Rel}$$

where

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

$$\text{Gr}(A) \stackrel{\text{def}}{=} A;$$

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

$$\text{Gr}_{A,B} : \text{Sets}(A, B) \rightarrow \underbrace{\text{Rel}(\text{Gr}(A), \text{Gr}(B))}_{\stackrel{\text{def}}{=} \text{Rel}(A, B)}$$

of Gr at (A, B) is defined by

$$\text{Gr}_{A,B}(f) \stackrel{\text{def}}{=} \text{Gr}(f),$$

where $\text{Gr}(f)$ is the graph of f as in **Definition 5.3.1.1**.

In particular:

¹⁸Further Notation: We write $\text{Gr}(A)$ for $\text{Gr}(\text{id}_A)$, and call it the **graph** of A .

- *Preservation of Identities.* We have

$$\text{Gr}(\text{id}_A) = \chi_A$$

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

- *Preservation of Composition.* We have

$$\text{Gr}(g \circ f) = \text{Gr}(g) \diamond \text{Gr}(f)$$

for each pair of functions $f: A \rightarrow B$ and $g: B \rightarrow C$.

2. *Adjointness Inside **Rel**.* We have an adjunction

$$(\text{Gr}(f) \dashv f^{-1}): \quad \begin{array}{c} \text{Gr}(f) \\ \text{---} \\ A \end{array} \begin{array}{c} \curvearrowright \\ \perp \\ \curvearrowleft \end{array} \begin{array}{c} \text{Gr}(f) \\ \text{---} \\ B \end{array} \quad f^{-1}$$

in **Rel**, where f^{-1} is the inverse of f of [Definition 5.3.2.1.1](#).

3. *Adjointness.* We have an adjunction

$$(\text{Gr} \dashv \mathcal{P}_*): \quad \begin{array}{c} \text{Gr} \\ \text{---} \\ \text{Sets} \end{array} \begin{array}{c} \curvearrowright \\ \perp \\ \curvearrowleft \end{array} \begin{array}{c} \text{Rel}, \\ \mathcal{P}_* \end{array}$$

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 $B \in \text{Obj}(\text{Rel})$.

4. *Interaction With Inverses.* We have

$$\begin{aligned} \text{Gr}(f)^\dagger &= f^{-1}, \\ (f^{-1})^\dagger &= \text{Gr}(f). \end{aligned}$$

5. *Cocontinuity.* The functor $\text{Gr}: \text{Sets} \rightarrow \text{Rel}$ of [Item 1](#) preserves colimits.

6. *Characterisations.* Let $R: A \rightarrow B$ be a relation. The following conditions are equivalent:

- (a) There exists a function $f: A \rightarrow B$ such that $R = \text{Gr}(f)$.
- (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, Functoriality:** Clear.

Item 2, Adjointness Inside Rel: We need to check that there are inclusions

$$\begin{aligned}\chi_A &\subset f^{-1} \diamond \text{Gr}(f), \\ \text{Gr}(f) \diamond f^{-1} &\subset \chi_B.\end{aligned}$$

These correspond respectively to the following conditions:

1. For each $a \in A$, there exists some $b \in B$ such that $a \sim_{\text{Gr}(f)} b$ and $b \sim_{f^{-1}} a$.
2. For each $a, b \in A$, if $a \sim_{\text{Gr}(f)} b$ and $b \sim_{f^{-1}} a$, then $a = b$.

In other words, the first condition states that the image of any $a \in A$ by f is nonempty, whereas the second condition states that f is not multivalued. As f is a function, both of these statements are true, and we are done.

Item 3, Adjointness: The stated bijection follows from Remark 5.1.1.3, 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 Item 4 of Proposition 5.2.5.1.1.
- **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 Item 4 of Proposition 5.2.5.1.1.

This finishes the proof. □

5.3.2 The Inverse of a Function

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

Definition 5.3.2.1.1. The **inverse of f** is the relation $f^{-1}: B \rightarrow A$ defined as follows:

- Viewing relations from B to A as subsets of $B \times A$, we define

$$f^{-1} \stackrel{\text{def}}{=} \left\{ (b, f^{-1}(b)) \in B \times A \mid a \in A \right\},$$

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 $B \times A \rightarrow \{\text{true, false}\}$, 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 5.3.2.1.2. Let $f: A \rightarrow B$ be a function.

- Functionality.* The assignment $A \mapsto A, f \mapsto f^{-1}$ defines a functor

$$(-)^{-1}: \text{Sets} \rightarrow \text{Rel}$$

where

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

$$[(-)^{-1}](A) \stackrel{\text{def}}{=} A;$$

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

$$(-)^{-1}_{A,B}: \text{Sets}(A, B) \rightarrow \text{Rel}(A, B)$$

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 5.3.2.1.1](#).

In particular:

- *Preservation of Identities.* We have

$$\text{id}_A^{-1} = \chi_A$$

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

- *Preservation of Composition.* We have

$$(g \circ f)^{-1} = g^{-1} \diamond f^{-1}$$

for pair of functions $f: A \rightarrow B$ and $g: B \rightarrow C$.

2. *Adjointness Inside **Rel**.* We have an adjunction

$$\left(\text{Gr}(f) \dashv f^{-1} \right): \quad A \begin{array}{c} \xrightarrow{\text{Gr}(f)} \\ \perp \\ \xleftarrow{f^{-1}} \end{array} B$$

in **Rel**.

3. *Interaction With Inverses of Relations.* We have

$$\begin{aligned} \left(f^{-1} \right)^\dagger &= \text{Gr}(f), \\ \text{Gr}(f)^\dagger &= f^{-1}. \end{aligned}$$

Proof. **Item 1**, Functoriality: Clear.

Item 2, Adjointness Inside **Rel**: This is proved in **Item 2** of [Proposition 5.3.1.1.2](#).

Item 3, Interaction With Inverses of Relations: Clear. □

5.3.3 Representable Relations

Let A and B be sets.

Definition 5.3.3.1.1. Let $f: A \rightarrow B$ and $g: B \rightarrow A$ be functions.¹⁹

¹⁹More generally, given functions

$$\begin{aligned} f: A &\rightarrow C, \\ g: B &\rightarrow D \end{aligned}$$

and a relation $B \rightarrow D$, we may consider the composite relation

$$A \times B \xrightarrow{f \times g} C \times D \xrightarrow{R} \{\text{true, false}\},$$

for which we have $a \sim_{R \circ (f \times g)} b$ iff $f(a) \sim_R g(b)$.

1. The **representable relation associated to f** is the relation $\chi_f: A \rightarrow B$ defined as the composition

$$A \times B \xrightarrow{f \times \text{id}_B} B \times B \xrightarrow{\chi_B} \{\text{true, false}\},$$

i.e. given by declaring $a \sim_{\chi_f} b$ iff $f(a) = b$.

2. The **corepresentable relation associated to g** is the relation $\chi^g: B \rightarrow A$ defined as the composition

$$B \times A \xrightarrow{g \times \text{id}_A} A \times A \xrightarrow{\chi_A} \{\text{true, false}\},$$

i.e. given by declaring $b \sim_{\chi^g} a$ iff $g(b) = a$.

5.3.4 The Domain and Range of a Relation

Let A and B be sets.

Definition 5.3.4.1.1. Let $R \subset A \times B$ be a relation.^{20,21}

1. The **domain of R** is the subset $\text{dom}(R)$ of A defined by

$$\text{dom}(R) \stackrel{\text{def}}{=} \left\{ a \in A \middle| \begin{array}{l} \text{there exists some } b \in B \\ \text{such that } a \sim_R b \end{array} \right\}.$$

²⁰Following ??, we may compute the (characteristic functions associated to the) domain and range of a relation using the following colimit formulas:

$$\begin{aligned} \chi_{\text{dom}(R)}(a) &\cong \underset{b \in B}{\text{colim}}(R_b^a) & (a \in A) \\ &\cong \bigvee_{b \in B} R_b^a, \\ \chi_{\text{range}(R)}(b) &\cong \underset{a \in A}{\text{colim}}(R_b^a) & (b \in B) \\ &\cong \bigvee_{a \in A} R_b^a, \end{aligned}$$

where the join \vee is taken in the poset $(\{\text{true, false}\}, \leq)$ of ??.

²¹Viewing R as a function $R: A \rightarrow \mathcal{P}(B)$, we have

$$\begin{aligned} \text{dom}(R) &\cong \underset{y \in Y}{\text{colim}}(R(y)) \\ &\cong \bigcup_{y \in Y} R(y), \\ \text{range}(R) &\cong \underset{x \in X}{\text{colim}}(R(x)) \\ &\cong \bigcup_{x \in X} R(x), \end{aligned}$$

2. The **range of R** is the subset $\text{range}(R)$ of B defined by

$$\text{range}(R) \stackrel{\text{def}}{=} \left\{ b \in B \mid \begin{array}{l} \text{there exists some } a \in A \\ \text{such that } a \sim_R b \end{array} \right\}.$$

5.3.5 Binary Unions of Relations

Let A and B be sets and let R and S be relations from A to B .

Definition 5.3.5.1.1. The **union of R and S** ²² 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 define²³

$$R \cup S \stackrel{\text{def}}{=} \{(a, b) \in B \times A \mid \text{we have } a \sim_R b \text{ or } a \sim_S b\}.$$

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$[R \cup S](a) \stackrel{\text{def}}{=} R(a) \cup S(a)$$

for each $a \in A$.

Proposition 5.3.5.1.2. 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 .

- Interaction With Inverses.* We have

$$(R \cup S)^\dagger = R^\dagger \cup S^\dagger.$$

- 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:

- The condition for $(S_1 \diamond R_1) \cup (S_2 \diamond R_2)$ is:

- There exists some $b \in B$ such that:

- $a \sim_{R_1} b$ and $b \sim_{S_1} c$;

or

- $a \sim_{R_2} b$ and $b \sim_{S_2} c$;

- The condition for $(S_1 \cup S_2) \diamond (R_1 \cup R_2)$ is:

²²Further Terminology: Also called the **binary union of R and S** , for emphasis.

²³This is the same as the union of R and S as subsets of $A \times B$.

(a) There exists some $b \in B$ such that:

$$\text{i. } a \sim_{R_1} b \text{ or } a \sim_{R_2} b;$$

and

$$\text{i. } b \sim_{S_1} c \text{ or } b \sim_{S_2} c.$$

These two conditions may fail to agree (counterexample omitted), and thus the two resulting relations on $A \times C$ may differ. \square

5.3.6 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 5.3.6.1.1. 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 define²⁴

$$\bigcup_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a, b) \in (A \times B)^{\times I} \mid \begin{array}{l} \text{there exists some } i \in I \\ \text{such that } a \sim_{R_i} b \end{array} \right\}.$$

- 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 5.3.6.1.2. 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. \square

5.3.7 Binary Intersections of Relations

Let A and B be sets and let R and S be relations from A to B .

Definition 5.3.7.1.1. The **intersection of R and S** ²⁵ is the relation $R \cap S$ from A to B

²⁴This is the same as the union of $\{R_i\}_{i \in I}$ as a collection of subsets of $A \times B$.

²⁵Further Terminology: Also called the **binary intersection of R and S** , for emphasis.

defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define²⁶

$$R \cap S \stackrel{\text{def}}{=} \{(a, b) \in B \times A \mid \text{we have } a \sim_R b \text{ and } a \sim_S b\}.$$

- 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 5.3.7.1.2. 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 .

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

²⁶This is the same as the intersection of R and S as subsets of $A \times B$.

5.3.8 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 5.3.8.1.1. 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 define²⁷

$$\bigcup_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a, b) \in (A \times B)^{\times I} \mid \begin{array}{l} \text{for each } i \in I, \\ \text{we have } a \sim_{R_i} b \end{array} \right\}.$$

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$\left[\bigcap_{i \in I} R_i \right] (a) \stackrel{\text{def}}{=} \bigcap_{i \in I} R_i(a)$$

for each $a \in A$.

Proposition 5.3.8.1.2. 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. □

5.3.9 Binary Products of Relations

Let A , B , X , and Y be sets, let $R : A \rightarrow B$ be a relation from A to B , and let $S : X \rightarrow Y$ be a relation from X to Y .

Definition 5.3.9.1.1. The **product of R and S** ²⁸ 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 $B \times Y$;²⁹
- Viewing relations from $A \times X$ to $B \times Y$ as functions $A \times X \rightarrow \mathcal{P}(B \times Y)$, we

²⁷This is the same as the intersection of $\{R_i\}_{i \in I}$ as a collection of subsets of $A \times B$.

²⁸Further Terminology: Also called the **binary product of R and S** , for emphasis.

²⁹That is, $R \times S$ is the relation given by declaring $(a, x) \sim_{R \times S} (b, y)$ iff $a \sim_R b$ and $x \sim_S y$.

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 5.3.9.1.2. Let A, B, X , and Y be sets.

1. *Interaction With Inverses.* Let

$$\begin{aligned} R &: A \nrightarrow A, \\ S &: X \nrightarrow X \end{aligned}$$

We have

$$(R \times S)^{\dagger} = R^{\dagger} \times S^{\dagger}.$$

2. *Interaction With Composition.* Let

$$\begin{aligned} R_1 &: A \nrightarrow B, \\ S_1 &: B \nrightarrow C, \\ R_2 &: X \nrightarrow Y, \\ S_2 &: Y \nrightarrow Z \end{aligned}$$

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

5.3.10 Products of Families of Relations

Let $\{A_i\}_{i \in I}$ and $\{B_i\}_{i \in I}$ be families of sets, and let $\{R_i : A_i \rightarrow B_i\}_{i \in I}$ be a family of relations.

Definition 5.3.10.1.1. 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 $(a_i)_{i \in I} \in \prod_{i \in I} R_i$.

5.3.11 The Inverse of a Relation

Let A , B , and C be sets and let $R \subset A \times B$ be a relation.

Definition 5.3.11.1.1. The **inverse of R** ³⁰ is the relation R^\dagger defined as follows:

³⁰Further Terminology: Also called the **opposite of R** , the **transpose of R** , or the **converse of R** .

- Viewing relations as subsets, we define

$$R^\dagger \stackrel{\text{def}}{=} \{(b, a) \in B \times A \mid \text{we have } b \sim_R a\}.$$

- Viewing relations as functions $A \times B \rightarrow \{\text{true, false}\}$, we define

$$[R^\dagger]_a^b \stackrel{\text{def}}{=} R_b^a$$

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 5.3.11.1.2. Here are some examples of inverses of relations.

- Less Than Equal Signs.* We have $(\leq)^\dagger = \geq$.
- Greater Than Equal Signs.* Dually to ??, we have $(\geq)^\dagger = \leq$.
- 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 5.3.11.1.3. Let $R : A \rightarrow B$ and $S : B \rightarrow C$ be relations.

- Interaction With Ranges and Domains.* We have

$$\begin{aligned} \text{dom}(R^\dagger) &= \text{range}(R), \\ \text{range}(R^\dagger) &= \text{dom}(R). \end{aligned}$$

- Interaction With Composition I.* We have

$$(S \diamond R)^\dagger = R^\dagger \diamond S^\dagger.$$

- Interaction With Composition II.* We have

$$\begin{aligned} \chi_B(-1, -2) &\subset R \diamond R^\dagger, \\ \chi_A(-1, -2) &\subset R^\dagger \diamond R. \end{aligned}$$

- Invertibility.* We have

$$(R^\dagger)^\dagger = R.$$

5. *Identity.* We have

$$\chi_A^\dagger(-_1, -_2) = \chi_A(-_1, -_2).$$

Proof. **Item 1, Interaction With Ranges and Domains:** Clear.

Item 2, Interaction With Composition I: Clear.

Item 3, Interaction With Composition II: Clear.

Item 4, Invertibility: Clear.

Item 5, Identity: Clear. \square

5.3.12 Composition of Relations

Let A , B , and C be sets and let $R \subset A \times B$ and $S \subset B \times C$ be relations.

Definition 5.3.12.1.1. 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

$$S \diamond R \stackrel{\text{def}}{=} \left\{ (a, c) \in A \times C \middle| \begin{array}{l} \text{there exists some } b \in B \text{ such} \\ \text{that } a \sim_R b \text{ and } b \sim_S c \end{array} \right\}.$$

- Viewing relations as functions $A \times B \rightarrow \{\text{true, false}\}$, we define

$$\begin{aligned} (S \diamond R)^{-1}_{-2} &\stackrel{\text{def}}{=} \int^{y \in B} S_y^{-1} \times R_{-2}^y \\ &= \bigvee_{y \in B} S_y^{-1} \times R_{-2}^y, \end{aligned}$$

where the join \bigvee is taken in the poset $(\{\text{true, false}\}, \leq)$ of ??.

- Viewing relations as functions $A \rightarrow \mathcal{P}(B)$, we define

$$\begin{array}{ccc} B & \xrightarrow{S} & \mathcal{P}(C), \\ S \diamond R \stackrel{\text{def}}{=} \text{Lan}_{\chi_B}(S) \circ R, & \chi_B \downarrow & \nearrow \text{Lan}_{\chi_B}(S) \\ A & \xrightarrow{R} & \mathcal{P}(B) \end{array}$$

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 by³¹

$$\begin{aligned}[S \diamond R](a) &\stackrel{\text{def}}{=} S(R(a)) \\ &\stackrel{\text{def}}{=} \bigcup_{x \in R(a)} S(x).\end{aligned}$$

for each $a \in A$.

Example 5.3.12.1.2. 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 5.3.12.1.3. Let $R: A \rightarrow B$, $S: B \rightarrow C$, and $T: C \rightarrow D$ be relations.

1. *Interaction With Ranges and Domains.* We have

$$\begin{aligned}\text{dom}(S \diamond R) &\subset \text{dom}(R), \\ \text{range}(S \diamond R) &\subset \text{range}(S).\end{aligned}$$

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

$$\begin{aligned}\chi_B(-_1, -_2) &\subset R \diamond R^\dagger, \\ \chi_A(-_1, -_2) &\subset R^\dagger \diamond R.\end{aligned}$$

³¹That 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

Proof. **Item 1, Interaction With Ranges and Domains:** Clear.

Item 2, Associativity: Indeed, we have

$$\begin{aligned}
 (T \diamond S) \diamond R &\stackrel{\text{def}}{=} \left(\int^{y \in C} T_x^{-1} \times S_{-2}^x \right) \diamond R \\
 &\stackrel{\text{def}}{=} \int^{x \in B} \left(\int^{y \in C} T_x^{-1} \times S_y^x \right) \diamond R_{-2}^y \\
 &= \int^{x \in B} \int^{y \in C} \left(T_x^{-1} \times S_y^x \right) \diamond R_{-2}^y \\
 &= \int^{y \in C} \int^{x \in B} \left(T_x^{-1} \times S_y^x \right) \diamond R_{-2}^y \\
 &= \int^{y \in C} \int^{x \in B} T_x^{-1} \times \left(S_y^x \diamond R_{-2}^y \right) \\
 &= \int^{x \in B} T_x^{-1} \times \left(\int^{y \in C} S_y^x \diamond R_{-2}^y \right) \\
 &\stackrel{\text{def}}{=} \int^{x \in B} T_x^{-1} \times (S \diamond R)_{-2}^x \\
 &\stackrel{\text{def}}{=} T \diamond (S \diamond R).
 \end{aligned}$$

In the language of relations, given $a \in A$ and $d \in D$, the stated equality witnesses the equivalence of the following two statements:

1. We have $a \sim_{(T \diamond S) \diamond R} d$, i.e. there exists some $b \in B$ such that:
 - (a) We have $a \sim_R b$;
 - (b) We have $b \sim_{T \diamond S} d$, i.e. there exists some $c \in C$ such that:
 - i. We have $b \sim_S c$;
 - ii. We have $c \sim_T d$;
2. We have $a \sim_{T \diamond (S \diamond R)} d$, i.e. there exists some $c \in C$ such that:
 - (a) We have $a \sim_{S \diamond R} c$, i.e. there exists some $b \in B$ such that:
 - i. We have $a \sim_R b$;
 - ii. We have $b \sim_S c$;
 - (b) We have $c \sim_T d$;

both of which are equivalent to the statement

- There exist $b \in B$ and $c \in C$ such that $a \sim_R b \sim_S c \sim_T d$.

may send the image of each of the b_i 's to a number of elements $\{S(b_i)\}_{i \in I} = \left\{ \{c_{j_i}\}_{j_i \in J_i} \right\}_{i \in I}$ in C .

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. □

5.3.13 The Collage of a Relation

Let A and B be sets and let $R: A \rightarrow B$ be a relation from A to B .

Definition 5.3.13.1.1. The **collage** of R ³² is the poset $\mathbf{Coll}(R) \stackrel{\text{def}}{=} (\mathbf{Coll}(R), \leq_{\mathbf{Coll}(R)})$ consisting of

- *The Underlying Set.* The set $\mathbf{Coll}(R)$ defined by

$$\mathbf{Coll}(R) \stackrel{\text{def}}{=} A \coprod B.$$

- *The Partial Order.* The partial order

$$\leq_{\mathbf{Coll}(R)} : \mathbf{Coll}(R) \times \mathbf{Coll}(R) \rightarrow \{\text{true, false}\}$$

on $\mathbf{Coll}(R)$ defined by

$$\leq(a, b) \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if } a = b \text{ or } a \sim_R b, \\ \text{false} & \text{otherwise.} \end{cases}$$

Proposition 5.3.13.1.2. Let A and B be sets and let $R: A \rightarrow B$ be a relation from A to B .

1. *Functoriality I.* The assignment $R \mapsto \mathbf{Coll}(R)$ defines a functor³³

$$\mathbf{Coll}: \mathbf{Rel}(A, B) \rightarrow \mathbf{Pos}_{/\Delta^1}(A, B),$$

where

³²Further Terminology: Also called the **cograph** of R .

³³Here $\mathbf{Pos}_{/\Delta^1}(A, B)$ is the category defined as the pullback

$$\mathbf{Pos}_{/\Delta^1}(A, B) \stackrel{\text{def}}{=} \text{pt} \times_{[A], \mathbf{Pos}, \text{fib}_0} \mathbf{Pos}_{/\Delta^1} \times_{\text{fib}_1, \mathbf{Pos}, [B]} \text{pt},$$

as in the diagram

$$\begin{array}{ccccc} & & \mathbf{Pos}_{/\Delta^1}(A, B) & & \\ & \swarrow & & \searrow & \\ \mathbf{Pos}_{/\Delta^1} \times_{\mathbf{Pos}} \text{pt} & & & \text{pt} \times_{\mathbf{Pos}} \mathbf{Pos}_{/\Delta^1} & \\ \swarrow & \searrow & & \swarrow & \searrow \\ \text{pt} & & \mathbf{Pos}_{/\Delta^1} & & \text{pt.} \\ \searrow & \swarrow & \searrow & \swarrow & \searrow \\ [A] & & \mathbf{Pos} & & [B] \end{array}$$

Explicitly, an object of $\mathbf{Pos}_{/\Delta^1}(A, B)$ is a pair (X, ϕ_X) consisting of

- A poset X ;
- A morphism $\phi_X: X \rightarrow \Delta^1$;

- *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 5.3.13.1.1](#);
- The morphism $\phi_R : \mathbf{Coll}(R) \rightarrow \Delta^1$ is given by

$$\phi_R(x) \stackrel{\text{def}}{=} \begin{cases} 0 & \text{if } x \in A, \\ 1 & \text{if } x \in B \end{cases}$$

for each $x \in \mathbf{Coll}(R)$;

- *Action on Morphisms.* For each $R, S \in \text{Obj}(\mathbf{Rel}(A, B))$, the action on Hom-sets

$$\mathbf{Coll}_{R,S} : \text{Hom}_{\mathbf{Rel}(A, B)}(R, S) \rightarrow \text{Pos}(\mathbf{Coll}(R), \mathbf{Coll}(S))$$

of \mathbf{Coll} at (R, S) is given by sending an inclusion

$$\iota : R \subset S$$

to the morphism

$$\mathbf{Coll}(\iota) : \mathbf{Coll}(R) \rightarrow \mathbf{Coll}(S)$$

of posets over Δ^1 defined by

$$[\mathbf{Coll}(\iota)](x) \stackrel{\text{def}}{=} x$$

for each $x \in \mathbf{Coll}(R)$.³⁴

2. *Equivalence.* The functor of [Item 1](#) is an equivalence of categories.

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

[Item 2, Equivalence:](#) Omitted. □

5.4 Equivalence Relations

5.4.1 Reflexive Relations

5.4.1.1 Foundations

Let A be a set.

such that $\phi_X^{-1}(0) = A$ and $\phi_X^{-1}(1) = B$, with morphisms between such objects being morphisms of posets over Δ^1 .

³⁴Note that this is indeed a morphism of posets: if $x \leq_{\mathbf{Coll}(R)} y$, then $x = y$ or $x \sim_R y$, so we have

Definition 5.4.1.1.1. A **reflexive relation** is equivalently:³⁵

- 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 5.4.1.1.2. 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 5.4.1.1.3. 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 5.4.1.1.4. 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. □

5.4.1.2 The Reflexive Closure of a Relation

Let R be a relation on A .

Definition 5.4.1.2.1. The **reflexive closure** of \sim_R is the relation \sim_R^{refl} ³⁶ satisfying the following universal property:³⁷

- (★) 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 5.4.1.2.2. Concretely, \sim_R^{refl} is the free pointed object on R in $(\mathbf{Rel}(A, A), \chi_A)$ ³⁸, being given by

$$\begin{aligned} R^{\text{refl}} &\stackrel{\text{def}}{=} R \coprod^{\mathbf{Rel}(A, A)} \Delta_A \\ &= R \cup \Delta_A \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } a = b\}. \end{aligned}$$

either $x = y$ or $x \sim_S y$ (as $R \subset S$), and thus $x \leq_{\mathbf{Coll}(S)} y$.

³⁵Note that since $\mathbf{Rel}(A, A)$ is posetal, reflexivity is a property of a relation, rather than extra structure.

³⁶Further Notation: Also written R^{refl} .

³⁷Slogan: The reflexive closure of R is the smallest reflexive relation containing R .

³⁸Or, equivalently, the free \mathbb{E}_0 -monoid on R in $(N_\bullet(\mathbf{Rel}(A, A)), \chi_A)$.

Proof. Clear. □

Proposition 5.4.1.2.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$\left((-)^{\text{refl}} \dashv \text{忘} \right) : \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{refl}}} \\ \perp \\ \text{忘} \end{array} \mathbf{Rel}^{\text{refl}}(A, A),$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\text{refl}}(R^{\text{refl}}, S) \cong \mathbf{Rel}(R, S),$$

natural in $R \in \text{Obj}(\mathbf{Rel}^{\text{refl}}(A, A))$ and $S \in \text{Obj}(\mathbf{Rel}(A, A))$.

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

$$\begin{array}{ccc} \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{refl}}} & \mathbf{Rel}(A, A) \\ \left(R^{\dagger} \right)^{\text{refl}} = \left(R^{\text{refl}} \right)^{\dagger}, & \downarrow (-)^{\dagger} & \downarrow (-)^{\dagger} \\ \mathbf{Rel}(A, A) & \xrightarrow{(-)^{\text{refl}}} & \mathbf{Rel}(A, A). \end{array}$$

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 5.4.1.2.1](#).

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 5.4.1.1.4](#). □

5.4.2 Symmetric Relations

5.4.2.1 Foundations

Let A be a set.

Definition 5.4.2.1.1. A relation R on A is **symmetric** if, for each $a, b \in A$, the following conditions are equivalent:³⁹

1. We have $a \sim_R b$.
2. We have $b \sim_R a$.

Definition 5.4.2.1.2. 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 5.4.2.1.3. 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. □

5.4.2.2 The Symmetric Closure of a Relation

Let R be a relation on A .

Definition 5.4.2.2.1. The **symmetric closure** of \sim_R is the relation \sim_R^{symm} ⁴⁰ satisfying the following universal property:⁴¹

- (★) 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 5.4.2.2.2. Concretely, \sim_R^{symm} is the symmetric relation on A defined by

$$\begin{aligned} R^{\text{symm}} &\stackrel{\text{def}}{=} R \cup R^\dagger \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } b \sim_R a\}. \end{aligned}$$

Proof. Clear. □

³⁹That is, R is symmetric if $R^\dagger = R$.

⁴⁰Further Notation: Also written R^{symm} .

⁴¹Slogan: The symmetric closure of R is the smallest symmetric relation containing R .

Proposition 5.4.2.2.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$((-)^{\text{symm}} \dashv \text{忘}): \quad \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{symm}}} \\ \perp \\ \xleftarrow{\text{忘}} \end{array} \mathbf{Rel}^{\text{symm}}(A, A),$$

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 5.4.2.2.1](#).

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 5.4.2.1.3](#). \square

5.4.3 Transitive Relations

5.4.3.1 Foundations

Let A be a set.

Definition 5.4.3.1.1. A **transitive relation** is equivalently:⁴²

- 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 5.4.3.1.2. 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:

- (★) If there exists some $b \in A$ such that $a \sim_R b$ and $b \sim_R c$, then $a \sim_R c$.

Definition 5.4.3.1.3. 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 5.4.3.1.4. 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 [MSE2096272].⁴³ □

⁴²Note that since $\mathbf{Rel}(A, A)$ is posetal, transitivity is a property of a relation, rather than extra structure.

⁴³*Intuition:* Transitivity for R and S fails to imply that of $S \diamond R$ because the composition operation for relations intertwines R and S in an incompatible way:

1. If $a \sim_{S \diamond R} c$ and $c \sim_{S \diamond R} e$, then:
 - (a) There is some $b \in A$ such that:
 - i. $a \sim_R b$;
 - ii. $b \sim_S c$;
 - (b) There is some $d \in A$ such that:
 - i. $c \sim_R d$;
 - ii. $d \sim_S e$.

5.4.3.2 The Transitive Closure of a Relation

Let R be a relation on A .

Definition 5.4.3.2.1. The **transitive closure** of \sim_R is the relation \sim_R^{trans} ⁴⁴ satisfying the following universal property:⁴⁵

- (★) 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 5.4.3.2.2. Concretely, \sim_R^{trans} is the free non-unital monoid on R in $(\mathbf{Rel}(A, A), \diamond)$ ⁴⁶, being given by

$$\begin{aligned} R^{\text{trans}} &\stackrel{\text{def}}{=} \bigcup_{n=1}^{\infty} R^{\diamond n} \\ &\stackrel{\text{def}}{=} \bigcup_{n=1}^{\infty} R^{\diamond n} \\ &\stackrel{\text{def}}{=} \left\{ (a, b) \in A \times B \mid \begin{array}{l} \text{there exists some } (x_1, \dots, x_n) \in R^{\times n} \\ \text{such that } a \sim_R x_1 \sim_R \dots \sim_R x_n \sim_R b \end{array} \right\}. \end{aligned}$$

Proof. Clear. □

Proposition 5.4.3.2.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$((-)^{\text{trans}} \dashv \text{忘}): \quad \mathbf{Rel}(A, A) \begin{array}{c} \xrightarrow{(-)^{\text{trans}}} \\ \perp \\ \xleftarrow{\text{忘}} \end{array} \mathbf{Rel}^{\text{trans}}(A, A),$$

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 $R^{\text{trans}} = R$.

3. *Idempotency.* We have

$$(R^{\text{trans}})^{\text{trans}} = R^{\text{trans}}.$$

⁴⁴Further Notation: Also written R^{trans} .

⁴⁵Slogan: The transitive closure of R is the smallest transitive relation containing R .

⁴⁶Or, equivalently, the free non-unital \mathbb{E}_1 -monoid on R in $(\mathbf{N}_{\bullet}(\mathbf{Rel}(A, A)), \diamond)$.

4. *Interaction With Inverses.* We have

$$\begin{array}{ccc} \text{Rel}(A, A) & \xrightarrow{(-)^{\text{trans}}} & \text{Rel}(A, A) \\ \left(R^\dagger\right)^{\text{trans}} = \left(R^{\text{trans}}\right)^\dagger, & \downarrow (-)^\dagger & \downarrow (-)^\dagger \\ \text{Rel}(A, A) & \xrightarrow{(-)^{\text{trans}}} & \text{Rel}(A, A). \end{array}$$

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 5.4.3.2.1](#).

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

$$\begin{aligned} \left(R^\dagger\right)^{\text{trans}} &= \bigcup_{n=1}^{\infty} \left(R^\dagger\right)^{\diamond n} && \text{(by Construction 5.4.3.2.2)} \\ &= \bigcup_{n=1}^{\infty} \left(R^{\diamond n}\right)^\dagger && \text{(by Item 4 of Proposition 5.3.12.1.3)} \\ &= \left(\bigcup_{n=1}^{\infty} R^{\diamond n}\right)^\dagger && \text{(by Item 1 of Proposition 5.3.6.1.2)} \\ &= \left(R^{\text{trans}}\right)^\dagger. && \text{(by Construction 5.4.3.2.2)} \end{aligned}$$

Item 5, Interaction With Composition: This follows from [Item 2](#) of [Proposition 5.4.3.1.4](#). □

5.4.4 Equivalence Relations

5.4.4.1 Foundations

Let A be a set.

Definition 5.4.4.1.1. A relation R is an **equivalence relation** if it is reflexive, symmetric, and transitive.⁴⁷

⁴⁷Further Terminology: If instead R is just symmetric and transitive, then it is called a **partial equivalence relation**.

Example 5.4.4.1.2. The **kernel of a function** $f: A \rightarrow B$ is the equivalence $\sim_{\text{Ker}(f)}$ on A obtained by declaring $a \sim_{\text{Ker}(f)} b$ iff $f(a) = f(b)$.⁴⁸

Definition 5.4.4.1.3. 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 $\text{Rel}^{\text{eq}}(A, B)$ of $\text{Rel}(A, B)$ spanned by the equivalence relations.

5.4.4.2 The Equivalence Closure of a Relation

Let R be a relation on A .

Definition 5.4.4.2.1. The **equivalence closure**⁴⁹ of \sim_R is the relation \sim_R^{eq} ⁵⁰ satisfying the following universal property:⁵¹

- (★) 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 5.4.4.2.2. Concretely, \sim_R^{eq} is the equivalence relation on A defined by

$$\begin{aligned} R^{\text{eq}} &\stackrel{\text{def}}{=} \left(\left(R^{\text{refl}} \right)^{\text{symm}} \right)^{\text{trans}} \\ &= \left(\left(R^{\text{symm}} \right)^{\text{trans}} \right)^{\text{refl}} \\ &= \left\{ (a, b) \in A \times B \mid \begin{array}{l} \text{there exists } (x_1, \dots, x_n) \in R^{\times n} \text{ satisfying at} \\ \text{least one of the following conditions:} \end{array} \right\} \\ &\quad \left. \begin{array}{l} 1. \text{ The following conditions are satisfied:} \\ \quad (a) \text{ We have } a \sim_R x_1 \text{ or } x_1 \sim_R a; \\ \quad (b) \text{ We have } x_i \sim_R x_{i+1} \text{ or } x_{i+1} \sim_R x_i \\ \quad \text{for each } 1 \leq i \leq n-1; \\ \quad (c) \text{ We have } b \sim_R x_n \text{ or } x_n \sim_R b; \\ 2. \text{ We have } a = b. \end{array} \right\}. \end{aligned}$$

Proof. From the universal properties of the reflexive, symmetric, and transitive closures of a relation (Definitions 5.4.1.2.1, 5.4.2.2.1 and 5.4.3.2.1), we see that it suffices to prove that:

⁴⁸The kernel $\text{Ker}(f): A \nrightarrow A$ of f is the monad induced by the adjunction $\text{Gr}(f) \dashv f^{-1}: A \rightleftarrows B$ in Rel of Item 2 of Proposition 5.3.1.1.2.

⁴⁹Further Terminology: Also called the **equivalence relation associated to \sim_R** .

⁵⁰Further Notation: Also written R^{eq} .

⁵¹Slogan: The equivalence closure of R is the smallest equivalence relation containing R .

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 5.4.4.2.3. Let R be a relation on A .

1. *Adjointness.* We have an adjunction

$$((-)^{\text{eq}} \dashv \text{忘}) : \mathbf{Rel}(A, B) \begin{array}{c} \xrightarrow{(-)^{\text{eq}}} \\ \perp \\ \text{忘} \end{array} \mathbf{Rel}^{\text{eq}}(A, B),$$

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 5.4.4.2.1](#).

Item 2, The Equivalence Closure of an Equivalence Relation: Clear.

Item 3, Idempotency: This follows from [Item 2](#). \square

5.4.5 Quotients by Equivalence Relations

5.4.5.1 Equivalence Classes

Let A be a set, let R be a relation on A , and let $a \in A$.

Definition 5.4.5.1.1. The **equivalence class associated to a** is the set $[a]$ defined by

$$\begin{aligned} [a] &\stackrel{\text{def}}{=} \{x \in X \mid x \sim_R a\} \\ &= \{x \in X \mid a \sim_R x\}. \end{aligned} \quad (\text{since } R \text{ is symmetric})$$

5.4.5.2 Quotients of Sets by Equivalence Relations

Let A be a set and let R be a relation on A .

Definition 5.4.5.2.1. 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 5.4.5.2.2. 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 $[a] = [a]'$.⁵²

- *Transitivity.* If R is transitive, then $[a]$ and $[b]$ are disjoint iff $a \not\sim_R b$, and equal otherwise.

Proposition 5.4.5.2.3. Let $f: X \rightarrow Y$ be a function and let R be a relation on X .

1. *As a Coequaliser.* We have an isomorphism of sets

$$X/\sim_R^{\text{eq}} \cong \text{CoEq}\left(R \hookrightarrow X \times X \xrightarrow{\begin{smallmatrix} \text{pr}_1 \\ \text{pr}_2 \end{smallmatrix}} X\right),$$

where \sim_R^{eq} is the equivalence relation generated by \sim_R .

2. *As a Pushout.* We have an isomorphism of sets⁵³

$$\begin{array}{ccc} X/\sim_R^{\text{eq}} & \xleftarrow{\quad} & X \\ \uparrow \lrcorner & & \uparrow \\ X/\sim_R^{\text{eq}} & \cong X \coprod_{\text{Eq}(\text{pr}_1, \text{pr}_2)} X, & \\ & \uparrow & \\ & X & \\ & \xleftarrow{\quad} & \\ & \text{Eq}(\text{pr}_1, \text{pr}_2). & \end{array}$$

where \sim_R^{eq} is the equivalence relation generated by \sim_R .

⁵²When categorifying equivalence relations, one finds that $[a]$ and $[a]'$ correspond to presheaves and copresheaves; see ??.

⁵³Dually, we also have an isomorphism of sets

$$\begin{array}{ccc} \text{Eq}(\text{pr}_1, \text{pr}_2) & \longrightarrow & X \\ \downarrow \lrcorner & & \downarrow \\ X & \longrightarrow & X/\sim_R^{\text{eq}}. \end{array}$$

$$\text{Eq}(\text{pr}_1, \text{pr}_2) \cong X \times_{X/\sim_R^{\text{eq}}} X,$$

3. *The First Isomorphism Theorem for Sets.* We have an isomorphism of sets^{54,55}

$$X / \sim_{\text{Ker}(f)} \cong \text{Im}(f).$$

4. *Descending Functions to Quotient Sets, I.* Let R be an equivalence relation on X . The following conditions are equivalent:

- (a) There exists a map

$$\bar{f}: X / \sim_R \rightarrow Y$$

making the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ q \downarrow & \exists \nearrow \bar{f} & \\ X / \sim_R & & \end{array}$$

commute.

- (b) 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

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ q \downarrow & \exists! \nearrow \bar{f} & \\ X / \sim_R & & \end{array}$$

commute.

⁵⁴Further Terminology: The set $X / \sim_{\text{Ker}(f)}$ is often called the **coimage** of f , and denoted by $\text{Coim}(f)$.

⁵⁵In 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

$$\begin{aligned} \text{Ker}(f) &: X \dashv X, \\ \text{Im}(f) &\subset Y \end{aligned}$$

of f are respectively the induced monads and comonads of the adjunction

$$\left(\text{Gr}(f) \dashv f^{-1} \right): A \begin{array}{c} \xrightarrow{\quad} \\ \dashv \\ \xleftarrow{f^{-1}} \end{array} B$$

of Item 2 of Proposition 5.3.1.1.2.

6. *Descending Functions to Quotient Sets, III.* 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) For each $x, y \in X$, we have $x \sim_R y$ iff $f(x) = f(y)$.

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 $f: X \rightarrow Y$ is surjective.
- (b) The map $\bar{f}: X/\sim_R \rightarrow Y$ is surjective.

8. *Descending Functions to Quotient Sets, V.* 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

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ q \downarrow & \exists \nearrow \bar{f} & \\ X/\sim_R^{\text{eq}} & & \end{array}$$

commute.

- For each $x, y \in X$, if $x \sim_R^{\text{eq}} y$, then $f(x) = f(y)$.

- (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 [[Pro24y](#)].

[Item 6](#), Descending Functions to Quotient Sets, III: See [[Pro24n](#)].

[Item 7](#), Descending Functions to Quotient Sets, IV: See [[Pro24m](#)].

[Item 8](#), Descending Functions to Quotient Sets, V: The implication [Item 8a](#) \implies [Item 8b](#) is clear.

Conversely, suppose that, for each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$. Spelling out the definition of the equivalence closure of R , we see that the condition $x \sim_R^{\text{eq}} y$ unwinds to the following:

- (★) There exist $(x_1, \dots, x_n) \in R^{\times n}$ satisfying at least one of the following conditions:

1. The following conditions are satisfied:

- (a) We have $x \sim_R x_1$ or $x_1 \sim_R x$;
- (b) We have $x_i \sim_R x_{i+1}$ or $x_{i+1} \sim_R x_i$ for each $1 \leq i \leq n - 1$;
- (c) We have $y \sim_R x_n$ or $x_n \sim_R y$;

2. We have $x = y$.

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

5.5 Functoriality of Powersets

5.5.1 Direct Images

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

Definition 5.5.1.1. The **direct image function associated to R** is the function⁵⁶

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

defined by^{57,58}

$$\begin{aligned} R_*(U) &\stackrel{\text{def}}{=} R(U) \\ &\stackrel{\text{def}}{=} \bigcup_{a \in U} R(a) \\ &= \left\{ b \in B \middle| \begin{array}{l} \text{there exists some } a \in U \\ \text{such that } b \in R(a) \end{array} \right\} \end{aligned}$$

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

⁵⁶Further Notation: Also written $\exists_R: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$. This notation comes from the fact that the following statements are equivalent, where $b \in B$ and $U \in \mathcal{P}(A)$:

- We have $b \in \exists_R(U)$.
- There exists some $a \in U$ such that $b \in R(a)$.

⁵⁷Further Terminology: The set $R(U)$ is called the **direct image of U by R** .

⁵⁸We also have

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

Remark 5.5.1.1.2. Identifying subsets of A with relations from pt to A via ?? of ??, we see that the direct image function associated to R is equivalently the function

$$R_* : \underbrace{\mathcal{P}(A)}_{\cong \text{Rel}(\text{pt}, A)} \rightarrow \underbrace{\mathcal{P}(B)}_{\cong \text{Rel}(\text{pt}, B)}$$

defined by

$$R_*(U) \stackrel{\text{def}}{=} R \diamond U$$

for each $U \in \mathcal{P}(A)$, where $R \diamond U$ is the composition

$$\text{pt} \xrightarrow{U} A \xrightarrow{R} B.$$

Proposition 5.5.1.1.3. Let $R : A \dashrightarrow B$ 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

$$(R_* \dashv R_{-1}) : \mathcal{P}(A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{R_{-1}} \end{array} \mathcal{P}(B),$$

witnessed by a bijections of sets

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

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 $U \subset R_{-1}(V)$.

see Item 7 of Proposition 5.5.1.1.3.

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

$$\left(R_*, R_*^\otimes, R_{*\mid\sharp}^\otimes \right): (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} R_{*\mid U,V}^\otimes: R_*(U) \cup R_*(V) &\xrightarrow{=} R_*(U \cup V), \\ R_{*\mid\sharp}^\otimes: \emptyset &\xrightarrow{=} \emptyset, \end{aligned}$$

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

$$\left(R_*, R_*^\otimes, R_{*\mid\sharp}^\otimes \right): (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} R_{*\mid U,V}^\otimes: R_*(U \cap V) &\subset R_*(U) \cap R_*(V), \\ R_{*\mid\sharp}^\otimes: R_*(A) &\subset B, \end{aligned}$$

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.

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 ??): applying Item 7 of Proposition 5.5.4.1.3 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

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

which finishes the proof. \square

Proposition 5.5.1.1.4. Let $R: A \rightarrow B$ 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 have⁵⁹

$$(\chi_A)_* = \text{id}_{\mathcal{P}(A)};$$

⁵⁹That is, the postcomposition function

$$(\chi_A)_*: \text{Rel}(\text{pt}, A) \rightarrow \text{Rel}(\text{pt}, A)$$

is equal to $\text{id}_{\text{Rel}(\text{pt}, A)}$.

4. *Interaction With Composition.* For each pair of composable relations $R: A \rightarrow B$ and $S: B \rightarrow C$, we have⁶⁰

$$\begin{array}{ccc} \mathcal{P}(A) & \xrightarrow{R_*} & \mathcal{P}(B) \\ (S \diamond R)_* = S_* \circ R_*, & \searrow & \downarrow S_* \\ & (S \diamond R)_* & \\ & & \mathcal{P}(C). \end{array}$$

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 5.5.1.1.3**. Thus $(S \diamond R)_* = S_* \circ R_*$. \square

⁶⁰That is, we have

$$\begin{array}{ccc} \text{Rel(pt, } A) & \xrightarrow{R_*} & \text{Rel(pt, } B) \\ (S \diamond R)_* = S_* \circ R_*, & \searrow & \downarrow S_* \\ & (S \diamond R)_* & \\ & & \text{Rel(pt, } C). \end{array}$$

5.5.2 Strong Inverse Images

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

Definition 5.5.2.1.1. The **strong inverse image function associated to R** is the function

$$R_{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

defined by⁶¹

$$R_{-1}(V) \stackrel{\text{def}}{=} \{a \in A \mid R(a) \subset V\}$$

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

Remark 5.5.2.1.2. Identifying subsets of B with relations from pt to B via ?? of ??, we see that the inverse image function associated to R is equivalently the function

$$R_{-1}: \underbrace{\mathcal{P}(B)}_{\cong \text{Rel}(\text{pt}, B)} \rightarrow \underbrace{\mathcal{P}(A)}_{\cong \text{Rel}(\text{pt}, A)}$$

defined by

$$R_{-1}(V) \stackrel{\text{def}}{=} \text{Rift}_R(V), \quad \begin{array}{ccc} & A & \\ \nearrow \text{Rift}_R(V) & \swarrow & \downarrow R \\ \text{pt} & \xrightarrow[V]{} & B, \end{array}$$

and being explicitly computed by

$$\begin{aligned} R_{-1}(V) &\stackrel{\text{def}}{=} \text{Rift}_R(V) \\ &\cong \int_{x \in B} \text{Hom}_{\{\text{t,f}\}}(R_{-1}^x, V_{-2}^x), \end{aligned}$$

where we have used Item 12 of Proposition 5.2.5.1.1.

⁶¹Further Terminology: The set $R_{-1}(V)$ is called the **strong inverse image of V by R** .

Proof. We have

$$\begin{aligned}
 \text{Rift}_R(V) &\cong \int_{x \in B} \text{Hom}_{\{\text{t,f}\}}(R_{-1}^x, V_{-2}^x) \\
 &= \left\{ a \in A \mid \int_{x \in B} \text{Hom}_{\{\text{t,f}\}}(R_a^x, V_\star^x) = \text{true} \right\} \\
 &= \left\{ a \in A \mid \begin{array}{l} \text{for each } x \in B, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } R_a^x = \text{false} \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} (a) \text{ We have } R_a^x = \text{true} \\ (b) \text{ We have } V_\star^x = \text{true} \end{array} \right\} \\
 &= \left\{ a \in A \mid \begin{array}{l} \text{for each } x \in B, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } x \notin R(a) \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} (a) \text{ We have } x \in R(a) \\ (b) \text{ We have } x \in V \end{array} \right\} \\
 &= \{a \in A \mid \text{for each } x \in R(a), \text{ we have } x \in V\} \\
 &= \{a \in A \mid R(a) \subset V\} \\
 &\stackrel{\text{def}}{=} R_{-1}(V).
 \end{aligned}$$

This finishes the proof. □

Proposition 5.5.2.1.3. Let $R: A \rightarrow B$ 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

$$(R_* \dashv R_{-1}): \mathcal{P}(A) \begin{array}{c} \xrightarrow{R_*} \\ \perp \\ \xleftarrow{R_{-1}} \end{array} \mathcal{P}(B),$$

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. *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

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

being equipped with inclusions

$$\begin{aligned} R_{-1|U,V}^{\otimes}: R_{-1}(U) \cup R_{-1}(V) &\subset R_{-1}(U \cup V), \\ R_{-1|*}^{\otimes}: \emptyset &\subset R_{-1}(\emptyset), \end{aligned}$$

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

$$\left(R_{-1}, R_{-1}^{\otimes}, R_{-1|*}^{\otimes} \right) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

$$\begin{aligned} R_{-1|U,V}^{\otimes} &: R_{-1}(U \cap V) \xrightarrow{\cong} R_{-1}(U) \cap R_{-1}(V), \\ R_{-1|*}^{\otimes} &: R_{-1}(A) \xrightarrow{\cong} B, \end{aligned}$$

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 $R: A \rightarrow B$ 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 5.3.1.1.2](#). \square

Proposition 5.5.2.1.4. Let $R: A \rightarrow B$ 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 $R: A \rightarrow B$ and $S: B \rightarrow C$, we have

$$\begin{array}{ccc} \mathcal{P}(C) & \xrightarrow{S_{-1}} & \mathcal{P}(B) \\ (S \diamond R)_{-1} = R_{-1} \circ S_{-1}, & \searrow & \downarrow R_{-1} \\ & & \mathcal{P}(A). \end{array}$$

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 5.5.2.1.3](#), which implies that the conditions

- We have $S_*(R(a)) \subset U$;
- We have $R(a) \subset S_{-1}(U)$;

are equivalent. Thus $(S \diamond R)_{-1} = R_{-1} \circ S_{-1}$. □

5.5.3 Weak Inverse Images

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

Definition 5.5.3.1.1. The **weak inverse image function associated to R** ⁶² is the function

$$R^{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$$

defined by⁶³

$$R^{-1}(V) \stackrel{\text{def}}{=} \{a \in A \mid R(a) \cap V \neq \emptyset\}$$

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

Remark 5.5.3.1.2. Identifying subsets of B with relations from B to pt via ?? of ??, 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

$$\begin{aligned} R^{-1}(V) &\stackrel{\text{def}}{=} V \diamond R \\ &\stackrel{\text{def}}{=} \int^{x \in B} V_x^{-1} \times R_{-2}^x. \end{aligned}$$

⁶²Further Terminology: Also called simply the **inverse image function associated to R** .

⁶³Further 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

$$\begin{aligned}
 V \diamond R &\stackrel{\text{def}}{=} \int^{x \in B} V_x^{-1} \times R_{-2}^x \\
 &= \left\{ a \in A \mid \int^{x \in B} V_x^\star \times R_a^x = \text{true} \right\} \\
 &= \left\{ a \in A \mid \begin{array}{l} \text{there exists } x \in B \text{ such that the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } V_x^\star = \text{true} \\ 2. \text{ We have } R_a^x = \text{true} \end{array} \right\} \\
 &= \left\{ a \in A \mid \begin{array}{l} \text{there exists } x \in B \text{ such that the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } x \in V \\ 2. \text{ We have } x \in R(a) \end{array} \right\} \\
 &= \{a \in A \mid \text{there exists } x \in V \text{ such that } x \in R(a)\} \\
 &= \{a \in A \mid R(a) \cap V \neq \emptyset\} \\
 &\stackrel{\text{def}}{=} R^{-1}(V)
 \end{aligned}$$

This finishes the proof. \square

Proposition 5.5.3.1.3. Let $R: A \rightarrow B$ 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:

(★) 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

$$(R^{-1}, R^{-1,\otimes}, R_{\sharp}^{-1,\otimes}) : (\mathcal{P}(A), \cup, \emptyset) \rightarrow (\mathcal{P}(B), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} R_{U,V}^{-1,\otimes} : R^{-1}(U) \cup R^{-1}(V) &\xrightarrow{=} R^{-1}(U \cup V), \\ R_{\sharp}^{-1,\otimes} : \emptyset &\xrightarrow{=} \emptyset, \end{aligned}$$

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

$$\left(R^{-1}, R^{-1, \otimes}, R_{\sharp}^{-1, \otimes} \right) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with inclusions

$$\begin{aligned} R_{U,V}^{-1, \otimes} &: R^{-1}(U \cap V) \subset R^{-1}(U) \cap R^{-1}(V), \\ R_{\sharp}^{-1, \otimes} &: R^{-1}(A) \subset B, \end{aligned}$$

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 $R : A \rightarrow B$ 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 5.5.2.1.3](#).

[Item 8](#), *Interaction With Strong Inverse Images II*: This was proved in [Item 8](#) of [Proposition 5.5.2.1.3](#). \square

Proposition 5.5.3.1.4. Let $R : A \rightarrow B$ 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 have⁶⁴

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

4. *Interaction With Composition.* For each pair of composable relations $R: A \rightarrow B$ and $S: B \rightarrow C$, we have⁶⁵

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

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

Item 2, *Functionality II:* Clear.

Item 3, *Interaction With Identities:* This follows from ?? of ??.

Item 4, *Interaction With Composition:* This follows from ?? of ??.

□

5.5.4 Direct Images With Compact Support

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

Definition 5.5.4.1.1. The **direct image with compact support function associated to R** is the function⁶⁶

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

⁶⁴That is, the postcomposition

$$(\chi_A)^{-1}: \text{Rel(pt, } A) \rightarrow \text{Rel(pt, } A)$$

is equal to $\text{id}_{\text{Rel(pt, } A)}$.

⁶⁵That is, we have

$$\begin{array}{ccc} \text{Rel(pt, } C) & \xrightarrow{R^{-1}} & \text{Rel(pt, } B) \\ (S \diamond R)^{-1} = R^{-1} \circ S^{-1}, & \searrow^{(S \diamond R)^{-1}} & \downarrow S^{-1} \\ & & \text{Rel(pt, } A). \end{array}$$

⁶⁶Further Notation: Also written $\forall_R: \mathcal{P}(A) \rightarrow \mathcal{P}(B)$. This notation comes from the fact that the following statements are equivalent, where $b \in B$ and $U \in \mathcal{P}(A)$:

- We have $b \in \forall_R(U)$.
- For each $a \in A$, if $b \in R(a)$, then $a \in U$.

defined by^{67,68}

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

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

Remark 5.5.4.1.2. Identifying subsets of B with relations from pt to B via ?? of ??, 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

$$R_!(U) \stackrel{\text{def}}{=} \text{Ran}_R(U), \quad \begin{array}{ccc} & B & \\ & \nearrow R & \downarrow \\ A & \xrightarrow[U]{\quad} & \text{pt}, \end{array} \quad \text{Ran}_R(U)$$

being explicitly computed by

$$\begin{aligned} R^*(U) &\stackrel{\text{def}}{=} \text{Ran}_R(U) \\ &\cong \int_{a \in A} \text{Hom}_{\{\text{t,f}\}}(R_a^{-2}, U_a^{-1}), \end{aligned}$$

where we have used Item 11 of Proposition 5.2.5.1.1.

⁶⁷Further Terminology: The set $R_!(U)$ is called the **direct image with compact support of U by R** .

⁶⁸We also have

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

see Item 7 of Proposition 5.5.4.1.3.

Proof. We have

$$\begin{aligned}
 \text{Ran}_R(V) &\cong \int_{a \in A} \text{Hom}_{\{\text{t,f}\}}(R_a^{-2}, U_a^{-1}) \\
 &= \left\{ b \in B \mid \int_{a \in A} \text{Hom}_{\{\text{t,f}\}}(R_a^b, U_a^\star) = \text{true} \right\} \\
 &= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } R_a^b = \text{false} \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} (a) \text{ We have } R_a^b = \text{true} \\ (b) \text{ We have } U_a^\star = \text{true} \end{array} \right\} \\
 &= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ at least one of the} \\ \text{following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} 1. \text{ We have } b \notin R(A) \\ 2. \text{ The following conditions hold:} \end{array} \right. \\
 &\quad \left. \begin{array}{l} (a) \text{ We have } b \in R(a) \\ (b) \text{ We have } a \in U \end{array} \right\} \\
 &= \left\{ b \in B \mid \begin{array}{l} \text{for each } a \in A, \text{ if we have} \\ b \in R(a), \text{ then } a \in U \end{array} \right\} \\
 &= \{b \in B \mid R^{-1}(b) \subset U\} \\
 &\stackrel{\text{def}}{=} R^{-1}(U).
 \end{aligned}$$

This finishes the proof. □

Proposition 5.5.4.1.3. Let $R: A \rightarrow B$ 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

$$(R^{-1} \dashv R_!): \quad \mathcal{P}(B) \begin{array}{c} \xrightarrow{R^{-1}} \\ \perp \\ \xleftarrow{R_!} \end{array} \mathcal{P}(A),$$

witnessed by a bijections of sets

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

natural in $U \in \mathcal{P}(A)$ and $V \in \mathcal{P}(B)$, i.e. such that:

(★) The following conditions are equivalent:

- We have $R^{-1}(U) \subset V$;
- We have $U \subset R_!(V)$.

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

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

being equipped with inclusions

$$\begin{aligned} R_{!|U,V}^\otimes: R_!(U) \cup R_!(V) &\subset R_!(U \cup V), \\ R_{!|k}^\otimes: \emptyset &\subset R_!(\emptyset), \end{aligned}$$

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

$$\left(R_!, R_!^\otimes, R_{!|*}^\otimes \right) : (\mathcal{P}(A), \cap, A) \rightarrow (\mathcal{P}(B), \cap, B),$$

being equipped with equalities

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

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 5.5.1.1.3](#). Alternatively, we may prove it directly as follows, with the proof proceeding in the same way as in the case of functions (?? of ??).

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 5.5.4.1.4. Let $R: A \rightarrow B$ be a relation.

1. *Functionality I.* The assignment $R \mapsto R_!$ defines a function

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

2. *Functionality II.* The assignment $R \mapsto R_!$ defines a function

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

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

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

4. *Interaction With Composition.* For each pair of composable relations $R: A \rightarrow B$ and $S: B \rightarrow C$, 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

$$\begin{aligned} (\chi_A)_!(U) &\stackrel{\text{def}}{=} \{a \in A \mid \chi_A^{-1}(a) \subset U\} \\ &\stackrel{\text{def}}{=} \{a \in A \mid \{a\} \subset U\} \\ &= U \end{aligned}$$

for each $U \in \mathcal{P}(A)$. Thus $(\chi_A)_! = \text{id}_{\mathcal{P}(A)}$.

Item 4, Interaction With Composition: Indeed, we have

$$\begin{aligned} (S \diamond R)_!(U) &\stackrel{\text{def}}{=} \{c \in C \mid [S \diamond R]^{-1}(c) \subset U\} \\ &\stackrel{\text{def}}{=} \{c \in C \mid S^{-1}(R^{-1}(c)) \subset U\} \\ &= \{c \in C \mid R^{-1}(c) \subset S_!(U)\} \\ &\stackrel{\text{def}}{=} R_!(S_!(U)) \\ &\stackrel{\text{def}}{=} [R_! \circ S_!](U) \end{aligned}$$

for each $U \in \mathcal{P}(C)$, where we used **Item 2 of Proposition 5.5.4.1.3**, 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

5.5.5 Functoriality of Powersets

Proposition 5.5.5.1.1. The assignment $X \mapsto \mathcal{P}(X)$ defines functors⁶⁹

$$\begin{aligned}\mathcal{P}_*: \text{Rel} &\rightarrow \text{Sets}, \\ \mathcal{P}_{-1}: \text{Rel}^{\text{op}} &\rightarrow \text{Sets}, \\ \mathcal{P}^{-1}: \text{Rel}^{\text{op}} &\rightarrow \text{Sets}, \\ \mathcal{P}_!: \text{Rel} &\rightarrow \text{Sets}\end{aligned}$$

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

$$\begin{aligned}\mathcal{P}_*(R): \mathcal{P}(A) &\rightarrow \mathcal{P}(B), \\ \mathcal{P}_{-1}(R): \mathcal{P}(B) &\rightarrow \mathcal{P}(A), \\ \mathcal{P}^{-1}(R): \mathcal{P}(B) &\rightarrow \mathcal{P}(A), \\ \mathcal{P}_!(R): \mathcal{P}(A) &\rightarrow \mathcal{P}(B)\end{aligned}$$

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 5.5.1.1.1, 5.5.2.1.1, 5.5.3.1.1 and 5.5.4.1.1.

Proof. This follows from Items 3 and 4 of Proposition 5.5.1.1.4, Items 3 and 4 of Proposition 5.5.2.1.4, Items 3 and 4 of Proposition 5.5.3.1.4, and Items 3 and 4 of Proposition 5.5.4.1.4. \square

5.5.6 Functoriality of Powersets: Relations on Powersets

Let A and B be sets and let $R: A \rightarrow B$ be a relation.

⁶⁹The functor $\mathcal{P}_*: \text{Rel} \rightarrow \text{Sets}$ admits a left adjoint; see Item 3 of Proposition 5.3.1.1.2.

Definition 5.5.6.1.1. The **relation on powersets associated to R** is the relation

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

defined by⁷⁰

$$\mathcal{P}(R)_U^V \stackrel{\text{def}}{=} \mathbf{Rel}(\chi_{\text{pt}}, V \diamond R \diamond U)$$

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

Remark 5.5.6.1.2. 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

$$\int^{a \in A} \int^{b \in B} V_b^\star \times R_a^b \times U_\star^a = \text{true}.$$

- There exists some $a \in A$ and some $b \in B$ such that:
 - We have $U_\star^a = \text{true}$;
 - We have $R_a^b = \text{true}$;
 - We have $V_b^\star = \text{true}$.
- There exists some $a \in A$ and some $b \in B$ such that:
 - We have $a \in U$;
 - We have $a \sim_R b$;
 - We have $b \in V$.

Proposition 5.5.6.1.3. The assignment $R \mapsto \mathcal{P}(R)$ defines a functor

$$\mathcal{P} : \mathbf{Rel} \rightarrow \mathbf{Rel}.$$

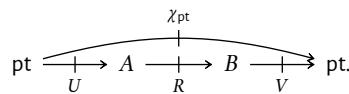
Proof. Omitted. □

5.6 Relative Preorders

5.6.1 The Left Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

Let A and B be sets and let $J : A \rightarrow B$ be a relation.

⁷⁰Illustration:



5.6.1.1 The Left Skew Monoidal Product

Definition 5.6.1.1.1. 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

$$S \triangleleft_J R \stackrel{\text{def}}{=} S \diamond \text{Rift}_J(R), \quad \begin{array}{ccc} A & \xrightarrow{S} & B \\ \text{Rift}_J(R) \swarrow & \downarrow J & \downarrow \\ A & \xrightarrow{R} & B \end{array}$$

- *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 by⁷¹

$$\beta \triangleleft_J \alpha \stackrel{\text{def}}{=} \beta \diamond \text{Rift}_J(\alpha), \quad \begin{array}{ccc} A & \xrightarrow{S} & B \\ \text{Rift}_J(R) \swarrow & \downarrow J & \downarrow \\ A & \xrightarrow{R} & B \\ \text{Rift}_J(\alpha) \downarrow & \downarrow & \downarrow \\ A & \xrightarrow{R'} & B \\ \beta \downarrow & \downarrow & \downarrow \\ A & \xrightarrow{S'} & B \end{array}$$

for each $\beta \in \text{Hom}_{\mathbf{Rel}(A,B)}(S, S')$ and each $\alpha \in \text{Hom}_{\mathbf{Rel}(A,B)}(R, R')$.

5.6.1.2 The Left Skew Monoidal Unit

Definition 5.6.1.2.1. The **left J -skew monoidal unit of $\mathbf{Rel}(A, B)$** is the functor

$$\mathbb{1}_{\triangleleft}^{\mathbf{Rel}(A,B)} : \text{pt} \rightarrow \mathbf{Rel}(A, B)$$

picking the object

$$\mathbb{1}_{\triangleleft}^{\mathbf{Rel}(A,B)} \stackrel{\text{def}}{=} J$$

of $\mathbf{Rel}(A, B)$.

⁷¹Since $\mathbf{Rel}(A, B)$ is posetal, this is to say that if $S \subset S'$ and $R \subset R'$, then $S \triangleleft_J R \subset S' \triangleleft_J R'$.

5.6.1.3 The Left Skew Associators

Definition 5.6.1.3.1. The **left J -skew associator of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\alpha^{\mathbf{Rel}(A, B), \triangleleft} : \triangleleft_J \circ (\triangleleft_J \times \text{id}) \Longrightarrow \triangleleft_J \circ (\text{id} \times \triangleleft_J),$$

whose component

$$\alpha_{T, S, R}^{\mathbf{Rel}(A, B), \triangleleft} : \underbrace{(T \triangleleft_J S) \triangleleft_J R}_{\stackrel{\text{def}}{=} T \diamond \text{Rift}_J(S) \diamond \text{Rift}_J(R)} \hookrightarrow \underbrace{T \triangleleft_J (S \triangleleft_J R)}_{\stackrel{\text{def}}{=} T \diamond \text{Rift}_J(S \diamond \text{Rift}_J(R))}$$

at (T, S, R) is given by

$$\alpha_{T, S, R}^{\mathbf{Rel}(A, B), \triangleleft} \stackrel{\text{def}}{=} \text{id}_T \diamond \gamma,$$

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 $\epsilon : J \diamond \text{Rift}_J \Longrightarrow \text{id}_{\mathbf{Rel}(A, B)}$ is the counit of the adjunction $J_* \dashv \text{Rift}_J$.

5.6.1.4 The Left Skew Left Unitors

Definition 5.6.1.4.1. The **left J -skew left unitor of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\lambda^{\mathbf{Rel}(A, B), \triangleleft} : \triangleleft_J \circ (\mathbb{1}_{\triangleleft}^{\mathbf{Rel}(A, B)} \times \text{id}) \Longrightarrow \text{id},$$

whose component

$$\lambda_R^{\mathbf{Rel}(A, B), \triangleleft} : \underbrace{J \triangleleft_J R}_{\stackrel{\text{def}}{=} J \diamond \text{Rift}_J(R)} \hookrightarrow R$$

at R is given by

$$\lambda_R^{\mathbf{Rel}(A, B), \triangleleft} \stackrel{\text{def}}{=} \epsilon_R,$$

where $\epsilon : J \diamond \text{Rift}_J \Longrightarrow \text{id}_{\mathbf{Rel}(A, B)}$ is the counit of the adjunction $J_* \dashv \text{Rift}_J$.

5.6.1.5 The Left Skew Right Unitors

Definition 5.6.1.5.1. The **left J -skew right unitor of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\rho^{\mathbf{Rel}(A, B), \triangleleft} : \text{id} \Longrightarrow \triangleleft_J \circ (\text{id} \times \mathbb{1}_{\triangleleft}^{\mathbf{Rel}(A, B)}),$$

whose component

$$\rho_R^{\mathbf{Rel}(A,B),\triangleleft} : R \hookrightarrow \underbrace{R \triangleleft_J J}_{\stackrel{\text{def}}{=} R \diamond \text{Rift}_J(J)}$$

at R is given by

$$\rho_R^{\mathbf{Rel}(A,B),\triangleleft} \stackrel{\text{def}}{=} \text{id}_R \star \sigma,$$

where $\sigma : \text{id}_A \implies \text{Rift}_J(J)$ is the universal transformation included in the data of the right Kan lift $\text{Rift}_J(J)$.

5.6.1.6 The Left Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

Definition 5.6.1.6.1. The **left J -skew monoidal category of relations from A to B** is the left skew monoidal category

$$\left(\mathbf{Rel}(A, B), \triangleleft_J, \mu_{\triangleleft}^{\mathbf{Rel}(A,B)}, \alpha^{\mathbf{Rel}(A,B),\triangleleft}, \lambda^{\mathbf{Rel}(A,B),\triangleleft}, \rho^{\mathbf{Rel}(A,B),\triangleleft} \right)$$

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 5.1.1.2](#);
- *The Skew Monoidal Product.* The functor \triangleleft_J of [Definition 5.6.1.1.1](#);
- *The Skew Monoidal Unit.* The functor $\mu_{\triangleleft}^{\mathbf{Rel}(A,B)}$ of [Definition 5.6.1.2.1](#);
- *The Skew Associators.* The natural transformation $\alpha^{\mathbf{Rel}(A,B),\triangleleft}$ of [Definition 5.6.1.3.1](#);
- *The Skew Left Unitors.* The natural transformation $\lambda^{\mathbf{Rel}(A,B),\triangleleft}$ of [Definition 5.6.1.4.1](#);
- *The Skew Right Unitors.* The natural transformation $\rho^{\mathbf{Rel}(A,B),\triangleleft}$ of [Definition 5.6.1.5.1](#).

5.6.2 Left Relative Preorders

Let A and B be sets and let $J : A \rightarrow B$ be a relation.

Definition 5.6.2.1.1. A **left J -relative preorder from A to B** is equivalently:

- An \mathbb{E}_1 -skew monoid in $(N_{\bullet}(\mathbf{Rel}(A, B)), \triangleleft_J, J)$;
- A skew monoid in $(\mathbf{Rel}(A, B), \triangleleft_J, J)$.

Remark 5.6.2.1.2. In detail, a **left J -relative preorder** (R, μ_R, η_R) **from A to B** consists of

- *The Underlying Relation.* A relation

$$R : A \rightarrow B,$$

called the **underlying relation of** (R, μ_R, η_R) ;

- *The Multiplication Inclusion.* An inclusion of relations

$$\mu_R: R \triangleleft J \subset R,$$

called the **multiplication** of (R, μ_R, η_R) ;

- *The Unit Inclusion.* An inclusion of relations

$$\eta_R: J \subset R,$$

called the **unit** of (R, μ_R, η_R) .

Remark 5.6.2.1.3. In other words, a **left J -relative preorder from A to B** is a relation $R: A \rightarrow B$ from A to B satisfying the following conditions:

1. *J -Transitivity.* For each $a \in A$ and each $c \in B$, we have

$$a \sim_{R \diamond \text{Rift}_J(R)} c$$

i.e. the following condition is satisfied:⁷²

- (★) If there exists some $b \in A$ such that:

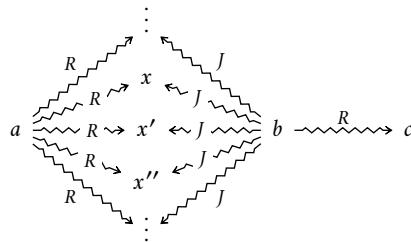
- We have $a \sim_{\text{Rift}_J(R)} b$, i.e. for each $x \in B$, if $b \sim_J x$, then $a \sim_R x$;⁷³
- We have $b \sim_R c$;

then $a \sim_R c$.

2. *J -Unitality.* For each $a \in A$ and each $b \in B$, the following condition is satisfied:

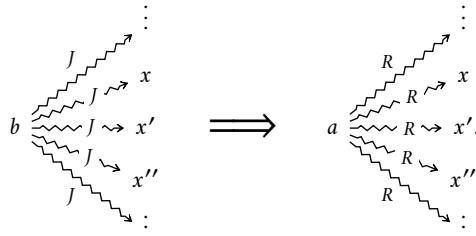
- (★) If $a \sim_J b$, then $a \sim_R b$.

⁷² Illustration: If we have



then $a \sim_R c$.

⁷³ Illustration:



5.6.3 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.

5.6.3.1 The Right Skew Monoidal Product

Definition 5.6.3.1.1. The **right J -skew monoidal product of $\mathbf{Rel}(A, B)$** is the functor

$$\triangleright_J: \mathbf{Rel}(A, B) \times \mathbf{Rel}(A, B) \rightarrow \mathbf{Rel}(A, B)$$

where

- *Action on Objects.* For each $R, S \in \text{Obj}(\mathbf{Rel}(A, B))$, we have

$$S \triangleright_J R \stackrel{\text{def}}{=} \text{Ran}_J(S) \diamond R;$$

- *Action on Morphisms.* For each $R, S, R', S' \in \text{Obj}(\mathbf{Rel}(A, B))$, 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 by⁷⁴

$$\beta \triangleright_J \alpha \stackrel{\text{def}}{=} \text{Ran}_J(\beta) \diamond \alpha,$$

for each $\beta \in \text{Hom}_{\mathbf{Rel}(A,B)}(S, S')$ and each $\alpha \in \text{Hom}_{\mathbf{Rel}(A,B)}(R, R')$.

5.6.3.2 The Right Skew Monoidal Unit

Definition 5.6.3.2.1. The **right J -skew monoidal unit of $\mathbf{Rel}(A, B)$** is the functor

$$\mathbb{1}_{\triangleright}^{\mathbf{Rel}(A,B)}: \text{pt} \rightarrow \mathbf{Rel}(A, B)$$

picking the object

$$\mathbb{1}_{\triangleright}^{\mathbf{Rel}(A,B)} \stackrel{\text{def}}{=} J$$

of $\mathbf{Rel}(A, B)$.

⁷⁴Since $\mathbf{Rel}(A, B)$ is posetal, this is to say that if $S \subset S'$ and $R \subset R'$, then $S \triangleright_J R \subset S' \triangleright_J R'$.

5.6.3.3 The Right Skew Associators

Definition 5.6.3.3.1. The **right J -skew associator of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\alpha^{\mathbf{Rel}(A,B),\triangleright} : \triangleright_J \circ (\text{id} \times \triangleright_J) \Longrightarrow \triangleright_J \circ (\triangleright_J \times \text{id}),$$

whose component

$$\alpha_{T,S,R}^{\mathbf{Rel}(A,B),\triangleright} : \underbrace{T \triangleright_J (S \triangleright_J R)}_{\stackrel{\text{def}}{=} \text{Ran}_J(T) \diamond (\text{Ran}_J(S) \diamond R)} \hookrightarrow \underbrace{(T \triangleright_J S) \triangleright_J R}_{\stackrel{\text{def}}{=} \text{Ran}_J(\text{Ran}_J(T) \diamond S) \diamond R}$$

at (T, S, R) is given by

$$\alpha_{T,S,R}^{\mathbf{Rel}(A,B),\triangleright} \stackrel{\text{def}}{=} \gamma \diamond \text{id}_R,$$

where

$$\gamma : \text{Ran}_J(T) \diamond \text{Ran}_J(S) \hookrightarrow \text{Ran}_J(\text{Ran}_J(T) \diamond S)$$

is the inclusion adjunct to the inclusion

$$\text{id}_{\text{Ran}_J(T)} \diamond \epsilon_S : \underbrace{\text{Ran}_J(T) \diamond \text{Ran}_J(S) \diamond J}_{\stackrel{\text{def}}{=} J^*(\text{Ran}_J(T) \diamond \text{Ran}_J(S))} \hookrightarrow \text{Ran}_J(T) \diamond S$$

under the adjunction $J^* \dashv \text{Ran}_J$, where $\epsilon : \text{Ran}_J \diamond J \Longrightarrow \text{id}_{\mathbf{Rel}(A,B)}$ is the counit of the adjunction $J^* \dashv \text{Ran}_J$.

5.6.3.4 The Right Skew Left Unitors

Definition 5.6.3.4.1. The **right J -skew left unit of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\lambda^{\mathbf{Rel}(A,B),\triangleright} : \text{id} \Longrightarrow \triangleright_J \circ (\text{id} \times \mathbb{1}_{\triangleright}^{\mathbf{Rel}(A,B)} \times \text{id}),$$

whose component

$$\lambda_R^{\mathbf{Rel}(A,B),\triangleright} : R \hookrightarrow \underbrace{J \triangleright_J R}_{\stackrel{\text{def}}{=} \text{Ran}_J(J) \diamond R}$$

at R is given by

$$\lambda_R^{\mathbf{Rel}(A,B),\triangleright} \stackrel{\text{def}}{=} \sigma \diamond \text{id}_R,$$

where $\sigma : \text{id}_B \Longrightarrow \text{Ran}_J(J)$ is the universal transformation included in the data of the right Kan extension $\text{Ran}_J(J)$.

5.6.3.5 The Right Skew Right Unitors

Definition 5.6.3.5.1. The **right J -skew right unit of $\mathbf{Rel}(A, B)$** is the natural transformation

$$\rho^{\mathbf{Rel}(A,B),\triangleright} : \triangleright_J \circ (\text{id} \times \mathbb{1}_{\triangleright}^{\mathbf{Rel}(A,B)}) \Longrightarrow \text{id},$$

whose component

$$\rho_S^{\mathbf{Rel}(A,B),\triangleright} : \underbrace{S \triangleright_J J}_{\stackrel{\text{def}}{=} \text{Ran}_J(S) \diamond J} \hookrightarrow S$$

at S is given by

$$\rho_S^{\mathbf{Rel}(A,B),\triangleright} \stackrel{\text{def}}{=} \epsilon_R,$$

where $\epsilon : \text{Ran}_J \diamond J \Rightarrow \text{id}_{\mathbf{Rel}(A,B)}$ is the counit of the adjunction $J^* \dashv \text{Ran}_J$.

5.6.3.6 The Right Skew Monoidal Structure on $\mathbf{Rel}(A, B)$

Definition 5.6.3.6.1. The **right J -skew monoidal category of functors from A to B** is the right skew monoidal category

$$\left(\mathbf{Rel}(A, B), \triangleright_J, \mu_{\triangleright}^{\mathbf{Rel}(A,B)}, \alpha^{\mathbf{Rel}(A,B),\triangleright}, \lambda^{\mathbf{Rel}(A,B),\triangleright}, \rho^{\mathbf{Rel}(A,B),\triangleright} \right)$$

consisting of

- *The Underlying Category.* The posetal category associated to the poset $\mathbf{Rel}(A, B)$ of relations from A to B of Item 2 of Definition 5.1.1.1.2;
- *The Skew Monoidal Product.* The functor \triangleright_J of Definition 5.6.3.1.1;
- *The Skew Monoidal Unit.* The functor $\mu_{\triangleright}^{\mathbf{Rel}(A,B)}$ of Definition 5.6.3.2.1;
- *The Skew Associators.* The natural transformation $\alpha^{\mathbf{Rel}(A,B),\triangleright}$ of Definition 5.6.3.3.1;
- *The Skew Left Unitors.* The natural transformation $\lambda^{\mathbf{Rel}(A,B),\triangleright}$ of Definition 5.6.3.4.1;
- *The Skew Right Unitors.* The natural transformation $\rho^{\mathbf{Rel}(A,B),\triangleright}$ of Definition 5.6.3.5.1.

5.6.4 Right Relative Preorders

Let A and B be sets and let $J : A \rightarrow B$ be a relation.

Definition 5.6.4.1.1. A **right J -relative preorder from A to B** is equivalently:

- An \mathbb{E}_1 -skew monoid in $(N_*(\mathbf{Rel}(A, B)), \triangleright_J, J)$;
- A skew monoid in $(\mathbf{Rel}(A, B), \triangleright_J, J)$.

Remark 5.6.4.1.2. In detail, a **right J -relative preorder** (R, μ_R, η_R) **from A to B** consists of

- *The Underlying Relation.* A relation

$$R : A \rightarrow B,$$

called the **underlying relation of** (R, μ_R, η_R) ;

- *The Multiplication Inclusion.* An inclusion of relations

$$\mu_R: R \triangleright_J R \subset R,$$

called the **multiplication** of (R, μ_R, η_R) ;

- *The Unit Inclusion.* An inclusion of relations

$$\eta_R: J \subset R,$$

called the **unit** of (R, μ_R, η_R) .

Remark 5.6.4.1.3. In other words, a **right J -relative preorder from A to B** is a relation $R: A \rightarrow B$ from A to B satisfying the following conditions:

1. *J -Transitivity.* For each $a \in A$ and each $c \in B$, we have

$$a \sim_{\text{Ran}_J(R) \diamond R} c,$$

i.e. the following condition is satisfied:⁷⁵

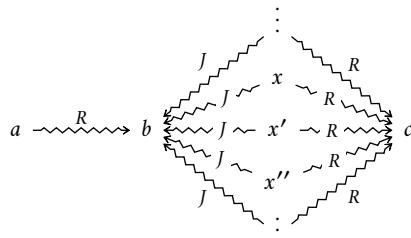
- (★) If there exists some $b \in B$ such that:

- We have $a \sim_R b$;
 - We have $b \sim_{\text{Ran}_J(R)} c$, i.e. for each $x \in A$, if $x \sim_J b$, then $x \sim_R c$;⁷⁶
- then $a \sim_R c$.

2. *J -Unitality.* For each $a \in A$ and each $b \in B$, the following condition is satisfied:

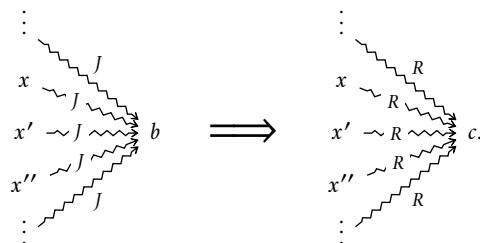
- (★) If $a \sim_J b$, then $a \sim_R b$.

⁷⁵Illustration: If we have



then $a \sim_R c$.

⁷⁶Illustration:



Appendices

5.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets
5. Relations
6. Spans
7. Posets

Indexed and Fibred Sets

7. Indexed Sets
8. Fibred Sets
9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories
12. Types of Morphisms in Categories
13. Adjunctions and the Yoneda Lemma
14. Constructions With Categories
15. Profunctors
16. Cartesian Closed Categories
17. Kan Extensions

Bicategories

18. Bicategories
19. Internal Adjunctions

Internal Category Theory

20. Internal Categories

33. Hypersemirings and Hyperrings

Cyclic Stuff

21. The Cycle Category

34. Quantales

Cubical Stuff

22. The Cube Category

Near-Rings

Globular Stuff

23. The Globe Category

35. Near-Semirings

Cellular Stuff

24. The Cell Category

Real Analysis

Monoids

25. Monoids

37. Real Analysis in One Variable

26. Constructions With Monoids

38. Real Analysis in Several Variables

Monoids With Zero

27. Monoids With Zero

Measure Theory

28. Constructions With Monoids With
Zero

39. Measurable Spaces

Groups

29. Groups

40. Measures and Integration

30. Constructions With Groups

Probability Theory

Hyper Algebra

31. Hypermonoids

40. Probability Theory

32. Hypergroups

Stochastic Analysis

41. Stochastic Processes, Martingales,
and Brownian Motion

42. Itô Calculus

43. Stochastic Differential Equations

Differential Geometry

44. Topological and Smooth Manifolds

Schemes

45. Schemes

5.2 Other Chapters

Sets	Cyclic Stuff
1. Sets	21. The Cycle Category
2. Constructions With Sets	Cubical Stuff
3. Pointed Sets	22. The Cube Category
4. Tensor Products of Pointed Sets	Globular Stuff
5. Relations	23. The Globe Category
6. Spans	Cellular Stuff
7. Posets	24. The Cell Category
Indexed and Fibred Sets	Monoids
7. Indexed Sets	25. Monoids
8. Fibred Sets	26. Constructions With Monoids
9. Un/Straightening for Indexed and Fibred Sets	Monoids With Zero
Category Theory	27. Monoids With Zero
11. Categories	28. Constructions With Monoids With Zero
12. Types of Morphisms in Categories	Groups
13. Adjunctions and the Yoneda Lemma	29. Groups
14. Constructions With Categories	30. Constructions With Groups
15. Profunctors	Hyper Algebra
16. Cartesian Closed Categories	31. Hypermonoids
17. Kan Extensions	32. Hypergroups
Bicategories	33. Hypersemirings and Hyperrings
18. Bicategories	34. Quantales
19. Internal Adjunctions	Near-Rings
Internal Category Theory	35. Near-Semirings
20. Internal Categories	36. Near-Rings
	Real Analysis
	37. Real Analysis in One Variable

- 38. Real Analysis in Several Variables
- Measure Theory
- 39. Measurable Spaces
- 40. Measures and Integration
- Probability Theory
- 40. Probability Theory
- Stochastic Analysis
- 41. Stochastic Processes, Martingales, and Brownian Motion
- 42. Itô Calculus
- 43. Stochastic Differential Equations
- Differential Geometry
- 44. Topological and Smooth Manifolds
- Schemes
- 45. Schemes

Chapter 6

Spans

This chapter contains some material about spans. Notably, we discuss and explore:

1. The basic definitions around spans ([Section 6.1](#));
2. The relation between spans and functions ([Proposition 6.8.1.1.1](#));
3. The relation between spans and relations ([Propositions 6.8.2.2.1](#) and [6.8.3.1.1](#) and [Remark 6.8.5.1.1](#)).
4. “Hyperpointed sets” (??). I don’t know why I wrote this...

TODO:

1. https://www.sciencedirect.com/science/article/pii/0022404994900094?ref=pdf_download&fr=RR-2&rr=834107b75c906aa4
2. <https://arxiv.org/abs/1605.08100>
3. <https://arxiv.org/abs/1603.08181>
4. <https://arxiv.org/abs/1601.02307>
5. <https://arxiv.org/abs/1507.01460>
6. <https://arxiv.org/abs/1506.08870>
7. <https://arxiv.org/abs/1505.00048>
8. <https://arxiv.org/abs/1501.07592>
9. <https://arxiv.org/abs/1501.04664>
10. <https://arxiv.org/abs/1501.00792>
11. <https://arxiv.org/abs/1412.6560>
12. <https://arxiv.org/abs/1412.0212>

13. <https://arxiv.org/abs/1409.0837>
14. <https://arxiv.org/abs/1408.5220>
15. <https://arxiv.org/abs/1308.6548>
16. <https://arxiv.org/abs/1304.0219>
17. <https://arxiv.org/abs/1210.8192>
18. <https://arxiv.org/abs/1210.1433>
19. <https://arxiv.org/abs/1201.3789>
20. <https://arxiv.org/abs/1112.0560>
21. <https://arxiv.org/abs/1109.1598>
22. <https://arxiv.org/abs/1101.4594>
23. <https://arxiv.org/abs/1012.6001>
24. <https://arxiv.org/abs/1011.3243>
25. <https://arxiv.org/abs/0910.2996>
26. <https://arxiv.org/abs/0810.2361>
27. <https://arxiv.org/abs/0803.2429>
28. <https://arxiv.org/abs/0712.2525>
29. <https://arxiv.org/abs/0706.1286>
30. <https://arxiv.org/abs/math/0611930>
31. <https://arxiv.org/abs/2311.15342>
32. <https://arxiv.org/abs/2310.19428>
33. <https://arxiv.org/abs/2309.08084>
34. <https://arxiv.org/abs/2308.01662>
35. <https://arxiv.org/abs/2301.11860>
36. <https://arxiv.org/abs/2301.01199>
37. <https://arxiv.org/abs/2212.09060>
38. <https://arxiv.org/abs/2208.07183>
39. <https://arxiv.org/abs/2205.06892>

40. <https://arxiv.org/abs/2203.16179>
41. <https://arxiv.org/abs/2201.09551>
42. <https://arxiv.org/abs/2112.04599>
43. <https://arxiv.org/abs/2111.10968>
44. <https://arxiv.org/abs/2107.07621>
45. <https://arxiv.org/abs/2106.14743>
46. <https://arxiv.org/abs/2105.14654>
47. <https://arxiv.org/abs/2102.08051>
48. <https://arxiv.org/abs/2102.04386>
49. <https://arxiv.org/abs/2101.06734>
50. <https://arxiv.org/abs/2011.11042>
51. <https://arxiv.org/abs/2010.15722>
52. <https://arxiv.org/abs/2006.10375>
53. <https://arxiv.org/abs/2006.10375>
54. <https://arxiv.org/abs/2005.10496>
55. <https://arxiv.org/abs/2003.11541>
56. <https://arxiv.org/abs/2002.10334>
57. <https://arxiv.org/abs/1909.00069>
58. <https://arxiv.org/abs/1907.02695>
59. <https://arxiv.org/abs/1905.06671>
60. define a relational span
61. consider giving Ran and Rift their dedicated sections on the relations chapter,
perhaps together with the other sections on co/limits
62. <https://arxiv.org/abs/1710.02742>
63. <https://arxiv.org/search/math?searchtype=author&query=Walker,+Charles>
64. <https://arxiv.org/abs/1706.09575>
65. <https://arxiv.org/abs/1710.01465>

-
- 66. fibred categories: <https://arxiv.org/abs/1806.02376>
 - 67. <https://arxiv.org/abs/1806.10477v2>
 - 68. double categorical limits in $\mathbf{Rel}^{\mathrm{dbl}}$
 - 69. double categorical limits in $\mathbf{Span}^{\mathrm{dbl}}$
 - 70. internal adjoint equivalences in **Rel**
 - 71. internal adjoint equivalences in \mathbf{Span}
 - 72. 2-categorical limits in **Rel**;
 - 73. morphism of internal adjunctions in **Rel**;
 - 74. morphism of internal adjunctions in \mathbf{Span} ;
 - 75. morphism of co/monads in \mathbf{Span} ;
 - 76. What is $\mathrm{Adj}(\mathbf{Span}(A, B))$?
 - 77. monoids, comonoids, pseudomonoids, etc. in \mathbf{Span} .
 - 78. write down the dumb intuition about spans inducing morphisms $\mathrm{Sets}(S, A) \rightarrow \mathrm{Sets}(S, B)$ instead of $\mathcal{P}(A) \rightarrow \mathcal{P}(B)$ from the similarity between

$$S \rightarrow A \times B$$

and

$$A \times B \rightarrow \{t, f\}.$$

This intuition is justified by taking $A = \mathrm{pt}$ or $B = \mathrm{pt}$.

- 79. What about using the direct image with compact support in $g(f^{-1}(a))$?
- 80. Monads in \mathbf{Span} | develop this in the level of morphisms too
- 81. Comonads in \mathbf{Span} are spans whose legs are equal | develop this in the level of morphisms too
- 82. Does \mathbf{Span} have an internal **Hom**?
- 83. Examples of spans
- 84. Functional and total spans
- 85. closed symmetric monoidal category of spans
- 86. double category of relations
- 87. collage of a span

-
88. equivalence spans?
89. functoriality of powersets for spans
90. Is Span a closed bicategory?
91. skew monoidal structure on $\text{Span}(A, B)$
92. Adjunctions in Span
93. Isomorphisms in Span
94. Equivalences in Span
95. Interaction between the above notions in Span vs. in **Rel** via the comparison functors
96. $\text{Hom}_C(S, A) \times \text{Hom}_C(f^*(S), A)$.
97. Proof of non-existence of left Kan extensions/lifts in **Rel** (when do these exist btw?)
98. description of unitors and associators of span
99. add intuition for spans as relations with multiple witnesses:

(a) Given a span $A \xleftarrow{f} S \xrightarrow{g} B$, we have a functor

$$\text{St}(S) : (A \times B)_{\text{disc}} \rightarrow \text{Sets}$$

given by

$$\begin{aligned} [\text{St}(S)](a, b) &\stackrel{\text{def}}{=} \text{St}(S)_{ab} \\ &\stackrel{\text{def}}{=} \{s \in S \mid f(s) = a \text{ and } g(s) = b\}. \end{aligned}$$

(b) Given a functor

$$S : (A \times B)_{\text{disc}} \rightarrow \text{Sets},$$

we have a map of sets

$$\text{Un}(S) : \coprod_{(a,b) \in A \times B} S(a, b) \rightarrow A \times B,$$

determining a span from A to B .

- (c) How do these interact with left/right Kan extensions/lifts?
- (d) Un/straightening for spans of categories: assignment $(a, b) \mapsto \text{Wit}_S(a, b)$.
- (e) Fix the TODO below

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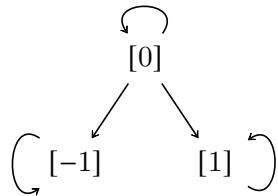
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6.1 Spans

6.1.1 The Walking Span

Definition 6.1.1.1. The **walking span** is the category Λ that looks like this:



6.1.2 Spans

Let A and B be sets.

Definition 6.1.2.1.1. A **span from A to B** ¹ is a functor $F: \Lambda \rightarrow \text{Sets}$ such that

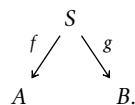
$$\begin{aligned} F([-1]) &= A, \\ F([1]) &= B. \end{aligned}$$

Remark 6.1.2.1.2. In detail, a **span from A to B** is a triple (S, f, g) consisting of^{2,3}

- *The Underlying Set.* A set S , called the **underlying set of (S, f, g)** ;
- *The Legs.* A pair of functions $f: S \rightarrow A$ and $g: S \rightarrow B$.

¹Further Terminology: Also called a **roof from A to B** or a **correspondence from A to B** .

²Picture:



³Every span (S, f, g) from A to B determines in particular a relation $R: A \nrightarrow B$ via

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

i.e. where $R(a) = g(f^{-1}(a))$ for each $a \in A$; see [Proposition 6.8.2.2.1](#).

Remark 6.1.2.1.3. A span

$$\begin{array}{ccc} & S & \\ f \swarrow & & \searrow g \\ A & & B. \end{array}$$

from A to B may be thought of as a relation from A to B which can relate an element $a \in A$ to an element $b \in B$ in multiple ways via f and g , with the “set of witnesses of $a \sim_S b$ ” being given by

$$\text{Wit}_S(a, b) \stackrel{\text{def}}{=} \{s \in S \mid a = f(s) \text{ and } g(s) = b\}.$$

This analogy is made precise by [Remark 6.8.5.1.1](#) and [Section 6.7](#).

6.1.3 Morphisms of Spans

Definition 6.1.3.1.1. A **morphism of spans from** (R, f_1, g_1) **to** (S, f_2, g_2) ⁴ is a natural transformation $(R, f_1, g_1) \Rightarrow (S, f_2, g_2)$.

Remark 6.1.3.1.2. In detail, a **morphism of spans from** (R, f_1, g_1) **to** (S, f_2, g_2) is a function $\phi: R \rightarrow S$ making the diagram⁵

$$\begin{array}{ccccc} & R & & S & \\ & \swarrow f_1 & \downarrow \phi & \searrow g_2 & \\ A & & B & & A \\ & \parallel & \parallel & \parallel & \parallel \\ & & & & B. \end{array}$$

commute.

6.1.4 Functional Spans

Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B \right)$ be a span.

⁴Further Terminology: Also called a **morphism of roofs from** (R, f_1, g_1) **to** (S, f_2, g_2) or a **morphism of correspondences from** (R, f_1, g_1) **to** (S, f_2, g_2) .

⁵Alternative Picture:

$$\begin{array}{ccccc} & R & & B & \\ & \swarrow f_1 & \downarrow \phi & \searrow g_1 & \\ A & & \phi & & B. \\ & \uparrow f_2 & \downarrow & \uparrow g_2 & \\ & & S & & \end{array}$$

Definition 6.1.4.1.1. The span λ is **functional** if f the following equivalent conditions are satisfied:

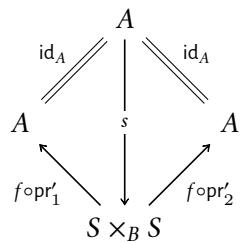
1. The associated relation $g \circ f^{-1}$ of λ is functional.
 2. For each $s, t \in S$, if $f(s) = f(t)$, then $g(s) = g(t)$.
 3. this “ f -relative injectivity” condition is the same as being a monomorphism/monoid/whatever in nice category | maybe this is the same as being a skew monoid in $\text{Span}(A, B)$ or something?

Definition 6.1.4.1.2. The span λ is **total** iff f is surjective.

Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B \right)$ be a span. A morphism of spans from id_A to $\lambda \diamond \lambda^\dagger$ is a morphism

$$s: A \rightarrow S \times_B S$$

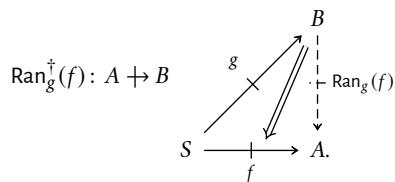
making the diagram



⁶Here we could perhaps also use the direct image with compact support $g_!$ of g (see ??) instead of the usual direct image, although the expression for $g_! \left(f^{-1}(a) \right)$ seems a bit weird. It can also actually be given as a right Kan extension (?? of ??):

$$\begin{aligned}
g_!(f^{-1}(a)) &= g_!(\{s \in S \mid f(s) = a\}) \\
&= \left\{ b \in B \mid g^{-1}(b) \subset \{s \in S \mid f(s) = a\} \right\} \\
&= \{b \in B \mid \text{for each } s \in S, \text{ if } g(s) = b, \text{ then } f(s) = a\} \\
&= [\text{Ran}_g^\dagger(f)](a)
\end{aligned}$$

as in the diagram



commute, where $S \times_B S$ is the pullback

$$\begin{array}{ccc} S \times_B S & \longrightarrow & S \\ \downarrow \lrcorner & & \downarrow g \\ S \times_B S \cong \{(s, t) \in S \times S \mid g(s) = g(t)\} & & \\ \downarrow & & \downarrow g \\ S & \xrightarrow{g} & B \end{array}$$

of S with itself along g . In particular, $\text{pr}_1 \circ s$ and $\text{pr}_2 \circ s$ are both left-inverses/retractions for f , i.e. we have

$$\begin{aligned} (\text{pr}_1 \circ s) \circ f &\cong \text{id}_A, \\ (\text{pr}_2 \circ s) \circ f &\cong \text{id}_A. \end{aligned}$$

Thus, by ?? of ??, f is injective if $A \neq \emptyset$.

6.1.5 Total Spans

6.2 Categories of Spans

6.2.1 The Category of Spans Between Two Sets

Let A and B be sets.

Definition 6.2.1.1.1. The **category of spans from A to B** is the category $\text{Span}(A, B)$ defined by

$$\text{Span}(A, B) \stackrel{\text{def}}{=} \text{Fun}(\Lambda, \text{Sets}) \underset{\text{ev}_{[-1]}, \text{Sets}, [A]}{\times} \text{pt}_{[B], \text{Sets}, \text{ev}_{[1]}} \times \text{Fun}(\Lambda, \text{Sets}),$$

as in the diagram

$$\begin{array}{ccccc} & \text{Span}(A, B) & & & \\ & \searrow \vee & \swarrow & & \\ & \text{Fun}(\Lambda, \text{Sets}) \times_{\text{Sets}} \text{pt} & & \text{pt} \times_{\text{Sets}} \text{Fun}(\Lambda, \text{Sets}) & \\ & \searrow \vee & \swarrow & & \searrow \vee \\ & \text{Fun}(\Lambda, \text{Sets}) & & \text{pt} & & \text{Fun}(\Lambda, \text{Sets}). \\ & \searrow \text{ev}_{[-1]} & & \searrow [A] & \searrow [B] & \searrow \text{ev}_{[1]} \\ & \text{Sets} & & \text{Sets} & \text{Sets} & \text{Sets} \end{array}$$

Remark 6.2.1.1.2. In detail, the **category of spans from A to B** is the category $\text{Span}(A, B)$ where

- *Objects.* The objects of $\text{Span}(A, B)$ are spans from A to B ;
- *Morphisms.* The morphism of $\text{Span}(A, B)$ are morphisms of spans;
- *Identities.* The unit map

$$\mu_{(S,f,g)}^{\text{Span}(A,B)} : \text{pt} \rightarrow \text{Hom}_{\text{Span}(A,B)}((S,f,g), (S,f,g))$$

of $\text{Span}(A, B)$ at (S, f, g) is defined by⁷

$$\text{id}_{(S,f,g)}^{\text{Span}(A,B)} \stackrel{\text{def}}{=} \text{id}_S;$$

- *Composition.* The composition map

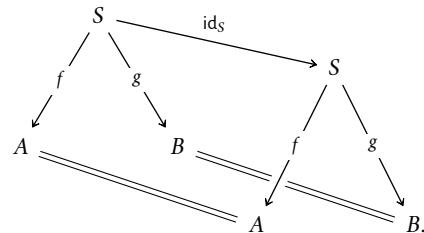
$$\circ_{R,S,T}^{\text{Span}(A,B)} : \text{Hom}_{\text{Span}(A,B)}(S, T) \times \text{Hom}_{\text{Span}(A,B)}(R, S) \rightarrow \text{Hom}_{\text{Span}(A,B)}(R, T)$$

of $\text{Span}(A, B)$ at $((R, f_1, g_1), (S, f_2, g_2), (T, f_3, g_3))$ is defined by⁸

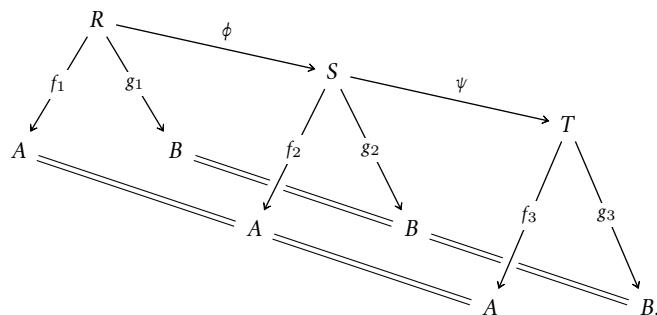
$$\psi \circ_{R,S,T}^{\text{Span}(A,B)} \phi \stackrel{\text{def}}{=} \psi \circ \phi.$$

Proposition 6.2.1.1.3. Let A and B be sets.

⁷Picture:



⁸Picture:



1. As a Pullback. We have an isomorphism of categories

$$\begin{array}{ccc} \text{Span}(A, B) & \longrightarrow & \text{Sets}_{/B} \\ \downarrow & \lrcorner & \downarrow \text{忘} \\ \text{Sets}_{/A} & \xrightarrow{\quad \text{忘} \quad} & \text{Sets}. \end{array}$$

Proof. Item 1, As a Pullback: In detail, the pullback $\text{Sets}_{/A} \times_{\text{Sets}} \text{Sets}_{/B}$ is the category where

- *Objects.* The objects of $\text{Sets}_{/A} \times_{\text{Sets}} \text{Sets}_{/B}$ consist of pairs $((S, f), (S', g))$ of objects of Sets consisting of
 - A pair (S, f) in $\text{Obj}(\text{Sets}_{/A})$ consisting of a set S and a map $f: S \rightarrow A$;
 - A pair (S', g) in $\text{Obj}(\text{Sets}_{/B})$ consisting of a set S' and a map $g: S' \rightarrow B$;

such that

$$\underbrace{\text{忘}(S, f)}_{\stackrel{\text{def}}{=} S} = \underbrace{\text{忘}(S', g)}_{\stackrel{\text{def}}{=} S'}.$$

Thus the objects of $\text{Sets}_{/A} \times_{\text{Sets}} \text{Sets}_{/B}$ are the same as spans from A to B .

- *Morphisms.* A morphism of $\text{Sets}_{/A} \times_{\text{Sets}} \text{Sets}_{/B}$ from $((S, f), (S', g))$ to $((S'', f'), (S''', g'))$ consists of a pair of morphisms

$$\begin{aligned} \phi: S &\rightarrow S' \\ \psi: S &\rightarrow S' \end{aligned}$$

such that the diagrams

$$\begin{array}{ccc} S & \xrightarrow{\phi} & S' \\ f \searrow & & \swarrow f' \\ & A & \end{array} \qquad \begin{array}{ccc} S & \xrightarrow{\psi} & S' \\ g \searrow & & \swarrow g' \\ & B & \end{array}$$

such that

$$\underbrace{\text{忘}(\phi)}_{\stackrel{\text{def}}{=} \phi} = \underbrace{\text{忘}(\psi)}_{\stackrel{\text{def}}{=} \psi}.$$

Thus the morphisms of $\text{Sets}_{/A} \times_{\text{Sets}} \text{Sets}_{/B}$ are also the same as morphisms of spans from (S, f, g) to (S', f', g') .

- *Identities and Composition.* The identities and composition of $\text{Sets}_{/A} \times_{\text{Sets}} \text{Sets}_{/B}$ are also the same as those in $\text{Span}(A, B)$.

This finishes the proof. □

6.2.2 The Bicategory of Spans

Definition 6.2.2.1.1. The **bicategory of spans** is the bicategory Span where

- *Objects.* The objects of Span are sets;
- *Hom-Categories.* For each $A, B \in \text{Obj}(\text{Span})$, we have

$$\text{Hom}_{\text{Span}}(A, B) \stackrel{\text{def}}{=} \text{Span}(A, B);$$

- *Identities.* For each $A \in \text{Obj}(\text{Span})$, the unit functor

$$\mathbb{1}_A^{\text{Span}} : \text{pt} \rightarrow \text{Span}(A, A)$$

of Span at A is the functor picking the span $(A, \text{id}_A, \text{id}_A)$:

$$\begin{array}{ccc} & A & \\ id_A \swarrow & & \searrow id_A \\ A & & A. \end{array}$$

- *Composition.* For each $A, B, C \in \text{Obj}(\text{Span})$, the composition bifunctor

$$\circ_{A,B,C}^{\text{Span}} : \text{Span}(B, C) \times \text{Span}(A, B) \rightarrow \text{Span}(A, C)$$

of Span at (A, B, C) is the bifunctor where

- *Action on Objects.* The composition of two spans

$$\begin{array}{ccc} & R & \\ f_1 \swarrow & & \searrow g_1 \\ A & & B \end{array} \quad \text{and} \quad \begin{array}{ccc} & S & \\ f_2 \swarrow & & \searrow g_2 \\ B & & C \end{array}$$

is the span $(R \times_B S, f_1 \circ \text{pr}_1, g_2 \circ \text{pr}_2)$, constructed as in the diagram

$$\begin{array}{ccccc} & & R \times_B S & & \\ & \nearrow f_1 \circ \text{pr}_1 & \downarrow \text{pr}_1 & \searrow \text{pr}_2 & \\ & R & \times_B & S & \\ \downarrow f_1 & & \downarrow & & \downarrow g_2 \circ \text{pr}_2 \\ A & & B & & C \end{array}$$

- *Action on Morphisms.* The horizontal composition of 2-morphisms is defined

via functoriality of pullbacks: given morphisms of spans

$$\begin{array}{ccc} & R & \\ f \swarrow & \downarrow & \searrow g \\ A & \phi & B \\ \uparrow f' & \downarrow & \nearrow g' \\ R' & & \end{array} \quad \text{and} \quad \begin{array}{ccc} & S & \\ h \swarrow & \downarrow & \searrow k \\ B & \psi & C \\ \uparrow h' & \downarrow & \nearrow k' \\ S' & & \end{array}$$

their horizontal composition is the morphism of spans

$$\begin{array}{ccc} & R \times_B S & \\ f \circ \text{opr}_1 \swarrow & \downarrow \exists! & \searrow k \circ \text{opr}_2 \\ A & & C \\ \uparrow h' \circ \text{opr}'_1 & \downarrow & \nearrow k' \circ \text{opr}'_2 \\ R' \times_B S' & & \end{array}$$

constructed as in the diagram

$$\begin{array}{ccccc} & R \times_B S & & & \\ & \swarrow \text{pr}_1 & \downarrow \exists! & \searrow \text{pr}_2 & \\ & R & & S & \\ f \swarrow & \downarrow & \searrow g & \swarrow & \searrow h \\ A & & B & & C \\ \uparrow f' & \downarrow & \nearrow g' & \uparrow h' & \nearrow k' \\ R' & & S' & & \\ \uparrow f' \circ \text{opr}'_1 & \downarrow \text{pr}'_1 & \uparrow \wedge & \downarrow \text{pr}'_2 & \uparrow k' \circ \text{opr}'_2 \\ R' \times_B S' & & & & \end{array}$$

- *Associators and Unitors.* The associator and unitors are defined using the universal property of the pullback.

6.2.3 The Monoidal Bicategory of Spans

6.2.4 The Double Category of Spans

Definition 6.2.4.1.1. The **double category of spans** is the double category Span^{dbl} where

- *Objects.* The objects of Span^{dbl} are sets;
- *Vertical Morphisms.* The vertical morphisms of Span^{dbl} are functions $f: A \rightarrow B$;
- *Horizontal Morphisms.* The horizontal morphisms of Span^{dbl} are spans $(S, \phi, \psi): A \dashrightarrow X$;
- *2-Morphisms.* A 2-cell

$$\begin{array}{ccc} A & \xrightarrow{(R, \phi_R, \psi_R)} & B \\ f \downarrow & \Downarrow \alpha & \downarrow g \\ X & \xrightarrow{(S, \phi_S, \psi_S)} & Y \end{array}$$

of Span^{dbl} is a morphism of spans from the span

$$\begin{array}{ccccc} & & R & & \\ & \swarrow \phi_R & & \searrow \psi_R & \\ A & & B & & Y \\ & \searrow g & & & \end{array}$$

to the span

$$\begin{array}{ccccc} & & A \times_X S & & \\ & \swarrow & \downarrow & \searrow & \\ & A & & S & \\ & \swarrow f & \searrow & \swarrow \phi_S & \searrow \psi_S \\ X & & X & & Y; \end{array}$$

- *Horizontal Identities.* The horizontal unit functor

$$\mathbb{U}^{\text{Span}^{\text{dbl}}}: (\text{Span}^{\text{dbl}})_0 \rightarrow (\text{Span}^{\text{dbl}})_1$$

of Span^{dbl} is the functor where

- *Action on Objects.* For each $A \in \text{Obj}(\text{Span}^{\text{dbl}})_0$, we have

$$\mathbb{1}_A \stackrel{\text{def}}{=} (A, \text{id}_A, \text{id}_A),$$

as in the diagram

$$\begin{array}{ccc} & A & \\ \text{id}_A \swarrow & & \searrow \text{id}_A \\ A & & A; \end{array}$$

- *Action on Morphisms.* For each vertical morphism $f: A \rightarrow B$ of Span^{dbl} , i.e. each map of sets f from A to B , the identity 2-morphism

$$\begin{array}{ccc} A & \xrightarrow{\mathbb{1}_A} & A \\ f \downarrow & \Downarrow \mathbb{1}_f & \downarrow f \\ B & \xrightarrow{\mathbb{1}_B} & B \end{array}$$

$\mathbb{1}_f$ is the morphism of spans from

$$\begin{array}{ccc} & A & \\ \text{id}_A \swarrow & & \searrow \text{id}_A \\ A & & A \\ & & \searrow f \\ & & B \end{array}$$

to

$$\begin{array}{ccccc} & & A \times_B B & & \\ & \swarrow & & \searrow & \\ & A & & B & \\ f \swarrow & \searrow f & \swarrow \text{id}_B & \searrow & \text{id}_B \\ B & & B & & B \end{array}$$

given by the isomorphism $A \xrightarrow{\cong} A \times_B B$;

- *Vertical Identities.* For each $A \in \text{Obj}(\text{Span}^{\text{dbl}})$, we have

$$\text{id}_A^{\text{Span}^{\text{dbl}}} \stackrel{\text{def}}{=} \text{id}_A;$$

- *Identity 2-Morphisms.* For each horizontal morphism $R: A \rightarrow B$ of Span^{dbl} , the identity 2-morphism

$$\begin{array}{ccc} A & \xrightarrow{S} & B \\ \downarrow \text{id}_A & \parallel & \downarrow \text{id}_B \\ A & \xrightarrow{S} & B \end{array}$$

of R is the morphism of spans from

$$\begin{array}{ccc} & S & \\ & \swarrow \phi_S & \searrow \psi_S \\ A & & B \\ & & \parallel \text{id}_B \end{array}$$

to

$$\begin{array}{ccccc} & A \times_A S & & & \\ & \swarrow & \downarrow & \searrow & \\ A & \xleftarrow{\text{id}_A} & A & \xrightarrow{\phi_S} & B \\ & \parallel & \parallel & \nearrow & \\ A & & A & & B \end{array}$$

given by the isomorphism $S \xrightarrow{\cong} A \times_A S$;

- *Horizontal Composition.* The horizontal composition functor

$$\odot^{\text{Span}^{\text{dbl}}} : (\text{Span}^{\text{dbl}})_1 \times_{(\text{Span}^{\text{dbl}})_0} (\text{Span}^{\text{dbl}})_1 \rightarrow (\text{Span}^{\text{dbl}})_1$$

of Span^{dbl} is the functor where

- *Action on Objects.* For each composable pair

$$A \xrightarrow{(R, \phi_R, \psi_R)} B \xrightarrow{(S, \phi_S, \psi_S)} C$$

of horizontal morphisms of Span^{dbl} , we have

$$(S, \phi_S, \psi_S) \odot (R, \phi_R, \psi_R) \stackrel{\text{def}}{=} S \circ_{A,B,C}^{\text{Span}} R,$$

where $S \circ_{A,B,C}^{\text{Span}} R$ is the composition of (R, ϕ_R, ψ_R) and (S, ϕ_S, ψ_S) defined as in [Definition 6.2.2.1.1](#);

- *Action on Morphisms.* For each horizontally composable pair

$$\begin{array}{ccc} A & \xrightarrow{(R,\phi_R,\psi_R)} & B \\ f \downarrow & \parallel \alpha \Downarrow & \downarrow g \\ X & \xrightarrow{(T,\phi_T,\psi_T)} & Y \end{array} \quad \begin{array}{ccc} B & \xrightarrow{(S,\phi_S,\psi_S)} & C \\ g \downarrow & \parallel \beta \Downarrow & \downarrow h \\ Y & \xrightarrow{(U,\phi_U,\psi_U)} & Z \end{array}$$

of 2-morphisms of Span^{dbl} ,

- *Vertical Composition of 1-Morphisms.* For each composable pair $A \xrightarrow{F} B \xrightarrow{G} C$ of vertical morphisms of Span^{dbl} , i.e. maps of sets, we have

$$g \circ^{\text{Span}^{\text{dbl}}} f \stackrel{\text{def}}{=} g \circ f;$$

- *Vertical Composition of 2-Morphisms.* For each vertically composable pair

$$\begin{array}{ccc} A & \xrightarrow{(R,\phi_R,\psi_R)} & X \\ f \downarrow & \parallel \alpha \Downarrow & \downarrow g \\ B & \xrightarrow{(S,\phi_S,\psi_S)} & Y \end{array} \quad \begin{array}{ccc} B & \xrightarrow{(S,\phi_S,\psi_S)} & Y \\ h \downarrow & \parallel \beta \Downarrow & \downarrow k \\ C & \xrightarrow{(T,\phi_T,\psi_T)} & Z \end{array}$$

of 2-morphisms of Span^{dbl} ,

- *Associators and Unitors.* The associator and unitors of Span^{dbl} are defined using the universal property of the pullback.

6.2.5 Properties of The Bicategory of Spans

Proposition 6.2.5.1.1. Let $\lambda = (A \xleftarrow{f} S \xrightarrow{g} B)$ be a span.

1. *Self-Duality.*
2. *Isomorphisms in Span.*
3. *Equivalences in Span.*
4. *Adjunctions in Span.* Let A and B be sets.⁹

⁹In the literature (e.g. [ref]),...are called maps and denoted by $\text{MapSpan}(A, B)$

(a) We have a natural bijection

$$\left\{ \begin{array}{c} \text{Adjunctions in Span} \\ \text{from } A \text{ to } B \end{array} \right\} \cong \left\{ \begin{array}{c} \text{Spans } A \xleftarrow{f} S \xrightarrow{g} B \\ \text{from } A \text{ to } B \text{ with} \\ f \text{ an isomorphism} \end{array} \right\}.$$

(b) We have an equivalence of categories

$$\text{MapSpan}(A, B) \stackrel{\text{eq.}}{\cong} \text{Sets}(A, B)_{\text{disc}},$$

where $\text{MapSpan}(A, B)$ is the full subcategory of $\text{Span}(A, B)$ spanned by the spans $A \xleftarrow{f} S \xrightarrow{g} B$ from A to B with f an isomorphism.

(c) We have a biequivalence of bicategories

$$\text{MapSpan} \stackrel{\text{eq.}}{\cong} \text{Sets}_{\text{bidisc}},$$

where MapSpan is the sub-bicategory of Span whose Hom-categories are given by $\text{MapSpan}(A, B)$.

- 5. *Monads in Span.*
- 6. *Comonads in Span.*
- 7. *Monomorphisms in Span.*
- 8. *Epimorphisms in Span.*
- 9. *Existence of Right Kan Extensions.*
- 10. *Existence of Right Kan Lifts.*
- 11. *Closedness.*

Proof. **Item 1, Self-Duality:**

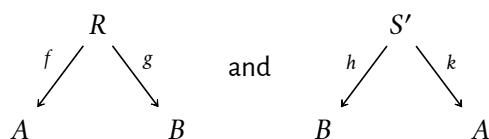
Item 2, Isomorphisms in Span:

Item 3, Equivalences in Span:

Item 4, Adjunctions in Span: We first prove **Item 4a.**

We proceed step by step:

1. *From Adjunctions in Span to Functions.* An adjunction in Span from A to B consists of a pair of spans



together with maps

$$\begin{array}{ccc}
 \begin{array}{c} A \\ \text{id}_A \swarrow \quad \searrow \text{id}_A \\ A \qquad \phi \qquad A \\ f \circ \text{pr}'_1 \swarrow \quad \searrow k \circ \text{pr}'_2 \\ S \times_B S' \end{array} & \text{and} & \begin{array}{c} S' \times_A S \\ h \circ \text{pr}_1 \swarrow \quad \searrow g \circ \text{pr}_2 \\ B \qquad \psi \qquad B \\ \text{id}_B \swarrow \quad \searrow \text{id}_B \\ B \end{array}
 \end{array}$$

We claim that these conditions

2. *From Functions to Adjunctions in Rel.*
3. *Invertibility: From Functions to Adjunctions Back to Functions.*
4. *Invertibility: From Adjunctions to Functions Back to Adjunctions.*

We now proceed to the proof of Item 4b. For this, we will construct a functor

$$F: \text{Sets}(A, B)_{\text{disc}} \rightarrow \text{MapSpan}(A, B)$$

and prove it to be essentially surjective and fully faithful, and thus an equivalence by ?? of ???. Indeed, given a map $f: A \rightarrow B$, let $F(f)$ be the representable span associated to f of Definition 6.5.1.1.1, and let F send the unique (identity) morphism from f to itself to the identity morphism of $F(f)$ in $\text{MapSpan}(A, B)$. We now prove that F is fully faithful and essentially surjective:

1. *F Is Fully Faithful:* Given maps $f, g: A \rightrightarrows B$, we need to show that

$$\text{Hom}_{\text{MapSpan}(A, B)}(F(f), F(g)) = \begin{cases} \text{pt} & \text{iff } f = g, \\ \emptyset & \text{otherwise.} \end{cases}$$

Indeed, a morphism from $F(f)$ to $F(g)$ takes the form

$$\begin{array}{ccc}
 & A & \\
 \text{id}_A \swarrow & \downarrow \phi & \searrow f \\
 A & & B. \\
 \text{id}_A \swarrow & \downarrow g & \searrow \\
 & A &
 \end{array}$$

From the relations $\text{id}_A = \text{id}_A \circ \phi$ and $f = g \circ \phi$, we see that $\phi = \text{id}_A$, and thus from the relation $f = g \circ \phi$ there is such a morphism iff $f = g$.

2. *F Is Essentially Surjective:* Let λ be a span of the form

$$\begin{array}{ccc}
 & S & \\
 \phi \swarrow & \downarrow & \searrow f \\
 A & & B.
 \end{array}$$

we claim that $\lambda \cong F(f \circ \phi^{-1})$. Indeed, we have morphisms

$$\begin{array}{ccc} & S & \\ \phi \swarrow & \downarrow f & \searrow \\ A & B & \text{and} & A & B, \\ \parallel \downarrow \phi & \nearrow f \circ \phi^{-1} & & \phi^{-1} \parallel \downarrow & \searrow f \\ & A & & S & \end{array}$$

inverse to each other in $\text{MapSpan}(A, B)$, and thus $\lambda \cong F(f \circ \phi^{-1})$.

Finally, we prove [Item 4c](#).

[Item 5](#), *Monads in Span*:

[Item 6](#), *Comonads in Span*:

[Item 7](#), *Monomorphisms in Span*:

[Item 8](#), *Epimorphisms in Span*:

[Item 9](#), *Existence of Right Kan Extensions*:

[Item 10](#), *Existence of Right Kan Lifts*:

[Item 11](#), *Closedness*:

□

6.3 Limits of Spans

6.3.1 tmp2

$$\text{Hom}_{\text{Rel}(A, X)}(\text{Lan}_S(R), T) \cong \text{Hom}_{\text{Rel}(B, X)}(R, T \diamond S)$$

1. $\text{Lan}_S(R) \subset T$, i.e. if $a \sim_{\text{Lan}_S(R)} x$, then $a \sim_T x$.
2. $R \subset T \diamond S$, i.e. if $b \sim_R x$, then there exists some $a \in A$ such that $a \sim_S b$ and $b \sim_T x$.

6.3.2 tmp

$$\begin{array}{ccccc} & S & & & \\ & f \swarrow & \searrow g & & \\ & A & & B & \\ & \downarrow \phi_{S'} & \searrow \psi_{S'} & \mapsto & f \circ \text{pr}_1 \swarrow \quad \searrow \psi_{S'} \circ \text{pr}_2 \\ S' & & X & & A & X \\ \phi_{S''} \swarrow & \searrow \psi_{S''} & \mapsto & ? \swarrow \quad \searrow ? & B & X \\ S'' & & X & & & \end{array}$$

$$\text{Hom}_{\text{Span}(A,X)}(S \times_B S', K) \cong \text{Hom}_{\text{Span}(B,X)}(S', R(K))$$

$$\begin{array}{ccc} & S \times_B S' & \\ f \circ \text{pr}_1 \swarrow & \downarrow & \searrow \psi_{S'} \circ \text{pr}_2 \\ A & \xi \downarrow & X \\ \phi_{S''} \swarrow & \nearrow \psi_{S''} & \\ S'' & & \end{array} \quad \begin{array}{ccc} & S' & \\ \phi_{S'} \swarrow & \downarrow \xi^\dagger & \searrow \psi_{S'} \\ B & \uparrow ? & X \\ \uparrow ? & \downarrow ? & \\ \Pi_g(S'') & & \end{array}$$

6.3.3 Left Kan Extensions

Let $\lambda = (A \xleftarrow{f} S \xrightarrow{g} B)$ be a span.

Proposition 6.3.3.1.1. The left Kan extension

$$\text{Lan}_\lambda : \text{Span}(A, X) \rightarrow \text{Span}(B, X)$$

along λ in Span exists and is the functor given on objects by sending a span λ' in $\text{Span}(A, X)$ as in

$$\begin{array}{ccc} & S' & \\ \phi \swarrow & \downarrow & \searrow \psi \\ A & & X \end{array}$$

to the span

$$\text{Lan}_\lambda(\lambda') \stackrel{\text{def}}{=} (\text{Lan}_\lambda(S'), \text{Lan}_\lambda(\phi), \text{Lan}_\lambda(\psi)),$$

in $\text{Span}(B, X)$ where

- The set $\text{Lan}_\lambda(S')$ is given by

$$\begin{aligned} \text{Lan}_\lambda(S') &\stackrel{\text{def}}{=} \Sigma_g(S') \\ &\stackrel{\text{def}}{=} S' \end{aligned}$$

where $\Sigma_g(S')$ is the dependent sum of $\phi: S' \rightarrow A$ along g of ??;

- The map $\text{Lan}_\lambda(\phi): \text{Lan}_\lambda(S') \rightarrow B$ is given by $\Sigma_g(\phi)$;
- The map $\text{Lan}_\lambda(\psi): \text{Lan}_\lambda(S') \rightarrow X$ is given by ψ .

Proof.

□

6.3.4 Right Kan Extensions

Let $\lambda = (A \xleftarrow{f} S \xrightarrow{g} B)$ be a span.

Proposition 6.3.4.1.1. The right Kan extension

$$\text{Ran}_\lambda : \text{Span}(A, X) \rightarrow \text{Span}(B, X)$$

along λ in Span exists and is the functor given on objects by sending a span λ' in $\text{Span}(A, X)$ as in

$$\begin{array}{ccc} & S' & \\ \phi_{S'} \swarrow & & \searrow \psi_{S'} \\ A & & X \end{array}$$

to the span

$$\text{Ran}_\lambda(\lambda') \stackrel{\text{def}}{=} (\text{Ran}_\lambda(S'), \text{Ran}_\lambda(\phi_{S'}), \text{Ran}_\lambda(\psi_{S'})),$$

in $\text{Span}(B, X)$ where

- The set $\text{Ran}_\lambda(S')$ is given by

$$\text{Ran}_\lambda(S') \stackrel{\text{def}}{=} \coprod_{b \in B} \prod_{s \in g^{-1}(b)} \phi_{S'}^{-1}(f(s));$$

- The map $\text{Ran}_\lambda(\phi_{S'}) : \text{Ran}_\lambda(S') \rightarrow B$ is given by

$$[\text{Ran}_\lambda(\phi_{S'})](b, (s'_s)_{s \in g^{-1}(b)}) \stackrel{\text{def}}{=} b;$$

for each $(b, (s'_s)_{s \in g^{-1}(b)}) \in \text{Ran}_\lambda(S')$;

- The map $\text{Ran}_\lambda(\psi_{S'}) : \text{Ran}_\lambda(S') \rightarrow X$ is given by

$$[\text{Ran}_\lambda(\psi_{S'})](b, (s'_s)_{s \in g^{-1}(b)}) \stackrel{\text{def}}{=} \psi_{S'}(s'_i)$$

for each $(b, (s'_s)_{s \in g^{-1}(b)}) \in \text{Ran}_\lambda(S')$, where the i in s'_i denotes any $s \in g^{-1}(b)$, as we have $\psi_{S'}(s'_i) = \psi_{S'}(s'_j)$ for all $s \in g^{-1}(b)$.¹⁰

Proof.

□

6.3.5 Right Kan Lifts

(Although right Kan lifts aren't really limits, this is probably the most appropriate to place this section.)

Let $\lambda = (A \xleftarrow{f} S \xrightarrow{g} B)$ be a span.

¹⁰Indeed

Proposition 6.3.5.1.1. The right Kan lift

$$\text{Rift}_\lambda : \text{Span}(X, B) \rightarrow \text{Span}(X, A)$$

along λ in Span exists and is the functor given on objects by sending a span λ' in $\text{Span}(X, B)$ as in

$$\begin{array}{ccc} & S' & \\ \phi \swarrow & & \searrow \psi \\ X & & B \end{array}$$

to the span

$$\text{Rift}_\lambda(\lambda') \stackrel{\text{def}}{=} (\text{Rift}_\lambda(S'), \text{Rift}_\lambda(\phi), \text{Rift}_\lambda(\psi)),$$

in $\text{Span}(X, A)$ where

- The set $\text{Rift}_\lambda(S')$ is given by

$$\text{Rift}_\lambda(S') \stackrel{\text{def}}{=} \Pi_f(S'),$$

where $\Pi_f(S')$ is the dependent product of $\psi : S' \rightarrow A$ along f of ??;

- The map $\text{Rift}_\lambda(\phi) : \text{Rift}_\lambda(S') \rightarrow X$ is given by ϕ ;
- The map $\text{Rift}_\lambda(\psi) : \text{Rift}_\lambda(S') \rightarrow A$ is given by $\Pi_f(\psi)$.

Proof.

□

6.4 Colimits of Spans

6.5 Constructions With Spans

6.5.1 Representable Spans

Definition 6.5.1.1.1. Let $f : A \rightarrow B$ be a function.

- The **representable span associated to f** is the span

$$\begin{array}{ccc} & A & \\ \text{id}_A \swarrow & & \searrow f \\ A & & B \end{array}$$

from A to B .

- The **corepresentable span associated to f** is the span

$$\begin{array}{ccc} & A & \\ f \swarrow & & \searrow \text{id}_A \\ B & & A \end{array}$$

from B to A .

6.5.2 Composition of Spans

Definition 6.5.2.1.1. The **composition** of two spans

$$\begin{array}{ccc} & R & \\ f_1 \swarrow & & \searrow g_1 \\ A & & B \end{array} \quad \text{and} \quad \begin{array}{ccc} & S & \\ f_2 \swarrow & & \searrow g_2 \\ B & & C \end{array}$$

is the span $(R \times_B S, f_1 \circ \text{pr}_1, g_2 \circ \text{pr}_2)$, constructed as in the diagram

$$\begin{array}{ccccc} & & R \times_B S & & \\ & \swarrow f_1 \circ \text{pr}_1 & \downarrow \text{pr}_1 & \searrow \text{pr}_2 & \\ & R & & S & \\ & \swarrow f_1 & \searrow g_1 & \swarrow f_2 & \searrow g_2 \\ A & & B & & C \end{array}$$

6.5.3 Horizontal Composition of Morphisms of Spans

Definition 6.5.3.1.1. The **horizontal composition** of a pair of 2-morphisms of spans

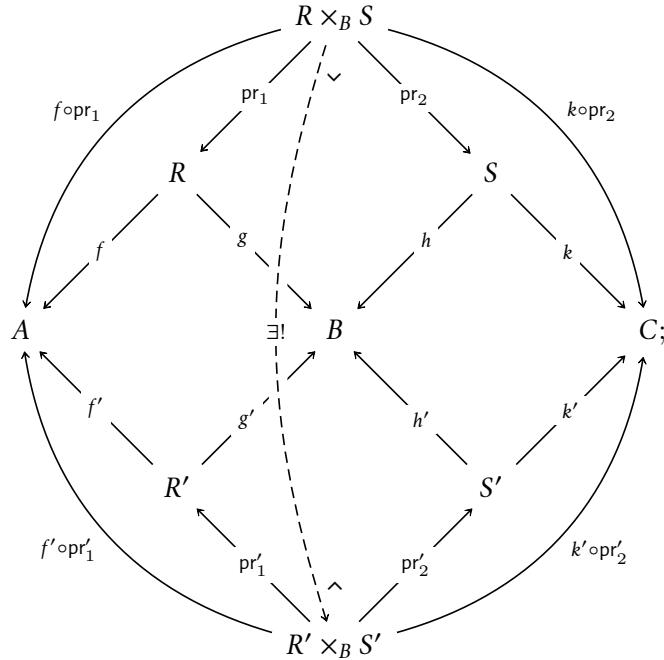
$$\begin{array}{ccc} & R & \\ f \swarrow & \downarrow \phi & \searrow g \\ A & & B \end{array} \quad \text{and} \quad \begin{array}{ccc} & S & \\ h \swarrow & \downarrow \psi & \searrow k \\ B & & C \end{array}$$

$$\begin{array}{ccc} & R' & \\ f' \swarrow & \downarrow & \searrow g' \\ A & & B \end{array} \quad \begin{array}{ccc} & S' & \\ h' \swarrow & \downarrow & \searrow k' \\ B & & C \end{array}$$

is the morphism of spans

$$\begin{array}{ccc} & R \times_B S & \\ f \circ \text{pr}_1 \swarrow & \downarrow \exists! & \searrow k \circ \text{pr}_2 \\ A & & C \\ h' \circ \text{pr}'_1 \swarrow & \downarrow & \searrow k' \circ \text{pr}'_2 \\ R' \times_B S' & & \end{array}$$

constructed as in the diagram



6.5.4 Properties of Composition of Spans

Proposition 6.5.4.1.1. Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B \right)$ be a span.

1. *Functoriality.*

Proof.

□

6.5.5 The Inverse of a Span

6.6 Functoriality of Spans

6.6.1 Direct Images

6.6.2 Functoriality of Spans on Powersets

6.7 Un/Straightening for Spans

6.7.1 Straightening for Spans

Let A and B be sets and let (S, f, g) be a span from A to B .

Definition 6.7.1.1.1. The **straightening** of (S, f, g) is the $(A \times B)$ -indexed set

$$\text{St}_{A,B}(S): (A \times B)_{\text{disc}} \rightarrow \text{Sets}$$

defined as the straightening of S , viewed as an $(A \times B)$ -fibred set, as in ??.

Remark 6.7.1.1.2. In detail, $\text{St}_{A,B}(S)$ is the $(A \times B)$ -indexed set defined by¹¹

$$\begin{aligned} [\text{St}_{A,B}(S)](a, b) &\stackrel{\text{def}}{=} \text{Wits}_S(a, b) \\ &\stackrel{\text{def}}{=} S_{ab} \\ &\stackrel{\text{def}}{=} \{s \in S \mid f(s) = a \text{ and } g(s) = b\}. \end{aligned}$$

Proposition 6.7.1.1.3. Let A and B be sets and let (S, f, g) be a span.

1. *Functoriality.* The assignment $(S, f, g) \mapsto \text{St}_{A,B}(S)$ defines a functor

$$\text{St}_{A,B} : \text{Span}(A, B) \rightarrow \text{ISets}(A \times B)$$

- *Action on Objects.* For each $(S, f, g) \in \text{Obj}(\text{Span}(A, B))$, we have

$$[\text{St}_{A,B}](S, f, g) \stackrel{\text{def}}{=} \text{St}_{A,B}(S);$$

- *Action on Morphisms.* For each $(S_1, f_1, g_1), (S_2, f_2, g_2) \in \text{Obj}(\text{Span}(A, B))$, the action on Hom-sets

$$\text{St}_{A,B|S_1, S_2} : \text{Hom}_{\text{Span}(A, B)}(S_1, S_2) \rightarrow \text{Hom}_{\text{ISets}(A \times B)}(\text{St}_{A,B}(S_1), \text{St}_{A,B}(S_2))$$

of $\text{St}_{A,B}$ at (S_1, S_2) is given by sending a morphism

$$\phi : (S_1, f_1, g_1) \rightarrow (S_2, f_2, g_2)$$

of spans from A to B to the morphism

$$\text{St}_{A,B}(\phi) : \text{St}_{A,B}(S_1) \rightarrow \text{St}_{A,B}(S_2)$$

of $(A \times B)$ -indexed sets defined by

$$\text{St}_{A,B}(\phi) \stackrel{\text{def}}{=} \{\phi_{ab}^*\}_{(a,b) \in A \times B},$$

where ϕ_{ab}^* is the transport map associated to ϕ at $(a, b) \in A \times B$ of ??.

Proof. **Item 1, Functoriality:** This is the special case of ?? of ?? where $K = A \times B$. □

6.7.2 Unstraightening for Spans

Let A and B be sets and let $S : (A \times B)_{\text{disc}} \rightarrow \text{Sets}$ be an $(A \times B)$ -indexed set.

¹¹Here we may think of $\text{Wits}_S(a, b)$ as the “set of witnesses in S that $a \sim b$ holds”; see Remark 6.1.2.1.3.

Definition 6.7.2.1.1. The **unstraightening** of S is the span

$$\begin{array}{ccc} & \text{Un}_{A,B}(S) & \\ f_{\text{Un}_{A,B}(S)} \swarrow & & \searrow g_{\text{Un}_{A,B}(S)} \\ A & & B \end{array}$$

from A to B where

$$\text{Un}_{A,B}(S) \stackrel{\text{def}}{=} \coprod_{(a,b) \in A \times B} S(a,b)$$

and where the maps $f_{\text{Un}_{A,B}(S)}$ and $g_{\text{Un}_{A,B}(S)}$ are given by

$$\begin{aligned} f_{\text{Un}_{A,B}(S)}((a,b), s) &\stackrel{\text{def}}{=} a, \\ g_{\text{Un}_{A,B}(S)}((a,b), s) &\stackrel{\text{def}}{=} b \end{aligned}$$

for each $((a,b), s) \in \text{Un}_{A,B}(S)$.

Proposition 6.7.2.1.2. Let A and B be sets.

1. *Functoriality.* The assignment $S \mapsto \text{Un}_{A,B}(S)$ defines a functor

$$\text{Un}_{A,B} : \text{ISets}(A \times B) \rightarrow \text{Span}(A, B)$$

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

$$[\text{Un}_{A,B}](S) \stackrel{\text{def}}{=} \text{Un}_{A,B}(S);$$

- *Action on Morphisms.* For each $S, S' \in \text{Obj}(\text{ISets}(A \times B))$, the action on Hom-sets

$$\text{Un}_{A,B|S,S'} : \text{Hom}_{\text{ISets}(A \times B)}(S, S') \rightarrow \text{Hom}_{\text{Span}(A, B)}(\text{Un}_{A,B}(S), \text{Un}_{A,B}(S'))$$

of $\text{Un}_{A,B}$ at (S, S') is defined by

$$\text{Un}_{A,B|S,S'}(f) \stackrel{\text{def}}{=} \coprod_{(a,b) \in A \times B} f_{ab}.$$

2. *Interaction With Fibres.* Viewing the legs of $\text{Un}_{A,B}(S)$ as a morphism $(f, g) : \text{Un}_{A,B}(S) \rightarrow A \times B$, we have a bijection of sets

$$(f, g)^{-1}_{\text{Un}_{A,B}(S)}(a, b) \cong S(a, b)$$

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

3. *As a Pullback.* We have a bijection of sets

$$\begin{array}{ccc} \text{Un}_{A,B}(S) & \longrightarrow & \text{Sets}_* \\ \text{Un}_{A,B}(S) \cong (A \times B)_{\text{disc}} \times_{\text{Sets}} \text{Sets}_*, & \downarrow \lrcorner & \downarrow \bar{\lrcorner} \\ (A \times B)_{\text{disc}} & \xrightarrow[S]{} & \text{Sets}_*. \end{array}$$

4. As a Colimit. We have a bijection of sets

$$\text{Un}_{A,B}(S) \cong \text{colim}(S).$$

Proof. **Item 1, Functoriality:** This is the special case of ?? of ?? where $K = A \times B$.

Item 2, Interaction With Fibres: This is the special case of ?? of ?? where $K = A \times B$.

Item 3, As a Pullback: This is the special case of ?? of ?? where $K = A \times B$.

Item 4, As a Colimit: This is the special case of ?? of ?? where $K = A \times B$. \square

6.7.3 The Un/Straightening Equivalence for Spans

Theorem 6.7.3.1.1. We have an isomorphism of categories

$$(\text{St}_{A,B} \dashv \text{Un}_{A,B}): \quad \text{Span}(A, B) \begin{array}{c} \xrightarrow{\text{St}_{A,B}} \\ \perp \\ \xleftarrow{\text{Un}_{A,B}} \end{array} \text{ISets}(A \times B).$$

Proof. This is the special case of ?? where $K = A \times B$. \square

6.8 Comparison of Spans to Functions and Relations

6.8.1 Comparison to Functions

Proposition 6.8.1.1.1. We have a pseudofunctor

$$\iota: \text{Sets}_{\text{bidisc}} \rightarrow \text{Span}$$

from $\text{Sets}_{\text{bidisc}}$ to Span where

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

$$\iota(A) \stackrel{\text{def}}{=} A;$$

- *Action on Hom-Categories.* For each $A, B \in \text{Obj}(\text{Sets}_{\text{bidisc}})$, the action on Hom-categories

$$\iota_{A,B}: \text{Sets}(A, B)_{\text{disc}} \rightarrow \text{Span}(A, B)$$

of ι at (A, B) is the functor defined on objects by sending a function $f: A \rightarrow B$ to the span

$$\begin{array}{ccc} & A & \\ \text{id}_A \swarrow & & \searrow f \\ A & & B \end{array}$$

from A to B .

- *Strict Unity Constraints.* For each $A \in \text{Obj}(\text{Sets}_{\text{bidisc}})$, the strict unity constraint

$$\iota_A^0 : \text{id}_{\iota(A)} \implies \iota(\text{id}_A)$$

of ι at A is given by the identity morphism of spans

$$\begin{array}{ccc} & A & \\ \text{id}_A \swarrow & \parallel & \searrow \text{id}_A \\ A & \text{id} & A, \\ \text{id}_A \swarrow & \parallel & \searrow \text{id}_A \\ & A & \end{array}$$

as indeed $\text{id}_{\iota(A)} = \iota(\text{id}_A)$;

- *Pseudofunctoriality Constraints.* For each $A, B, C \in \text{Obj}(\text{Sets}_{\text{bidisc}})$, each $f \in \text{Hom}_{\text{Sets}_{\text{bidisc}}}(A, B)$, and each $g \in \text{Hom}_{\text{Sets}_{\text{bidisc}}}(B, C)$, the pseudofunctoriality constraint

$$\iota_{g,f}^2 : \iota(g) \circ \iota(f) \implies \iota(g \circ f)$$

of ι at (f, g) is the morphism of spans from the span

$$\begin{array}{ccccc} & A \times_B B & & & \\ & \downarrow \text{pr}_1 & \quad \downarrow \text{pr}_2 & & \\ & A & \quad B & & \\ & \text{id}_A \swarrow & \quad \text{id}_B \swarrow & & \\ A & \xrightarrow{f} & B & \xrightarrow{g} & C. \end{array}$$

to the span

$$\begin{array}{ccc} & A & \\ \text{id}_A \swarrow & \searrow g \circ f & \\ A & & C \end{array}$$

given by the isomorphism $A \times_B B \cong A$.

Proof. Omitted. □

6.8.2 Comparison to Relations: From Span to Rel

6.8.2.1 Relations Associated to Spans

Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B \right)$ be a span.

Definition 6.8.2.1.1. The **relation associated to λ** is the relation

$$S(\lambda) : A \dashrightarrow B$$

from A to B defined as follows:

- Viewing relations from A to B as functions $A \times B \rightarrow \{\text{true}, \text{false}\}$, we define

$$\iota_{A,B}(S)_b^a \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if there exists } x \in S \text{ such} \\ & \text{that } a = f(x) \text{ and } b = g(x), \\ \text{false} & \text{otherwise} \end{cases}$$

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

- Viewing relations from A to B as functions $A \rightarrow \mathcal{P}(B)$, we define

$$[\iota_{A,B}(S)](a) \stackrel{\text{def}}{=} g(f^{-1}(a))$$

for each $a \in A$.

- Viewing relations from A to B as subsets of $A \times B$, we define

$$\iota_{A,B}(S) \stackrel{\text{def}}{=} \{(f(x), g(x)) \mid x \in S\}.$$

Proposition 6.8.2.1.2. Let $\lambda = \left(A \xleftarrow{f} S \xrightarrow{g} B\right)$ be a span.

1. *Interaction With Identities.*
2. *Interaction With Composition.*
3. *Interaction With Inverses.*

Proof.

□

6.8.2.2 The Comparison Functor from Span to Rel

Proposition 6.8.2.2.1. We have a pseudofunctor

$$\iota : \text{Span} \rightarrow \text{Rel}$$

from Span to **Rel** where

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

$$\iota(A) \stackrel{\text{def}}{=} A;$$

- *Action on Hom-Categories.* For each $A, B \in \text{Obj}(\text{Span})$, the action on Hom-categories

$$\iota_{A,B} : \text{Span}(A, B) \rightarrow \text{Rel}(A, B)$$

of ι at (A, B) is the functor where

- *Action on Objects.* Given a span

$$\begin{array}{ccc} & S & \\ f \swarrow & & \searrow g \\ A & & B \end{array}$$

from A to B , the image

$$\iota_{A,B}(S) : A \rightarrow B$$

of S by ι is the relation from A to B defined as follows:

- * Viewing relations as functions $A \times B \rightarrow \{\text{true, false}\}$, we define

$$\iota_{A,B}(S)_b^a \stackrel{\text{def}}{=} \begin{cases} \text{true} & \text{if there exists } x \in S \\ & \text{such that } a = f(x) \\ & \text{and } b = g(x), \\ \text{false} & \text{otherwise} \end{cases}$$

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

- * Viewing relations as functions $A \rightarrow \mathcal{P}(B)$, we define

$$[\iota_{A,B}(S)](a) \stackrel{\text{def}}{=} g(f^{-1}(a))$$

for each $a \in A$;

- * Viewing relations as subsets of $A \times B$, we define

$$\iota_{A,B}(S) \stackrel{\text{def}}{=} \{(f(x), g(x)) \mid x \in S\}.$$

- *Action on Morphisms.* Given a morphism of spans

$$\begin{array}{ccc} & R & \\ f_R \swarrow & \downarrow \phi & \searrow g_R \\ A & & B, \\ \uparrow f_S & \downarrow & \nearrow g_S \\ S & & \end{array}$$

we have a corresponding inclusion of relations

$$\iota_{A,B}(\phi) : \iota_{A,B}(R) \subset \iota_{A,B}(S),$$

since we have $a \sim_{\iota_{A,B}(R)} b$ iff there exists $x \in R$ such that $a = f_R(x)$ and $b = g_R(x)$, in which case we then have

$$\begin{aligned} a &= f_R(x) \\ &= f_S(\phi(x)), \\ b &= g_R(x) \\ &= g_S(\phi(x)), \end{aligned}$$

so that $a \sim_{\iota_{A,B}(S)} b$, and thus $\iota_{A,B}(R) \subset \iota_{A,B}(S)$.

Proof. Omitted. □

6.8.3 Comparison to Relations: From Rel to Span

Proposition 6.8.3.1.1. We have a lax functor

$$\left(\iota, \iota^2, \iota^0 \right) : \mathbf{Rel} \rightarrow \mathbf{Span}$$

from **Rel** to **Span** where

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

$$\iota(A) \stackrel{\text{def}}{=} A;$$

- *Action on Hom-Categories.* For each $A, B \in \text{Obj}(\mathbf{Span})$, the action on Hom-categories

$$\iota_{A,B} : \mathbf{Rel}(A, B) \rightarrow \mathbf{Span}(A, B)$$

of ι at (A, B) is the functor where

- *Action on Objects.* Given a relation $R : A \nrightarrow B$ from A to B , we define a span

$$\iota_{A,B}(R) : A \nrightarrow B$$

from A to B by

$$\iota_{A,B}(R) \stackrel{\text{def}}{=} (R, \uparrow \text{pr}_1 R, \uparrow \text{pr}_2 R),$$

where $R \subset A \times B$ and $\uparrow \text{pr}_1 R$ and $\uparrow \text{pr}_2 R$ are the restriction of the projections

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

to R ;

- *Action on Morphisms.* Given an inclusion $\phi : R \subset S$ of relations, we have a corresponding morphism of spans

$$\iota_{A,B}(\phi) : \iota_{A,B}(R) \rightarrow \iota_{A,B}(S)$$

as in the diagram

$$\begin{array}{ccc} & R & \\ \uparrow \text{pr}_1 R & \swarrow & \searrow \uparrow \text{pr}_2 R \\ A & & B \\ \downarrow \text{pr}_1 S & \nearrow & \searrow \uparrow \text{pr}_2 S \\ & S & \end{array}$$

- *The Lax Functoriality Constraints.* The lax functoriality constraint

$$\iota_{R,S}^2 : \iota(S) \circ \iota(R) \Longrightarrow \iota(S \diamond R)$$

of ι at (R, S) is given by the morphism of spans from

$$\begin{array}{ccccc} & & R \times_B S & & \\ & \swarrow \iota_{R,S}^2 & \downarrow \text{pr}_1 & \searrow \text{pr}_2 & \\ R & & & & S \\ \downarrow \iota_{R,S}^1 & \swarrow \iota_{R,R} & \downarrow \iota_{R,B} & \searrow \iota_{B,S} & \downarrow \iota_{S,C} \\ A & & B & & C \end{array}$$

to

$$\begin{array}{ccc} & S \diamond R & \\ \iota_{S,R} & \swarrow & \searrow \iota_{R,C} \\ A & & C \end{array}$$

given by the natural inclusion $R \times_B S \hookrightarrow S \diamond R$, since we have

$$\begin{aligned} R \times_B S &= \{((a_R, b_R), (b_S, c_S)) \in R \times S \mid b_R = b_S\}; \\ S \diamond R &= \left\{ (a, c) \in A \times C \middle| \begin{array}{l} \text{there exists some } b \in B \text{ such that} \\ (a, b) \in R \text{ and } (b, c) \in S \end{array} \right\}; \end{aligned}$$

- *The Lax Unity Constraints.* The lax unity constraint¹²

$$\iota_A^0 : \underbrace{\text{id}_{\iota(A)}}_{(A, \text{id}_A, \text{id}_A)} \Longrightarrow \underbrace{\iota(\chi_A)}_{(\Delta_A, \iota_{\text{pr}_1 \Delta_A}, \iota_{\text{pr}_2 \Delta_A})}$$

of ι at A is given by the diagonal morphism of A , as in the diagram

$$\begin{array}{ccc} & A & \\ & \swarrow \text{id}_A & \searrow \text{id}_A \\ A & \delta_A & A \\ \iota_{\text{pr}_1 \Delta_A} & \uparrow & \downarrow \iota_{\text{pr}_2 \Delta_A} \\ \Delta_A & & \end{array}$$

Proof. Omitted. □

¹²Which is in fact strong, as δ_A is an isomorphism.

6.8.4 Comparison to Relations: The Wehrheim–Woodward Construction

6.8.5 Comparison to Multirelations

Remark 6.8.5.1.1. The pseudofunctor of [Proposition 6.8.2.2.1](#) and the lax functor of [Proposition 6.8.3.1.1](#) fail to be equivalences of bicategories. This happens essentially because a span $(S, f, g): A \nrightarrow B$ from A to B may relate elements $a \in A$ and $b \in B$ by more than one element, e.g. there could be $s \neq s' \in S$ such that $a = f(s) = f(s')$ and $b = g(s) = g(s')$.

Thus, in a sense, spans may be thought of as “relations with multiplicity”. And indeed, if instead of considering relations from A to B , i.e. functions

$$R: A \times B \rightarrow \{\text{true, false}\}$$

from $A \times B$ to $\{\text{true, false}\} \cong \{0, 1\}$, we consider functions

$$R: A \times B \rightarrow \mathbb{N} \cup \{\infty\}$$

from $A \times B$ to $\mathbb{N} \cup \{\infty\}$, then we obtain the notion of a **multirelation from A to B** , and these turn out to assemble together with sets into a bicategory MRel that is biequivalent to Span ; see [\[some-algebraic-laws-for-spans-and-their-connections-with-multirelations\]](#).

6.8.6 Comparison to Relations via Double Categories

Remark 6.8.6.1.1. There are double functors between the double categories Rel^{dbl} and Span^{dbl} analogous to the functors of [Propositions 6.8.2.2.1](#) and [6.8.3.1.1](#), assembling moreover into a strict-lax adjunction of double functors; see [\[higher-dimensional-categories\]](#).

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3. [Pointed Sets](#)
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Indexed and Fibred Sets

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Chapter 7

Posets

Rename this to “Preorders, Partial Orders, and Posets”.

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Part II

Indexed and Fibred Sets

Chapter 8

Indexed Sets

This chapter contains a discussion of indexed sets, the set-theoretical counterpart to indexed categories. In particular, here we explore:

1. Indexed sets, i.e. functors $K_{\text{disc}} \rightarrow \text{Sets}$ with K a set;
2. The limits and colimits in the category of K -indexed sets;
3. Constructions with indexed sets like dependent sums, dependent products, and internal Hom.

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8.1 Indexed Sets

8.1.1 Foundations

Let K be a set.

Definition 8.1.1.1.1. A **K -indexed set** is a functor $X : K_{\text{disc}} \rightarrow \text{Sets}$.

Remark 8.1.1.1.2. By ??, a **K -indexed set** consists of a K -indexed collection

$$X^\dagger : K \rightarrow \text{Obj}(\text{Sets}),$$

of sets, assigning a set $X_x^\dagger \stackrel{\text{def}}{=} X_x$ to each element x of K .

8.1.2 Morphisms of Indexed Sets

Let $X : K_{\text{disc}} \rightarrow \text{Sets}$ and $Y : K_{\text{disc}} \rightarrow \text{Sets}$ be indexed sets.

Definition 8.1.2.1.1. A **morphism of K -indexed sets from X to Y** ¹ is a natural transformation

$$f : X \Rightarrow Y, \quad K_{\text{disc}} \begin{array}{c} X \\ \Downarrow f \\ Y \end{array} \text{Sets}$$

from X to Y .

Remark 8.1.2.1.2. In detail, a **morphism of K -indexed sets** consists of a K -indexed collection

$$\{f_x : X_x \rightarrow Y_x\}_{x \in K}$$

of maps of sets.

8.1.3 The Category of Sets Indexed by a Fixed Set

Let K be a set.

¹Further Terminology: Also called a **K -indexed map of sets from X to Y** .

Definition 8.1.3.1.1. The **category of K -indexed sets** is the category $\text{ISets}(K)$ defined by

$$\text{ISets}(K) \stackrel{\text{def}}{=} \text{Fun}(K_{\text{disc}}, \text{Sets}).$$

Remark 8.1.3.1.2. In detail, the **category of K -indexed sets** is the category $\text{ISets}(K)$ where

- *Objects.* The objects of $\text{ISets}(K)$ are K -indexed sets as in [Definition 8.1.1.1](#);
- *Morphisms.* The morphisms of $\text{ISets}(K)$ are morphisms of K -indexed sets as in [Definition 8.1.2.1](#);
- *Identities.* For each $X \in \text{Obj}(\text{ISets}(K))$, the unit map

$$\mathbb{1}_X^{\text{ISets}(K)} : \text{pt} \rightarrow \text{Hom}_{\text{ISets}(K)}(X, X)$$

of $\text{ISets}(K)$ at X is defined by

$$\text{id}_X^{\text{ISets}(K)} \stackrel{\text{def}}{=} \{\text{id}_{X_x}\}_{x \in K};$$

- *Composition.* For each $X, Y, Z \in \text{Obj}(\text{ISets}(K))$, the composition map

$$\circ_{X,Y,Z}^{\text{ISets}(K)} : \text{Hom}_{\text{ISets}(K)}(Y, Z) \times \text{Hom}_{\text{ISets}(K)}(X, Y) \rightarrow \text{Hom}_{\text{ISets}(K)}(X, Z)$$

of $\text{ISets}(K)$ at (X, Y, Z) is defined by

$$\{g_x\}_{x \in K} \circ_{X,Y,Z}^{\text{ISets}(K)} \{f_x\}_{x \in K} \stackrel{\text{def}}{=} \{g_x \circ f_x\}_{x \in K}.$$

8.1.4 The Category of Indexed Sets

Definition 8.1.4.1.1. The **category of indexed sets** is the category ISets defined as the Grothendieck construction of the functor $\text{ISets} : \text{Sets}^{\text{op}} \rightarrow \text{Cats}$ of [Proposition 8.4.1.4](#):

$$\text{ISets} \stackrel{\text{def}}{=} \int^{\text{Sets}} \text{ISets}.$$

Remark 8.1.4.1.2. In detail, the **category of indexed sets** is the category ISets where

- *Objects.* The objects of ISets are pairs (K, X) consisting of
 - *The Indexing Set.* A set K ;
 - *The Indexed Set.* A K -indexed set $X : K_{\text{disc}} \rightarrow \text{Sets}$;
- *Morphisms.* A morphism of ISets from (K, X) to (K', Y) is a pair (ϕ, f) consisting of
 - *The Reindexing Map.* A map of sets $\phi : K \rightarrow K'$;
 - *The Morphism of Indexed Sets.* A morphism of K -indexed sets $f : X \rightarrow \phi_*(Y)$

as in the diagram

$$f: X \rightarrow \phi_*(Y), \quad \begin{array}{ccc} K_{\text{disc}} & \xrightarrow{\phi} & K'_{\text{disc}} \\ & \searrow f \quad \nearrow & \\ X & & Y \\ & & \text{Sets;} \end{array}$$

- *Identities.* For each $(K, X) \in \text{Obj}(\text{ISets})$, the unit map

$$\mu_{(K,X)}^{\text{ISets}} : \text{pt} \rightarrow \text{ISets}((K,X), (K,X))$$

of ISets at (K, X) is defined by

$$\text{id}_{(K,X)}^{\text{ISets}} \stackrel{\text{def}}{=} (\text{id}_K, \text{id}_X).$$

- *Composition.* For each $\mathbf{X} = (K, X), \mathbf{Y} = (K', Y), \mathbf{Z} = (K'', Z) \in \text{Obj}(\text{ISets})$, the composition map

$$\circ_{\mathbf{X}, \mathbf{Y}, \mathbf{Z}}^{\text{ISets}} : \text{ISets}(\mathbf{Y}, \mathbf{Z}) \times \text{ISets}(\mathbf{X}, \mathbf{Y}) \rightarrow \text{ISets}(\mathbf{X}, \mathbf{Z})$$

of ISets at $(\mathbf{X}, \mathbf{Y}, \mathbf{Z})$ is defined by

$$(\psi, g) \circ (\phi, f) \stackrel{\text{def}}{=} (\psi \circ \phi, (g \star \text{id}_\phi) \circ f),$$

as in the diagram

$$\begin{array}{ccccc} K_{\text{disc}} & \xrightarrow{\phi} & K'_{\text{disc}} & \xrightarrow{\psi} & K''_{\text{disc}} \\ & \searrow f \quad \nearrow & \downarrow Y & \nearrow g \quad \searrow & \\ X & & Y & & Z \\ & & \text{Sets} & & \end{array}$$

for each $(\phi, f) \in \text{ISets}(\mathbf{X}, \mathbf{Y})$ and each $(\psi, g) \in \text{ISets}(\mathbf{Y}, \mathbf{Z})$.

8.2 Limits of Indexed Sets

8.2.1 Products of K -Indexed Sets

Let $X: K_{\text{disc}} \rightarrow \text{Sets}$ and $Y: K_{\text{disc}} \rightarrow \text{Sets}$ be indexed sets.

Definition 8.2.1.1.1. The **product of X and Y** is the K -indexed set $X \times Y: K_{\text{disc}} \rightarrow \text{Sets}$ defined by

$$(X \times Y)_k \stackrel{\text{def}}{=} X_k \times Y_k$$

for each $k \in K$.

Proof. That this agrees with the categorical product in $\text{ISets}(K)$ follows from ?? of ?? \square

8.2.2 Pullbacks of K -Indexed Sets

Let $X, Y, Z: K_{\text{disc}} \rightarrow \text{Sets}$ be K -indexed sets and let $f: X \rightarrow Z$ and $g: Y \rightarrow Z$ be morphisms of K -indexed sets.

Definition 8.2.2.1.1. The **pullback of X and Y over Z** is the K -indexed set $X \times_Z Y: K_{\text{disc}} \rightarrow \text{Sets}$ defined by

$$(X \times_Z Y)_k \stackrel{\text{def}}{=} X_k \times_{Z_k} Y_k$$

for each $k \in K$.

Proof. That this agrees with the categorical pullback in $\text{ISets}(K)$ follows from ?? of ??.

□

8.2.3 Equalisers of K -Indexed Sets

Let $X, Y: K_{\text{disc}} \rightarrow \text{Sets}$ be K -indexed sets and let $f, g: X \rightrightarrows Y$ be morphisms of K -indexed sets.

Definition 8.2.3.1.1. The **equaliser of f and g** is the K -indexed set $\text{Eq}(f, g): K_{\text{disc}} \rightarrow \text{Sets}$ defined by

$$(\text{Eq}(f, g))_k \stackrel{\text{def}}{=} \text{Eq}(f_k, g_k)$$

for each $k \in K$.

Proof. That this agrees with the categorical equaliser in $\text{ISets}(K)$ follows from ?? of ??.

□

8.2.4 Products in ISets

Let $X: K_{\text{disc}} \rightarrow \text{Sets}$ and $Y: K'_{\text{disc}} \rightarrow \text{Sets}$ be indexed sets.

Definition 8.2.4.1.1. The **product of X and Y** is the $(K \times K')$ -indexed set

$$X \times Y: (K \times K')_{\text{disc}} \rightarrow \text{Sets}$$

defined by

$$(X \times Y)_{(k, k')} \stackrel{\text{def}}{=} X_k \times Y_{k'}$$

for each $(k, k') \in K \times K'$.

Proof. We claim that this agrees with the categorical product in ISets .

□

8.2.5 Pullbacks in ISets

Let $X: K_{\text{disc}} \rightarrow \text{Sets}$ be a K -indexed set, let $Y: K'_{\text{disc}} \rightarrow \text{Sets}$ be a K' -indexed set, let $Z: K''_{\text{disc}} \rightarrow \text{Sets}$ be a K'' -indexed set, and let $(\phi, f): X \rightarrow Z$ and $(\psi, g): Y \rightarrow Z$ be morphisms of indexed sets (as in Remark 8.1.4.1.2).

Definition 8.2.5.1.1. The **pullback of X and Y over Z** is the $(K \times_{K''} K)$ -indexed set

$$X \times_Z Y: (K \times_{K''} K)_{\text{disc}} \rightarrow \text{Sets}$$

defined by

$$\begin{aligned} (X \times_Z Y)_{(k,k')} &\stackrel{\text{def}}{=} X_k \times_{Z_{\phi(k)}} Y_{k'} \\ &\stackrel{\text{def}}{=} X_k \times_{Z_{\psi(k)}} Y_{k'} \end{aligned}$$

for each $(k, k') \in K \times_{K''} K'$.

Proof. We claim that this agrees with the categorical pullback in ISets . \square

8.2.6 Equalisers in ISets

Let $X: K_{\text{disc}} \rightarrow \text{Sets}$ be a K -indexed set, let $Y: K'_{\text{disc}} \rightarrow \text{Sets}$ be a K' -indexed set, and let $(\phi, f), (\psi, g): X \rightarrow Y$ be morphisms of indexed sets (as in Remark 8.1.4.1.2).

Definition 8.2.6.1.1. The **equaliser of (ϕ, f) and (ψ, g)** is the $\text{Eq}(\phi, \psi)$ -indexed set $\text{Eq}(f, g): \text{Eq}(\phi, \psi) \rightarrow \text{Sets}$ defined by

$$(\text{Eq}(f, g))_k \stackrel{\text{def}}{=} \text{Eq}(f_k, g_k)$$

for each $k \in \text{Eq}(\phi, \psi)$.

Proof. We claim that this agrees with the categorical equaliser in ISets . \square

8.3 Colimits of Indexed Sets

8.3.1 Coproducts of K -Indexed Sets

Let $X: K_{\text{disc}} \rightarrow \text{Sets}$ and $Y: K_{\text{disc}} \rightarrow \text{Sets}$ be indexed sets.

Definition 8.3.1.1.1. The **coproduct** of X and Y is the K -indexed set $X \coprod Y: K_{\text{disc}} \rightarrow \text{Sets}$ defined by

$$(X \coprod Y)_k \stackrel{\text{def}}{=} X_k \coprod Y_k$$

for each $k \in K$.

Proof. That this agrees with the categorical coproduct in $\text{ISets}(K)$ follows from ?? of ??.

\square

8.3.2 Pushouts of K -Indexed Sets

Let $X, Y, Z: K_{\text{disc}} \rightarrow \text{Sets}$ be K -indexed sets and let $f: Z \rightarrow X$ and $g: Z \rightarrow Y$ be morphisms of K -indexed sets.

Definition 8.3.2.1.1. The **pushout** of X and Y is the K -indexed set $X \coprod_Z Y: K_{\text{disc}} \rightarrow \text{Sets}$ defined by

$$(X \coprod_Z Y)_k \stackrel{\text{def}}{=} X_k \coprod_{Z_k} Y_k$$

for each $k \in K$.

Proof. That this agrees with the categorical pushout in $\text{ISets}(K)$ follows from ?? of ??.

\square

8.3.3 Coequalisers of K -Indexed Sets

Let $X, Y: K_{\text{disc}} \rightarrow \text{Sets}$ be K -indexed sets and let $f, g: X \rightrightarrows Y$ be morphisms of K -indexed sets.

Definition 8.3.3.1.1. The **coequaliser** of X and Y is the K -indexed set $\text{CoEq}(f, g): K_{\text{disc}} \rightarrow \text{Sets}$ defined by

$$(\text{CoEq}(f, g))_k \stackrel{\text{def}}{=} \text{CoEq}(f_k, g_k)$$

for each $k \in K$.

Proof. That this agrees with the categorical coequaliser in $\text{ISets}(K)$ follows from ?? of ??.

□

8.4 Constructions With Indexed Sets

8.4.1 Change of Indexing

Let $\phi: K \rightarrow K'$ be a function and let X be a K' -indexed set.

Definition 8.4.1.1.1. The **change of indexing of X to K** is the K -indexed set $\phi^*(X)$ defined by

$$\phi^*(X) \stackrel{\text{def}}{=} X \circ \phi_{\text{disc}}.$$

Remark 8.4.1.1.2. In detail, the **change of indexing of X to K** is the K -indexed set $\phi^*(X)$ defined by

$$\phi^*(X)_x \stackrel{\text{def}}{=} X_{\phi(x)}$$

for each $x \in K$.

Proposition 8.4.1.1.3. The assignment $X \mapsto \phi^*(X)$ defines a functor

$$\phi^*: \text{ISets}(K') \rightarrow \text{ISets}(K),$$

where

- *Action on Objects.* For each $X \in \text{Obj}(\text{ISets}(K'))$, we have

$$[\phi^*](X) \stackrel{\text{def}}{=} \phi^*(X);$$

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

$$\phi_{X,Y}^*: \text{Hom}_{\text{ISets}(K')}(X, Y) \rightarrow \text{Hom}_{\text{ISets}(K)}(\phi^*(X), \phi^*(Y))$$

of ϕ^* at (X, Y) is the map sending a morphism of K' -indexed sets

$$f = \{f_x: X_x \rightarrow Y_x\}_{x \in K'}$$

from X to Y to the morphism of K -indexed sets defined by

$$\phi^*(f) \stackrel{\text{def}}{=} \{f_{\phi(x)}: X_{\phi(x)} \rightarrow Y_{\phi(x)}\}_{x \in K}.$$

Proof. Omitted. □

Proposition 8.4.1.1.4. The assignment $K \mapsto \text{ISets}(K)$ defines a functor

$$\text{ISets}: \text{Sets}^{\text{op}} \rightarrow \text{Cats},$$

where

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

$$[\text{ISets}](K) \stackrel{\text{def}}{=} \text{ISets}(K);$$

- *Action on Morphisms.* For each $K, K' \in \text{Obj}(\text{Sets})$, the action on Hom-sets

$$\text{ISets}_{K,K'}: \text{Sets}^{\text{op}}(K, K') \rightarrow \text{Fun}(\text{ISets}(K), \text{ISets}(K'))$$

of ISets at (K, K') is the map defined by

$$\text{ISets}_{K,K'}(\phi) \stackrel{\text{def}}{=} \phi^*$$

for each $\phi \in \text{Sets}^{\text{op}}(K, K')$.

Proof. Omitted. □

8.4.2 Dependent Sums

Let $\phi: K \rightarrow K'$ be a function and let X be a K -indexed set.

Definition 8.4.2.1.1. The **dependent sum of X** is the K' -indexed set $\Sigma_{\phi}(X)$ ² defined by

$$\Sigma_{\phi}(X) \stackrel{\text{def}}{=} \text{Lan}_{\phi}(X),$$

and hence given by

$$\Sigma_{\phi}(X)_x \cong \coprod_{y \in \phi^{-1}(x)} X_y$$

for each $x \in K'$.

Proposition 8.4.2.1.2. The assignment $X \mapsto \Sigma_{\phi}(X)$ defines a functor

$$\Sigma_{\phi}: \text{ISets}(K) \rightarrow \text{ISets}(K'),$$

where

- *Action on Objects.* For each $X \in \text{Obj}(\text{ISets}(K))$, we have

$$[\Sigma_{\phi}](X) \stackrel{\text{def}}{=} \Sigma_{\phi}(X);$$

²Further Notation: Also written $\phi_*(X)$.

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

$$\Sigma_\phi|_{X,Y}: \text{Hom}_{\text{ISets}(K)}(X, Y) \rightarrow \text{Hom}_{\text{ISets}(K')}\left(\Sigma_\phi(X), \Sigma_\phi(Y)\right)$$

of Σ_ϕ at (X, Y) is the map sending a morphism of K -indexed sets

$$f: X \rightarrow Y$$

to the morphism of K' -indexed sets defined by

$$\begin{aligned} \Sigma_\phi(f) &\stackrel{\text{def}}{=} \text{Lan}_\phi(f); \\ &\cong \coprod_{y \in \phi^{-1}(X)} f_y. \end{aligned}$$

Proof. Omitted. □

8.4.3 Dependent Products

Let $\phi: K \rightarrow K'$ be a function and let X be a K -indexed set.

Definition 8.4.3.1.1. The **dependent product** of X is the K' -indexed set $\Pi_\phi(X)$ ³ defined by

$$\Pi_\phi(X) \stackrel{\text{def}}{=} \text{Ran}_\phi(X),$$

and hence given by

$$\Pi_\phi(X)_x \cong \prod_{y \in \phi^{-1}(x)} X_y$$

for each $x \in K'$.

Proposition 8.4.3.1.2. The assignment $X \mapsto \Pi_\phi(X)$ defines a functor

$$\Pi_\phi: \text{ISets}(K) \rightarrow \text{ISets}(K'),$$

where

- *Action on Objects.* For each $X \in \text{Obj}(\text{ISets}(K))$, we have

$$[\Pi_\phi](X) \stackrel{\text{def}}{=} \Pi_\phi(X);$$

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

$$\Pi_\phi|_{X,Y}: \text{Hom}_{\text{ISets}(K)}(X, Y) \rightarrow \text{Hom}_{\text{ISets}(K')}\left(\Pi_\phi(X), \Pi_\phi(Y)\right)$$

³Further Notation: Also written $\phi_!(X)$.

of Π_ϕ at (X, Y) is the map sending a morphism of K -indexed sets

$$f: X \rightarrow Y$$

to the morphism of K' -indexed sets defined by

$$\begin{aligned} \Pi_\phi(f) &\stackrel{\text{def}}{=} \text{Ran}_\phi(f); \\ &\cong \prod_{y \in \phi^{-1}(x)} f_y. \end{aligned}$$

Proof. Omitted. □

8.4.4 Internal Hom

Let K be a set and let X and Y be K -indexed sets.

Definition 8.4.4.1.1. The **internal Hom of indexed sets from X to Y** is the indexed set $\mathbf{Hom}_{\mathbf{ISets}(K)}(X, Y)$ defined by

$$\mathbf{Hom}_{\mathbf{ISets}(K)}(X, Y) \stackrel{\text{def}}{=} \mathbf{Sets}(X_x, Y_x)$$

for each $x \in K$.

8.4.5 Adjointness of Indexed Sets

Let $\phi: K \rightarrow K'$ be a map of sets.

Proposition 8.4.5.1.1. We have a triple adjunction

$$(\Sigma_\phi \dashv \phi^* \dashv \Pi_\phi): \quad \mathbf{ISets}(K) \begin{array}{c} \xleftarrow{\perp} \\[-1ex] \xleftarrow{\phi^*} \\[-1ex] \xleftarrow{\perp} \end{array} \mathbf{ISets}(K').$$

Σ_ϕ
↑
 \perp
↓
 Π_ϕ

Proof. This follows from ?? of ??.

□

Appendices

8.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets
5. Relations
6. Spans
7. Posets

Indexed and Fibred Sets

7. Indexed Sets
8. Fibred Sets
9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories
12. Types of Morphisms in Categories
13. Adjunctions and the Yoneda Lemma
14. Constructions With Categories
15. Profunctors
16. Cartesian Closed Categories
17. Kan Extensions

Bicategories

18. Bicategories
19. Internal Adjunctions

Internal Category Theory

20. Internal Categories

Cyclic Stuff

21. The Cycle Category

Cubical Stuff

22. The Cube Category

Globular Stuff

23. The Globe Category

Cellular Stuff

24. The Cell Category

Monoids

25. Monoids

26. Constructions With Monoids

Monoids With Zero

27. Monoids With Zero

28. Constructions With Monoids With Zero

Groups

29. Groups

30. Constructions With Groups

Hyper Algebra

31. Hypermonoids

32. Hypergroups

33. Hypersemirings and Hyperrings

34. Quantales

Near-Rings

35. Near-Semirings

36. Near-Rings

Real Analysis

37. Real Analysis in One Variable

38. Real Analysis in Several Variables

41. Stochastic Processes, Martingales, and Brownian Motion

Measure Theory

39. Measurable Spaces

42. Itô Calculus

40. Measures and Integration

43. Stochastic Differential Equations

Probability Theory

40. Probability Theory

Differential Geometry

44. Topological and Smooth Manifolds

Stochastic Analysis

Schemes

45. Schemes

8.2 Other Chapters

Sets

15. Profunctors

1. Sets

16. Cartesian Closed Categories

2. Constructions With Sets

17. Kan Extensions

3. Pointed Sets

Bicategories

4. Tensor Products of Pointed Sets

18. Bicategories

5. Relations

19. Internal Adjunctions

6. Spans

Internal Category Theory

7. Posets

20. Internal Categories

Indexed and Fibred Sets

Cyclic Stuff

7. Indexed Sets

21. The Cycle Category

8. Fibred Sets

Cubical Stuff

9. Un/Straightening for Indexed and Fibred Sets

22. The Cube Category

Category Theory

Globular Stuff

11. Categories

23. The Globe Category

12. Types of Morphisms in Categories

Cellular Stuff

13. Adjunctions and the Yoneda Lemma

24. The Cell Category

14. Constructions With Categories

Monoids

25. Monoids

26. Constructions With Monoids

Monoids With Zero	37. Real Analysis in One Variable
27. Monoids With Zero	38. Real Analysis in Several Variables
28. Constructions With Monoids With Zero	Measure Theory
Groups	39. Measurable Spaces
29. Groups	40. Measures and Integration
30. Constructions With Groups	Probability Theory
Hyper Algebra	40. Probability Theory
31. Hypermonoids	Stochastic Analysis
32. Hypergroups	41. Stochastic Processes, Martingales, and Brownian Motion
33. Hypersemirings and Hyperrings	42. Itô Calculus
34. Quantales	43. Stochastic Differential Equations
Near-Rings	Differential Geometry
35. Near-Semirings	44. Topological and Smooth Manifolds
36. Near-Rings	Schemes
Real Analysis	45. Schemes

Chapter 9

Fibred Sets

This chapter contains a discussion of the un/straightening equivalence in the context of sets, as well as a general discussion of indexed and fibred sets. In particular, it contains:

1. A discussion of indexed sets (i.e. functors $K_{\text{disc}} \rightarrow \text{Sets}$ with K a set), constructions with them like dependent sums and dependent products, and their properties (????);
2. A discussion of fibred sets (i.e. maps of sets $X \rightarrow K$), constructions with them like dependent sums and dependent products, and their properties ([Sections 9.1](#) and [9.2](#));
3. A discussion of the un/straightening equivalence for indexed and fibred sets (??).

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9.1 Fibred Sets

9.1.1 Foundations

Let K be a set.

Definition 9.1.1.1.1. A **K -fibred set** is a pair (X, ϕ) consisting of¹

- *The Underlying Set.* A set X , called the **underlying set** of (X, ϕ) ;
- *The Fibration.* A map of sets $\phi: X \rightarrow K$.

9.1.2 Morphisms of Fibred Sets

Definition 9.1.2.1.1. A **morphism of K -fibred sets from (X, ϕ) to (Y, ψ)** is a function $f: X \rightarrow Y$ such that the diagram²

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \phi \searrow & & \swarrow \psi \\ & K & \end{array}$$

commutes.

¹Further Terminology: The **fibre of (X, ϕ) over $x \in K$** is the set $\phi^{-1}(x)$ (also written ϕ_x) defined by

$$\begin{array}{ccc} \phi^{-1}(x) & \xrightarrow{\quad} & X \\ \downarrow & \lrcorner & \downarrow \phi \\ \text{pt} & \xrightarrow{[x]} & K. \end{array}$$

$\phi^{-1}(x) \stackrel{\text{def}}{=} \text{pt} \times_{[x], K, \phi} X,$

²Further Terminology: The **transport map associated to f at $x \in K$** is the function

$$f_x^*: \phi^{-1}(x) \rightarrow \psi^{-1}(x)$$

given by the dashed map in the diagram

$$\begin{array}{ccccc} \phi^{-1}(x) & \xrightarrow{\quad} & X & \xrightarrow{f} & Y \\ \downarrow & \lrcorner & \downarrow \phi & \downarrow & \downarrow \psi \\ \psi^{-1}(x) & \xrightarrow{\quad} & & & \\ \text{pt} & \xrightarrow{[x]} & K & \xrightarrow{\quad} & K \\ \parallel & & \parallel & & \parallel \end{array}$$

$\phi^{-1}(x) \xrightarrow{\quad} X \xrightarrow{f} Y$

$\psi^{-1}(x) \xrightarrow{\quad} \text{pt} \xrightarrow{[x]} K \xrightarrow{\quad} K$

9.1.3 The Category of Fibred Sets Over a Fixed Base

Definition 9.1.3.1.1. The **category of K -fibred sets** is the category $\text{FibSets}(K)$ defined as the slice category $\text{Sets}_{/K}$ of Sets over K :

$$\text{FibSets}(K) \stackrel{\text{def}}{=} \text{Sets}_{/K}.$$

Remark 9.1.3.1.2. In detail $\text{FibSets}(K)$ is the category where

- *Objects.* The objects of $\text{FibSets}(K)$ are pairs (X, ϕ) consisting of
 - *The Fibred Set.* A set X ;
 - *The Fibration.* A function $\phi: X \rightarrow K$;
- *Morphisms.* A morphism of $\text{FibSets}(K)$ from (X, ϕ) to (Y, ψ) is a function $f: X \rightarrow Y$ making the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \phi \searrow & & \swarrow \psi \\ & X & \end{array}$$

commute;

- *Identities.* For each $(X, \phi) \in \text{Obj}(\text{FibSets}(K))$, the unit map

$$\text{id}_{(X, \phi)}^{\text{FibSets}(K)}: \text{pt} \rightarrow \text{Hom}_{\text{FibSets}(K)}((X, \phi), (X, \phi))$$

of $\text{FibSets}(K)$ at (X, ϕ) is given by

$$\text{id}_{(X, \phi)}^{\text{FibSets}(K)} \stackrel{\text{def}}{=} \text{id}_X,$$

as witnessed by the commutativity of the diagram

$$\begin{array}{ccc} X & \xlongequal{\text{id}_X} & X \\ \phi \searrow & & \swarrow \phi \\ & K & \end{array}$$

in Sets ;

- *Composition.* For each $\mathbf{X} = (X, \phi), \mathbf{Y} = (Y, \psi), \mathbf{Z} = (Z, \chi) \in \text{Obj}(\text{FibSets}(K))$, the composition map

$$\circ_{\mathbf{X}, \mathbf{Y}, \mathbf{Z}}^{\text{FibSets}(K)}: \text{Hom}_{\text{FibSets}(K)}(\mathbf{Y}, \mathbf{Z}) \times \text{Hom}_{\text{FibSets}(K)}(\mathbf{X}, \mathbf{Y}) \rightarrow \text{Hom}_{\text{FibSets}(K)}(\mathbf{X}, \mathbf{Z})$$

of $\text{FibSets}(K)$ at $(\mathbf{X}, \mathbf{Y}, \mathbf{Z})$ is defined by

$$\circ_{\mathbf{X}, \mathbf{Y}, \mathbf{Z}}^{\text{FibSets}(K)} \stackrel{\text{def}}{=} \circ_{X, Y, Z}^{\text{Sets}},$$

as witnessed by the commutativity of the diagram

$$\begin{array}{ccccc} X & \xrightarrow{f} & Y & \xrightarrow{g} & Z \\ & \searrow \phi & \downarrow \psi & \swarrow \chi & \\ & & K & & \end{array}$$

in Sets.

9.1.4 The Category of Fibred Sets

Definition 9.1.4.1.1. The **category of fibred sets** is the category FibSets defined as the Grothendieck construction of the functor FibSets: Sets^{op} → Cats of [Proposition 9.2.1.1.3](#):

$$\text{FibSets} \stackrel{\text{def}}{=} \int^{\text{Sets}} \text{FibSets}.$$

Remark 9.1.4.1.2. In detail, the **category of fibred sets** is the category FibSets where

- *Objects.* The objects of FibSets are pairs $(K, (X, \phi_X))$ consisting of
 - *The Base Set.* A set K ;
 - *The Fibred Set.* A K -fibred set $\phi_X: X \rightarrow K$;
- *Morphisms.* A morphism of FibSets from $(K, (X, \phi_X))$ to $(K', (Y, \phi_Y))$ is a pair (ϕ, f) consisting of
 - *The Base Map.* A map of sets $\phi: K \rightarrow K'$;
 - *The Morphism of Fibred Sets.* A morphism of K -fibred sets

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \times_{K'} K \\ f: (X, \phi_X) \rightarrow \phi_Y^*(Y), & \phi_X \searrow & \swarrow \text{pr}_2 \\ & & K; \end{array}$$

- *Identities.* For each $(K, X) \in \text{Obj}(\text{FibSets})$, the unit map

$$\text{id}_{(K,X)}^{\text{FibSets}}: \text{pt} \rightarrow \text{FibSets}((K, X), (K, X))$$

of FibSets at (K, X) is defined by

$$\text{id}_{(K,X)}^{\text{FibSets}} \stackrel{\text{def}}{=} (\text{id}_K, \sim),$$

where \sim is the isomorphism $X \rightarrow X \times_K K$ as in the diagram

$$\begin{array}{ccc} X & \xrightarrow{\sim} & X \times_K K \\ & \searrow \phi_X & \swarrow \text{pr}_2 \\ & & K; \end{array}$$

- Composition. For each $\mathbf{X} = (K, X), \mathbf{Y} = (K', Y), \mathbf{Z} = (K'', Z) \in \text{Obj}(\text{FibSets})$, the composition map

$$\circ^{\text{FibSets}}_{\mathbf{X}, \mathbf{Y}, \mathbf{Z}} : \text{FibSets}(\mathbf{Y}, \mathbf{Z}) \times \text{FibSets}(\mathbf{X}, \mathbf{Y}) \rightarrow \text{FibSets}(\mathbf{X}, \mathbf{Z})$$

of FibSets at $(\mathbf{X}, \mathbf{Y}, \mathbf{Z})$ is defined by

$$g \circ^{\text{FibSets}}_{\mathbf{X}, \mathbf{Y}, \mathbf{Z}} f \stackrel{\text{def}}{=} (g \times_{K'} \text{id}_K) \circ f$$

as in the diagram

$$\begin{array}{ccccc} & & & \cong_{Z \times_{K''} K} & \\ & & & \overbrace{(Z \times_{K''} K') \times_{K'} K} & \\ X & \xrightarrow{f} & Y \times_{K'} K & \xrightarrow{g \times_{K'} \text{id}_K} & \\ \phi_X \searrow & & \downarrow \text{pr}_2 & & \swarrow \text{pr}_2 \\ & & K; & & \end{array}$$

for each $f \in \text{Obj}(\text{FibSets}(\mathbf{X}, \mathbf{Y}))$ and each $g \in \text{Obj}(\text{FibSets}(\mathbf{Y}, \mathbf{Z}))$.

9.2 Constructions With Fibred Sets

9.2.1 Change of Base

Let $f: K \rightarrow K'$ be a function and let (X, ϕ_X) be a K' -fibred set.

Definition 9.2.1.1.1. The **change of base of** (X, ϕ_X) **to** K is the K -fibred set $f^*(X)$ defined by

$$f^*(X) \stackrel{\text{def}}{=} (K \times_{K'} X, \text{pr}_1), \quad \begin{array}{ccc} f^*(X) & \xrightarrow{\text{pr}_2} & X \\ \text{pr}_1 \downarrow & \lrcorner & \downarrow \phi_X \\ K & \xrightarrow{f} & K'. \end{array}$$

Proposition 9.2.1.1.2. The assignment $X \mapsto f^*(X)$ defines a functor

$$f^*: \text{FibSets}(K') \rightarrow \text{FibSets}(K),$$

where

- Action on Objects. For each $(X, \phi_X) \in \text{Obj}(\text{FibSets}(K'))$, we have

$$f^*(X, \phi_X) \stackrel{\text{def}}{=} f^*(X);$$

- *Action on Morphisms.* For each $(X, \phi_X), (Y, \phi_Y) \in \text{Obj}(\text{FibSets}(K'))$, the action on Hom-sets

$$f_{X,Y}^*: \text{Hom}_{\text{FibSets}(K')}(X, Y) \rightarrow \text{Hom}_{\text{FibSets}(K)}(f^*(X), f^*(Y))$$

of f^* at $((X, \phi_X), (Y, \phi_Y))$ is the map sending a morphism of K' -fibred sets

$$g: (X, \phi_X) \rightarrow (Y, \phi_Y)$$

to the morphism of K -fibred sets given by the dashed morphism in the diagram

$$\begin{array}{ccccc} f^*(X) & \xrightarrow{\quad} & X & \xrightarrow{\quad g \quad} & \\ \downarrow & \searrow & \downarrow \phi_X & \swarrow & \\ f^*(Y) & \xrightarrow{\quad} & Y & & \\ \downarrow & \downarrow & \downarrow & & \\ K & \xrightarrow{\quad f \quad} & K' & \xrightarrow{\quad \phi_Y \quad} & \\ \parallel & & \parallel & & \\ K & \xrightarrow{\quad f \quad} & K' & & \end{array}$$

Proof. Omitted. □

Proposition 9.2.1.1.3. The assignment $K \mapsto \text{FibSets}(K)$ defines a functor

$$\text{FibSets}: \text{Sets}^{\text{op}} \rightarrow \text{Cats},$$

where

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

$$[\text{FibSets}](K) \stackrel{\text{def}}{=} \text{FibSets}(K);$$

- *Action on Morphisms.* For each $K, K' \in \text{Obj}(\text{Sets})$, the action on Hom-sets

$$\text{Sets}_{/(-)|K,K'}: \text{Sets}^{\text{op}}(K, K') \rightarrow \text{Fun}(\text{FibSets}(K), \text{FibSets}(K'))$$

of $\text{Sets}_{/(-)}$ at (K, K') is the map sending a map of sets $f: K \rightarrow K'$ to the functor

$$\text{Sets}_{/f}: \text{FibSets}(K') \rightarrow \text{FibSets}(K)$$

defined by

$$\text{Sets}_{/f} \stackrel{\text{def}}{=} f^*.$$

Proof. Omitted. □

9.2.2 Dependent Sums

Let $f: K \rightarrow K'$ be a function and let (X, ϕ_X) be a K -fibred set.

Definition 9.2.2.1.1. The **dependent sum**³ of (X, ϕ_X) is the K' -fibred set $\Sigma_f(X)$ ⁴ defined by

$$\begin{aligned}\Sigma_f(X) &\stackrel{\text{def}}{=} (\Sigma_f(X), \Sigma_f(\phi_X)) \\ &\stackrel{\text{def}}{=} (X, f \circ \phi_X).\end{aligned}$$

Proposition 9.2.2.1.2. Let $f: K \rightarrow K'$ be a function.

1. *Functionality.* The assignment $X \mapsto \Sigma_f(X)$ defines a functor

$$\Sigma_f: \text{FibSets}(K) \rightarrow \text{FibSets}(K'),$$

where

- *Action on Objects.* For each $(X, \phi_X) \in \text{Obj}(\text{FibSets}(K))$, we have

$$\Sigma_f(X, \phi_X) \stackrel{\text{def}}{=} (\Sigma_f(X), \Sigma_f(\phi_X));$$

- *Action on Morphisms.* For each $(X, \phi_X), (Y, \phi_Y) \in \text{Obj}(\text{FibSets}(K))$, the action on Hom-sets

$$\Sigma_{f|X,Y}: \text{Hom}_{\text{FibSets}(K)}(X, Y) \rightarrow \text{Hom}_{\text{FibSets}(K)}(\Sigma_f(X), \Sigma_f(Y))$$

of Σ_f at $((X, \phi_X), (Y, \phi_Y))$ is the map sending a morphism of K -fibred sets

$$g: (X, \phi_X) \rightarrow (Y, \phi_Y)$$

to the morphism of K' -fibred sets defined by

$$\Sigma_f(g) \stackrel{\text{def}}{=} g.$$

2. *Interaction With Fibres.* We have a bijection of sets

$$\Sigma_f(\phi_X)^{-1}(k') \cong \coprod_{k \in f^{-1}(k')} \phi_X^{-1}(k)$$

for each $k' \in K'$.

³The name “dependent sum” comes from the fact that the fibre $\Sigma_f(\phi_X)^{-1}(x)$ of $\Sigma_f(X)$ at $x \in K'$ is given by

$$\Sigma_f(\phi_X)^{-1}(x) \cong \coprod_{y \in f^{-1}(x)} \phi_X^{-1}(y);$$

see Item 2 of Proposition 9.2.2.1.2.

⁴Further Notation: Also written $f_*(X)$.

Proof. **Item 1, Functoriality:** Omitted.

Item 2, Interaction With Fibres: Indeed, we have

$$\begin{aligned}\Sigma_f(\phi_X)^{-1}(k') &\stackrel{\text{def}}{=} \text{pt} \times_{[k'], K', f \circ \phi_X} X \\ &\cong \{x \in X \mid f(\phi_X(x)) = k'\} \\ &\cong \coprod_{k \in f^{-1}(k')} \{x \in X \mid \phi_X(x) = k\} \\ &\cong \coprod_{k \in f^{-1}(k')} \phi_X^{-1}(k)\end{aligned}$$

for each $k' \in K'$. □

9.2.3 Dependent Products

Let $f: K \rightarrow K'$ be a function and let (X, ϕ_X) be a K -fibred set.

Definition 9.2.3.1.1. The **dependent product**⁵ of (X, ϕ_X) is the K' -fibred set $\Pi_f(X)$ ⁶ consisting of⁷

- *The Underlying Set.* The set $\Pi_f(X)$ defined by

$$\Pi_f(X) \stackrel{\text{def}}{=} \coprod_{k' \in K'} \prod_{k \in f^{-1}(k')} \phi_X^{-1}(k);$$

- *The Fibration.* The map of sets

$$\Pi_f(\phi_X): \Pi_f(X) \rightarrow K'$$

defined by sending an element of

$$\Pi_f(X) \stackrel{\text{def}}{=} \coprod_{k' \in K'} \prod_{k \in f^{-1}(k')} \phi_X^{-1}(k)$$

to its index k' in K' .

Example 9.2.3.1.2. Here are some examples of dependent products of sets.

⁵The name “dependent product” comes from the fact that the fibre $\Pi_f(\phi_X)^{-1}(k')$ of $\Pi_f(X)$ at $k' \in K'$ is given by

$$\Pi_f(\phi_X)^{-1}(k') \cong \prod_{k \in f^{-1}(k')} \phi_X^{-1}(k);$$

see [Item 2 of Proposition 9.2.3.1.3](#).

⁶Further Notation: Also written $f_!(X)$.

⁷We can also define dependent products via the internal **Hom** in $\text{FibSets}(K')$; see [Item 3 of Proposition 9.2.3.1.3](#).

1. *Spaces of Sections.* Let $K = X, K' = \text{pt}$, let $\phi: E \rightarrow X$ be a map of sets, and write $!_X: X \rightarrow \text{pt}$ for the terminal map from X to pt . We have a bijection of sets

$$\begin{aligned}\Pi_{!_X}((E, \phi)) &\cong \Gamma_X(\phi) \\ &\stackrel{\text{def}}{=} \{h \in \text{Sets}(X, E) \mid \phi \circ h = \text{id}_X\}.\end{aligned}$$

2. *Function Spaces.* Let $K = K' = \text{pt}$ and write $!_X: X \rightarrow \text{pt}$ and $!_Y: Y \rightarrow \text{pt}$ for the terminal maps from X and Y to pt . We have a bijection of sets

$$\text{Sets}(X, Y) \cong \Pi_{!_X}(!^*_X(Y, !_Y)).$$

Proof. **Item 1, Spaces of Sections:** Indeed, we have

$$\begin{aligned}\Pi_{!_X}((E, \phi)) &\stackrel{\text{def}}{=} \coprod_{\star \in \text{pt}} \prod_{k \in !_X^{-1}(\star)} \phi_X^{-1}(k) \\ &= \prod_{x \in X} \phi_X^{-1}(x) \\ &\cong \{h \in \text{Sets}(X, E) \mid \phi_X \circ h = \text{id}_X\} \\ &\stackrel{\text{def}}{=} \Gamma_X(\phi).\end{aligned}$$

Item 2, Function Spaces: Indeed, we have

$$\begin{aligned}\Pi_{!_X}(!^*_X(Y, !_Y)) &\stackrel{\text{def}}{=} \Pi_{!_X}(X \times_{!_X, \text{pt}, !_Y} Y) \\ &\stackrel{\text{def}}{=} \coprod_{\star \in \text{pt}} \prod_{x \in !_X^{-1}(\star)} \text{pr}_1^{-1}(x) \\ &= \prod_{x \in X} Y \\ &\cong \text{Sets}(X, Y).\end{aligned}$$

This finishes the proof. □

Proposition 9.2.3.1.3. Let $f: K \rightarrow K'$ be a function.

1. *Functoriality.* The assignment $X \mapsto \Pi_f(X)$ defines a functor

$$\Pi_f: \text{FibSets}(K) \rightarrow \text{FibSets}(K'),$$

where

- *Action on Objects.* For each $(X, \phi_X) \in \text{Obj}(\text{FibSets}(K))$, we have

$$\Pi_f(X, \phi_X) \stackrel{\text{def}}{=} \Pi_f(X);$$

- *Action on Morphisms.* For each $(X, \phi_X), (Y, \phi_Y) \in \text{Obj}(\text{FibSets}(K))$, the

action on Hom-sets

$$\Pi_{f|X,Y} : \text{Hom}_{\text{FibSets}(K)}(X, Y) \rightarrow \text{Hom}_{\text{FibSets}(K')}(\Pi_f(X), \Pi_f(Y))$$

of Π_f at $((X, \phi_X), (Y, \phi_Y))$ is the map sending a morphism of K -fibred sets

$$\xi : (X, \phi_X) \rightarrow (Y, \phi_Y), \quad \begin{array}{ccc} X & \xrightarrow{\xi} & Y \\ \phi_X \searrow & & \swarrow \phi_Y \\ & K & \end{array}$$

to the morphism

$$\Pi_f(\xi) : (\Pi_f(X), \Pi_f(\phi_X)) \rightarrow (\Pi_f(Y), \Pi_f(\phi_Y)) \quad \begin{array}{ccc} \Pi_f(X) & \xrightarrow{\Pi_f(\xi)} & \Pi_f(Y) \\ \Pi_f(\phi_X) \searrow & & \swarrow \Pi_f(\phi_Y) \\ & K & \end{array}$$

of K' -fibred sets given by⁸

$$[\Pi_f(\xi)]((x_k)_{k \in f^{-1}(k')}) \stackrel{\text{def}}{=} (\xi(x_k))_{k \in f^{-1}(k')}$$

for each $(x_k)_{k \in f^{-1}(k')} \in \Pi_f(X)$.

2. *Interaction With Fibres.* We have a bijection of sets

$$\Pi_f(\phi_X)^{-1}(k') \cong \prod_{k \in f^{-1}(k')} \phi_X^{-1}(k);$$

for each $k' \in K'$.

3. *Construction Using the Internal Hom.* We have

$$\Pi_f(X, \phi_X) = \left(K' \times_{\text{Hom}_{\text{FibSets}(K')}((K, f), (K, f))} \text{Hom}_{\text{FibSets}(K')}((K, f), (X, f \circ \phi_X)), \text{pr}_1 \right),$$

⁸Note that we indeed have $\xi(x_k) \in \phi_Y^{-1}(k)$, since

$$\begin{aligned} \phi_Y(\xi(x_k)) &= [\phi_Y \circ \xi](x_k) \\ &= \phi_X(x_k) \\ &= k, \end{aligned}$$

where we have used that ξ is a morphism of K -fibred sets for the second equality.

forming a pullback diagram

$$\begin{array}{ccc} \Pi_f(X, \phi_X) & \xrightarrow{\text{pr}_2} & \mathbf{Hom}_{\mathbf{FibSets}(K')}((K, f), (X, f \circ \phi_X)) \\ \text{pr}_1 \downarrow & \lrcorner & \downarrow (\phi_X)_* \\ K' & \xrightarrow[I]{} & \mathbf{Hom}_{\mathbf{FibSets}(K')}((K, f), (K, f)), \end{array}$$

where the bottom map is given by

$$I(k') \stackrel{\text{def}}{=} \text{id}_{f^{-1}(k')}$$

for each $k' \in K'$ and where $\mathbf{Hom}_{\mathbf{FibSets}(K')}$ denotes the internal Hom of $\mathbf{FibSets}(K')$ of [Definition 9.2.4.1.1](#).

4. *Internal Hom via Dependent Products.* We have

$$\mathbf{Hom}_{\mathbf{FibSets}(K)}(X, Y) \cong \Pi_{\phi_X}(\phi_X^*(Y)).$$

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

[Item 2, Interaction With Fibres:](#) Clear.

[Item 3, Construction Using the Internal Hom:](#) Using the explicit formula for pullbacks of sets given in ??, we see that the pullback

$$K' \times_{\mathbf{Hom}_{\mathbf{FibSets}(K')}((K, f), (K, f))} \mathbf{Hom}_{\mathbf{FibSets}(K')}((K, f), (X, f \circ \phi_X))$$

is given by

$$\left\{ (k', h) \in \coprod_{k' \in K'} \text{Sets}\left(f^{-1}(k'), \phi_X^{-1}\left(f^{-1}(k')\right)\right) \middle| \phi_X \circ h = \text{id}_{f^{-1}(k')} \right\},$$

which is isomorphic to

$$\coprod_{k' \in K'} \left\{ h \in \text{Sets}\left(f^{-1}(k'), \phi_X^{-1}\left(f^{-1}(k')\right)\right) \middle| \phi_X \circ h = \text{id}_{f^{-1}(k')} \right\}.$$

We claim that

$$\left\{ h \in \text{Sets}\left(f^{-1}(k'), \phi_X^{-1}\left(f^{-1}(k')\right)\right) \middle| \phi_X \circ h = \text{id}_{f^{-1}(k')} \right\} \cong \prod_{k \in f^{-1}(k')} \phi_X^{-1}(k),$$

so that the pullback is indeed given by $\Pi_f(X)$. There are two cases:

1. If $f^{-1}(k') = \emptyset$, then there is only one map from $f^{-1}(k')$ to $\phi_X^{-1}(f^{-1}(k'))$ (the inclusion), so $\text{Sets}(f^{-1}(k'), \phi_X^{-1}(f^{-1}(k')) \cong \text{pt}$. Since products indexed by the empty set are isomorphic to pt, the isomorphism follows.

2. Otherwise, by the condition $\phi_X \circ h = \text{id}_{f^{-1}(k')}$, it follows that, for each $k \in f^{-1}(k')$, we must have

$$\phi_X(h(k)) = k,$$

and thus $h(k) \in \phi_X^{-1}(k)$. Therefore, a map from $f^{-1}(k')$ to $\phi_X^{-1}(f^{-1}(k'))$ consists of a choice of an element from $\phi_X^{-1}(k)$ for each $k \in f^{-1}(k')$, which is precisely given by an element of the product $\prod_{k \in f^{-1}(k')} \phi_X^{-1}(k)$, showing the bijection to be true.

Item 4, Internal Hom via Dependent Products: Indeed we have

$$\begin{aligned} \Pi_{\phi_X}(\phi_X^*(Y)) &\stackrel{\text{def}}{=} \Pi_{\phi_X}(X \times_K Y) \\ &\stackrel{\text{def}}{=} \coprod_{k \in K} \prod_{x \in \phi_X^{-1}(k)} \text{pr}_1^{-1}(x) \\ &\cong \coprod_{k \in K} \prod_{x \in \phi_X^{-1}(k)} \{y \in Y \mid \phi_X(x) = \phi_Y(y)\} \\ &\cong \coprod_{k \in K} \prod_{x \in \phi_X^{-1}(k)} \{y \in Y \mid k = \phi_Y(y)\} \\ &\cong \coprod_{k \in K} \prod_{x \in \phi_X^{-1}(k)} \phi_Y^{-1}(k) \\ &\cong \coprod_{k \in K} \text{Sets}(\phi_X^{-1}(k), \phi_Y^{-1}(k)) \\ &\stackrel{\text{def}}{=} \mathbf{Hom}_{\text{FibSets}(K)}(X, Y). \end{aligned}$$

This finishes the proof. □

9.2.4 Internal Hom

Let K be a set and let (X, ϕ_X) and (Y, ϕ_Y) be K -fibred sets.

Definition 9.2.4.1.1. The **internal Hom of fibred sets from** (X, ϕ_X) **to** (Y, ϕ_Y) is the fibred set $\mathbf{Hom}_{\text{FibSets}(K)}(X, Y)$ consisting of

- *The Underlying Set.* The set $\mathbf{Hom}_{\text{FibSets}(K)}(X, Y)$ defined by

$$\mathbf{Hom}_{\text{FibSets}(K)}(X, Y) \stackrel{\text{def}}{=} \coprod_{k \in K} \text{Sets}(\phi_X^{-1}(k), \phi_Y^{-1}(k));$$

- *The Fibration.* The map of sets⁹

$$\phi_{\mathbf{Hom}_{\text{FibSets}(K)}(X,Y)} : \underbrace{\mathbf{Hom}_{\text{FibSets}(K)}(X,Y)}_{\coprod_{k \in K} \text{Sets}(\phi_X^{-1}(k), \phi_Y^{-1}(k))} \rightarrow K$$

defined by sending a map $f : \phi_X^{-1}(k) \rightarrow \phi_Y^{-1}(k)$ to its index $k \in K$.

Proof. Omitted. □

Proposition 9.2.4.1.2. Let K be a set and let (X, ϕ_X) and (Y, ϕ_Y) be K -fibred sets.

1. *Functoriality.* Let (X, ϕ_X) and (Y, ϕ_Y) be K -fibred sets.

- (a) The assignment $X \mapsto \mathbf{Hom}_{\text{FibSets}(K)}(X, Y)$ defines a functor

$$\mathbf{Hom}_{\text{FibSets}(K)}(X, -) : \text{FibSets}(K) \rightarrow \text{FibSets}(K).$$

- (b) The assignment $Y \mapsto \mathbf{Hom}_{\text{FibSets}(K)}(X, Y)$ defines a functor

$$\mathbf{Hom}_{\text{FibSets}(K)}(-, Y) : \text{FibSets}(K)^{\text{op}} \rightarrow \text{FibSets}(K).$$

- (c) The assignment $(X, Y) \mapsto \mathbf{Hom}_{\text{FibSets}(K)}(X, Y)$ defines a functor

$$\mathbf{Hom}_{\text{FibSets}(K)}(-_1, -_2) : \text{FibSets}(K)^{\text{op}} \times \text{FibSets}(K) \rightarrow \text{FibSets}(K).$$

2. *Internal Hom via Dependent Products.* We have

$$\mathbf{Hom}_{\text{FibSets}(K)}(X, Y) \cong \Pi_{\phi_X}(\phi_X^*(Y)).$$

Proof. **Item 1, Functoriality:** Omitted.

Item 2, Internal Hom via Dependent Products: This was proved in [Item 4 of Proposition 9.2.3.1.3](#). □

9.2.5 Adjointness for Fibred Sets

Let $f : K \rightarrow K'$ be a map of sets.

⁹The fibres of the internal \mathbf{Hom} of $\text{FibSets}(K)$ are precisely the sets $\text{Sets}(\phi_X^{-1}(k), \phi_Y^{-1}(k))$, i.e. we have

$$\phi_{\mathbf{Hom}_{\text{FibSets}(K)}(X,Y)|k} \cong \text{Sets}(\phi_X^{-1}(k), \phi_Y^{-1}(k))$$

for each $k \in K$.

Proposition 9.2.5.1.1. We have a triple adjunction

$$(\Sigma_f \dashv f^* \dashv \Pi_f): \quad \text{FibSets}(K) \begin{array}{c} \xleftarrow{\perp} \\[-1ex] f^* \\[-1ex] \xrightarrow{\perp} \end{array} \text{FibSets}(K').$$

Σ_f

Π_f

We offer two proofs. The first uses the corresponding adjunction for indexed sets (??) and the un/straightening equivalence together with its compatibility with dependent sums and products to “transfer” the adjunction to fibred sets, while the second is a direct proof.

Proof. The Adjunction $\Sigma_f \dashv f^$:* The adjunction

$$(\Sigma_f \dashv f^*): \quad \text{ISets}(K) \begin{array}{c} \xleftarrow{\perp} \\[-1ex] f^* \\[-1ex] \xrightarrow{\perp} \end{array} \text{ISets}(K')$$

of ?? gives a unit and counit of the form

$$\begin{aligned} \eta: \text{id}_{\text{ISets}(K)} &\Longrightarrow \Sigma_f \circ f^*, \\ \epsilon: f^* \circ \Sigma_f &\Longrightarrow \text{id}_{\text{ISets}(K')}. \end{aligned}$$

With these in hand, we construct natural transformations

$$\begin{aligned} \eta': \text{id}_{\text{FibSets}(K)} &\Longrightarrow \Sigma_f \circ f^*, \\ \epsilon': f^* \circ \Sigma_f &\Longrightarrow \text{id}_{\text{FibSets}(K')} \end{aligned}$$

as follows:

1. *The Unit.* We define $\eta': \text{id}_{\text{FibSets}(K)} \Longrightarrow \Sigma_f \circ f^*$ as the pasting of the diagram

$$\begin{array}{ccccc}
 & & \text{FibSets}(K') & & \\
 & \nearrow \Sigma_f & \uparrow \text{St}_{K'} & \searrow f^* & \\
 \text{FibSets}(K) & (1) & \text{ISets}(K') & (2) & \text{FibSets}(K) \\
 \uparrow \text{id}_{\text{FibSets}(K)} & \swarrow \text{St}_K & \uparrow \eta & \downarrow \text{f}^* & \uparrow \text{id}_{\text{FibSets}(K)} \\
 & (3) & \text{ISets}(K) & (5) & \\
 & \nearrow \Sigma_f & \uparrow \text{id}_{\text{ISets}(K)} & \searrow \text{f}^* & \\
 & \text{FibSets}(K) & \longrightarrow & \text{ISets}(K) & \text{FibSets}(K), \\
 & \uparrow \text{Un}_K & & \downarrow \text{Un}_K & \\
 & & (4) & &
 \end{array}$$

where:

- (a) Subdiagram (1) commutes by ?? of ??.
- (b) Subdiagram (2) commutes by ?? of ??.
- (c) Subdiagram (3) commutes by ??.
- (d) Subdiagram (4) commutes by ??.
- (e) Subdiagram (5) commutes by unitality of composition.

2. *The Counit.* We define $\epsilon': f^* \circ \Sigma_f \Rightarrow \text{id}_{\text{FibSets}(K')}$ as the pasting of the diagram

$$\begin{array}{ccccc}
 \text{FibSets}(K') & \xrightarrow{\text{id}_{\text{FibSets}(K')}} & \text{FibSets}(K') & & \\
 \downarrow \text{id}_{\text{FibSets}(K')} & \swarrow \text{Un}_K & \uparrow \text{(1)} & \searrow \text{Un}_K & \downarrow \text{id}_{\text{FibSets}(K')} \\
 \text{ISets}(K') & \xrightarrow{\text{id}_{\text{ISets}(K)}} & \text{ISets}(K') & \xrightarrow{\text{id}_{\text{FibSets}(K')}} & \text{FibSets}(K') \\
 \downarrow \text{St}_{K'} & \swarrow \text{f}^* & \uparrow \epsilon & \searrow \Sigma_f & \downarrow \text{St}_{K'} \\
 \text{FibSets}(K') & \xrightarrow{\text{(4)}} & \text{ISets}(K) & \xrightarrow{\text{(5)}} & \text{FibSets}(K') \\
 & & \downarrow \text{St}_K & & \\
 & & \text{FibSets}(K) & \xrightarrow{\text{f}^*} & \Sigma_f
 \end{array}$$

where:

- (a) Subdiagram (1) commutes by unitality of composition.
- (b) Subdiagram (2) commutes by ??.
- (c) Subdiagram (3) commutes by ??.
- (d) Subdiagram (4) commutes by ?? of ??.
- (e) Subdiagram (5) commutes by ?? of ??.

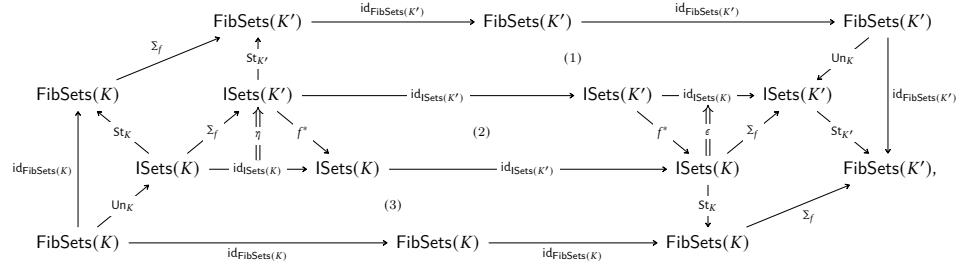
Next, we prove the left triangle identity,

$$\begin{array}{ccc}
 \text{FibSets}(K') & \xrightarrow{\text{id}_{\text{FibSets}(K')}} & \text{FibSets}(K') \\
 \downarrow \Sigma_f & \swarrow \eta & \uparrow \epsilon & \nearrow \Sigma_f \\
 \text{FibSets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K)}} & \text{FibSets}(K)
 \end{array} = \begin{array}{ccc}
 \text{FibSets}(K') & \xrightarrow{\text{id}_{\text{FibSets}(K')}} & \text{FibSets}(K') \\
 \downarrow \Sigma_f & \parallel & \downarrow \text{id}_{\Sigma_f} & \parallel & \downarrow \Sigma_f \\
 \text{FibSets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K)}} & \text{FibSets}(K)
 \end{array}$$

whose left side in our case looks like this:

$$\begin{array}{ccccccc}
 & \text{FibSets}(K') & \xrightarrow{\text{id}_{\text{FibSets}(K')}} & \text{FibSets}(K') & \xrightarrow{\text{id}_{\text{FibSets}(K')}} & \text{FibSets}(K') & \\
 & \downarrow \Sigma_f & \uparrow \text{St}_{K'} & \downarrow \text{f}^* & \downarrow \text{Un}_K & \downarrow \Sigma_f & \\
 \text{FibSets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K)}} & \text{ISets}(K') & \xrightarrow{\text{id}_{\text{ISets}(K)}} & \text{ISets}(K') & \xrightarrow{\text{id}_{\text{FibSets}(K')}} & \text{FibSets}(K') \\
 & \uparrow \text{St}_K & \uparrow \eta & \uparrow \text{f}^* & \uparrow \text{St}_{K'} & \uparrow \epsilon & \downarrow \text{St}_{K'} \\
 & \text{FibSets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K)}} & \text{ISets}(K) & \xrightarrow{\text{id}_{\text{ISets}(K)}} & \text{ISets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K')}} \text{FibSets}(K) \\
 & \uparrow \text{Un}_K & \parallel & \uparrow \text{f}^* & \uparrow \text{St}_K & \uparrow \Sigma_f & \downarrow \Sigma_f \\
 \text{FibSets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K)}} & \text{FibSets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K)}} & \text{FibSets}(K) & \xrightarrow{\text{id}_{\text{FibSets}(K)}} & \text{FibSets}(K)
 \end{array}$$

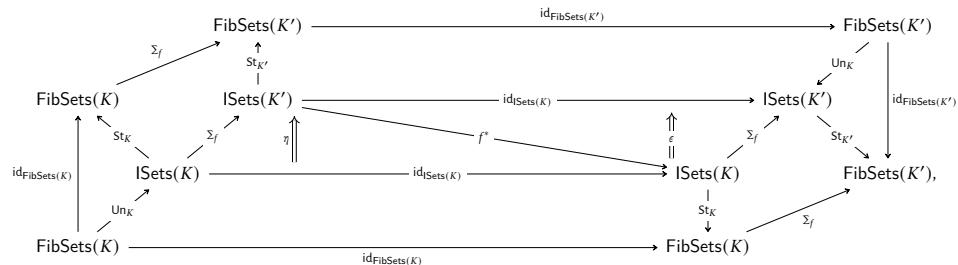
It can be rearranged into



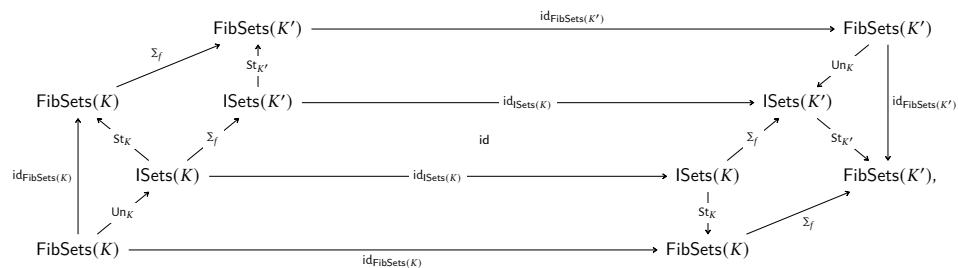
where:

1. Subdiagram (1) commutes by ??.
 2. Subdiagram (2) commutes by unitality of composition.
 3. Subdiagram (3) commutes by ??.

And then, it can be rearranged into



which by the left triangle identity for (η, ϵ) , becomes



finishing the proof of the left triangle identity. The proof of the right triangle identity is similar, and is thus omitted.

The Adjunction $f^ \dashv \Pi_f$:* This proof is similar to the proof of the adjunction $\Sigma_f \dashv f^*$, and is thus omitted. \square

We proceed to the direct proof of [Proposition 9.2.5.1.1](#).

Proof. *The Adjunction $\Sigma_f \dashv f^*$:* We claim there's a bijection

$$\text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X), Y) \cong \text{Hom}_{\text{FibSets}(K)}(X, f^*(Y)),$$

natural in $(X, \phi_X) \in \text{Obj}(\text{FibSets}(K))$ and $(Y, \phi_Y) \in \text{Obj}(\text{FibSets}(K'))$:

- *Map I.* We define a map

$$\Phi_{X,Y}: \text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X), Y) \rightarrow \text{Hom}_{\text{FibSets}(K)}(X, f^*(Y)),$$

by sending a morphism

$$\begin{array}{ccc} X & \xrightarrow{\xi} & Y \\ \xi: \Sigma_f(X) \rightarrow Y, & \phi_X \searrow & \swarrow \phi_Y \\ & K & \\ & f \downarrow & \\ & K' & \end{array}$$

of K' -fibred sets to the morphism

$$\begin{array}{ccc} X & \xrightarrow{\xi^\dagger} & K \times_{K'} Y \\ \xi^\dagger: X \rightarrow f^*(Y), & \phi_X \searrow & \swarrow \text{pr}_1 \\ & K' & \end{array}$$

of K -fibred sets given by the dashed morphism in the diagram

$$\begin{array}{ccccc} X & \xrightarrow{\xi} & K \times_{K'} Y & \xrightarrow{\text{pr}_2} & Y \\ \exists! \searrow & & \downarrow \text{pr}_1 & & \downarrow \phi_Y \\ \phi_X \searrow & & K & \xrightarrow{f} & K' \\ & & & & \end{array}$$

- *Map II.* We define a map

$$\Psi_{X,Y}: \text{Hom}_{\text{FibSets}(K)}(X, f^*(Y)) \rightarrow \text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X), Y),$$

given by sending a map

$$\begin{array}{ccc} X & \xrightarrow{\xi} & K \times_{K'} Y \\ \xi: X \rightarrow f^*(Y), & \phi_X \searrow & \swarrow \text{pr}_1 \\ & K' & \end{array}$$

of K' -fibred sets to the map

$$\xi^\dagger: \Sigma_f(X) \rightarrow Y, \quad \begin{array}{ccc} X & \xrightarrow{\xi^\dagger} & Y \\ \phi_X \searrow & K & \swarrow \phi_Y \\ f \searrow & K' & \end{array}$$

of K -fibred sets given by

$$\xi^\dagger \stackrel{\text{def}}{=} \text{pr}_2 \circ \xi,$$

where we indeed have

$$\begin{aligned} \phi_Y \circ (\text{pr}_2 \circ \xi) &= (\phi_Y \circ \text{pr}_2) \circ \xi \\ &= (f \circ \text{pr}_1) \circ \xi && \text{(by the pullback square of } K \times_{K'} Y \text{)} \\ &= f \circ (\text{pr}_1 \circ \xi) \\ &= f \circ \phi_X. && \text{(since } \xi \text{ is a morphism of } K'\text{-fibred sets)} \end{aligned}$$

- *Naturality I.* We need to show that, given a morphism

$$\alpha: (X, \phi_X) \rightarrow (X', \phi_{X'})$$

of K -fibred sets, the diagram

$$\begin{array}{ccc} \text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X'), Y) & \xrightarrow{\Phi_{X',Y}} & \text{Hom}_{\text{FibSets}(K)}(X', f^*(Y)), \\ \downarrow \Sigma_f(\alpha)^* & & \downarrow \alpha^* \\ \text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X), Y) & \xrightarrow{\Phi_{X,Y}} & \text{Hom}_{\text{FibSets}(K)}(X, f^*(Y)) \end{array}$$

commutes. Indeed, given a morphism

$$\xi: \Sigma_f(X') \rightarrow Y, \quad \begin{array}{ccc} X' & \xrightarrow{\xi} & Y \\ \phi_{X'} \searrow & K & \swarrow \phi_Y \\ f \searrow & K' & \end{array}$$

of K' -fibred sets, the map $\Phi_{X',Y}(\xi) \circ \alpha$ is the composition, coloured in **vermillion**,

of the dashed arrow with α in the diagram

$$\begin{array}{ccccc}
 X & \xrightarrow{\quad \text{dashed} \quad} & X' & \xrightarrow{\quad \text{dashed} \quad} & K \times_{K'} Y \\
 \downarrow \alpha & \nearrow \xi \circ \alpha & \downarrow \exists! & \nearrow \xi & \downarrow \text{pr}_2 \\
 & & X' & \xrightarrow{\quad \text{dashed} \quad} & Y \\
 \phi_{X'} \circ \alpha & & \phi_{X'} & \nearrow \exists! & \downarrow \text{pr}_1 \\
 & & & \nearrow \exists! & \downarrow \phi_Y \\
 & & K \times_{K'} Y & \xrightarrow{\quad \text{dashed} \quad} & Y \\
 & & \downarrow \text{pr}_1 & & \downarrow \phi_Y \\
 & & K & \xrightarrow{f} & K'
 \end{array}$$

while $\Phi_{X,Y}(\xi \circ \Sigma_f(\alpha))$ is given by the dashed arrow, coloured in blue. Since both the blue arrow and the vermillion arrow make the outer pullback diagram commute, it follows from the universal property of the pullback that they must be equal, i.e. that

$$\Phi_{X',Y}(\xi) \circ \alpha = \Phi_{X,Y}(\xi \circ \Sigma_f(\alpha)),$$

showing that the naturality diagram above indeed commutes.

- *Naturality II.* We need to show that, given a morphism

$$\beta: (Y, \phi_Y) \rightarrow (Y', \phi_{Y'})$$

of K -fibred sets, the diagram

$$\begin{array}{ccc}
 \text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X), Y) & \xrightarrow{\Phi_{X,Y}} & \text{Hom}_{\text{FibSets}(K)}(X, f^*(Y)), \\
 \beta_* \downarrow & & \downarrow f^*(\beta)_* \\
 \text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X), Y') & \xrightarrow{\Phi_{X,Y'}} & \text{Hom}_{\text{FibSets}(K)}(X, f^*(Y'))
 \end{array}$$

commutes. Indeed, given a morphism

$$\begin{array}{ccc}
 X' & \xrightarrow{\xi} & Y \\
 \xi: \Sigma_f(X') \rightarrow Y, & \phi_{X'} \searrow & \swarrow \phi_Y \\
 & K & \\
 & f \searrow & \swarrow \phi_Y \\
 & K' &
 \end{array}$$

of K' -fibred-sets, the map $f^*(\beta) \circ \Phi_{X,Y}(\xi)$ is the composition, coloured in vermillion, of the dashed arrow from X to $K \times_{K'} Y$ with the dashed arrow from $K \times_{K'} Y$

to $K \times_{K'} Y'$ in the diagram

$$\begin{array}{ccccc}
X & \xrightarrow{\quad \xi \quad} & K \times_{K'} Y & \xrightarrow{\quad \beta \quad} & Y \\
\phi_X \downarrow & \nearrow \exists! & \downarrow \exists! & \downarrow \phi_Y & \downarrow \beta \\
& K \times_{K'} Y' & \xrightarrow{\quad \text{id} \quad} & Y' & \\
\downarrow & \nearrow \exists! & \downarrow \text{id} & \downarrow \phi_{Y'} & \downarrow \phi_{Y'} \\
K & \xrightarrow{\quad f \quad} & K & \xrightarrow{\quad f \quad} & K' \\
\parallel & \nearrow \parallel & \downarrow \parallel & \nearrow \parallel & \downarrow \parallel \\
K & \xrightarrow{\quad f \quad} & K' & &
\end{array}$$

while $\Phi_{X,Y'}(\beta \circ \xi)$ is given by the dashed arrow from X to $K \times_{K'} Y'$, coloured in blue. Since both the blue arrow and the vermillion arrow make the outer pullback diagram for $K \times_{K'} Y'$ commute, it follows from the universal property of the pullback that they must be equal, i.e. that

$$f^*(\beta) \circ \Phi_{X,Y}(\xi) = \Phi_{X,Y'}(\beta \circ \xi),$$

showing that the naturality diagram above indeed commutes.

- *Invertibility I.* We claim that

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \text{id}_{\text{Hom}_{\text{FibSets}(K')}(\Sigma_f(X), Y)}.$$

Indeed, $\Phi_{X,Y}$ sends a map

$$\xi: \Sigma_f(X) \rightarrow Y, \quad \begin{array}{ccc} X & \xrightarrow{\quad \xi \quad} & Y \\ \phi_X \searrow & & \swarrow \phi_Y \\ K & \xrightarrow{\quad f \quad} & K' \end{array}$$

of K' -fibred sets to the dashed morphism in the diagram

$$\begin{array}{ccccc}
X & \xrightarrow{\quad \xi \quad} & K \times_{K'} Y & \xrightarrow{\quad \text{pr}_2 \quad} & Y \\
\phi_X \downarrow & \nearrow \exists! & \downarrow \text{id} & \downarrow \text{id} & \downarrow \phi_Y \\
& K \times_{K'} Y & \xrightarrow{\quad \text{pr}_1 \quad} & K & \\
\downarrow & & \downarrow & \downarrow f & \downarrow \phi_Y \\
K & \xrightarrow{\quad f \quad} & K' & &
\end{array}$$

and $\Psi_{X,Y}$ then postcomposes that map with pr_2 , which, by the commutativity of the diagram above, is ξ again, showing the claimed equality to be true.

- *Invertibility II.* We claim that

$$\Phi_{X,Y} \circ \Psi_{X,Y} = \text{id}_{\text{Hom}_{\text{FibSets}(K)}(X, f^*(Y))}.$$

Indeed, $\Psi_{X,Y}$ sends a map

$$\begin{array}{ccc} X & \xrightarrow{\xi} & K \times_{K'} Y \\ \xi: X \rightarrow f^*(Y), & \phi_X \searrow & \swarrow \text{pr}_1 \\ & K' & \end{array}$$

of K' -fibred sets to $\text{pr}_2 \circ \xi$, which is then sent by $\Phi_{X,Y}$ to the dashed morphism in the diagram

$$\begin{array}{ccccc} X & \xrightarrow{\quad \exists! \quad} & K \times_{K'} Y & \xrightarrow{\text{pr}_2 \circ \xi} & Y \\ \phi_X \searrow & \nearrow (\dagger) & \downarrow \text{pr}_1 & \nearrow \text{pr}_2 & \downarrow \phi_Y \\ & & K & \xrightarrow{f} & K', \end{array}$$

which, by the commutativity of the subdiagram marked with (\dagger) , is given by ξ again, showing the claimed equality to be true.

The Adjunction $f^ \dashv \Pi_f$:* We claim there's a bijection

$$\text{Hom}_{\text{FibSets}(K)}(f^*(X), Y) \cong \text{Hom}_{\text{FibSets}(K')}(X, \Pi_f(Y))$$

natural in $(X, \phi_X) \in \text{Obj}(\text{FibSets}(K'))$ and $(Y, \phi_Y) \in \text{Obj}(\text{FibSets}(K))$:

1. *Map I.* We define a map

$$\Phi_{X,Y}: \text{Hom}_{\text{FibSets}(K)}(f^*(X), Y) \rightarrow \text{Hom}_{\text{FibSets}(K')}(X, \Pi_f(Y))$$

defined as follows. Given a morphism

$$\begin{array}{ccc} \xi: f^*(X) \rightarrow Y, & K \times_{K'} X & \xrightarrow{\xi} Y \\ & \text{pr}_1 \searrow & \swarrow \phi_Y \\ & K & \end{array}$$

of K -fibred sets, where

$$\begin{aligned} f^*(X) &\stackrel{\text{def}}{=} K \times_{K'} X \\ &\stackrel{\text{def}}{=} \{(k, x) \in K \times X \mid f(k) = \phi_X(x)\}, \end{aligned}$$

we construct a morphism

$$\xi^\dagger: X \rightarrow \Pi_f(Y), \quad \begin{array}{ccc} X & \xrightarrow{\xi^\dagger} & \Pi_f(Y) \\ \phi_X \searrow & & \swarrow \Pi_f(\phi_Y) \\ & K' & \end{array}$$

of K' -fibred sets, where

$$\Pi_f(Y) \stackrel{\text{def}}{=} \coprod_{k' \in K'} \prod_{k \in f^{-1}(k')} \phi_Y^{-1}(k),$$

by defining

$$\xi^\dagger(x) \stackrel{\text{def}}{=} (\xi(k, x))_{k \in f^{-1}(\phi_X(x))}$$

for each $x \in X$. There are two things to be checked here:

- We have $\xi(k, x) \in \phi_Y^{-1}(\phi_X(x))$ since $\phi_Y(\xi(k, x)) = \phi_X(x)$ as ξ is a morphism of K -fibred sets.
- The map ξ^\dagger is indeed a morphism of K' -fibred sets, i.e. we have

$$\Pi_f(\phi_Y) \circ \xi^\dagger = \phi_X,$$

since

$$[\Pi_f(\phi_Y)]((\xi(k, x))_{k \in f^{-1}(\phi_X(x))}) = \phi_X(x)$$

for each $x \in X$.

2. *Map II.* We define a map

$$\Psi_{X,Y}: \text{Hom}_{\text{FibSets}(K')}(X, \Pi_f(Y)) \rightarrow \text{Hom}_{\text{FibSets}(K)}(f^*(X), Y)$$

as follows. Given a morphism

$$\xi: X \rightarrow \Pi_f(Y), \quad \begin{array}{ccc} X & \xrightarrow{\xi} & \Pi_f(Y) \\ \phi_X \searrow & & \swarrow \Pi_f(\phi_Y) \\ & K' & \end{array}$$

of K' -fibred sets, where

$$\Pi_f(Y) \stackrel{\text{def}}{=} \coprod_{k' \in K'} \prod_{k \in f^{-1}(k')} \phi_Y^{-1}(k),$$

we construct a morphism

$$\xi^\dagger: f^*(X) \rightarrow Y, \quad \begin{array}{ccc} K \times_{K'} X & \xrightarrow{\xi^\dagger} & Y \\ \text{pr}_1 \searrow & & \downarrow \phi_Y \\ & & K \end{array}$$

of K -fibred sets, where

$$\begin{aligned} f^*(X) &\stackrel{\text{def}}{=} K \times_{K'} X \\ &\stackrel{\text{def}}{=} \{(k, x) \in K \times X \mid f(k) = \phi_X(x)\}, \end{aligned}$$

by defining

$$\xi^\dagger(k, x) \stackrel{\text{def}}{=} \xi(x)_k$$

for each $(k, x) \in f^*(X)$, where $\xi(x)_k$ is the k th component of $\xi(x) = (y_k)_{k \in f^{-1}(k')}$. We also need to check that ξ^\dagger is a morphism of K -fibred sets, i.e. that

$$\phi_Y \circ \xi^\dagger = \text{pr}_1,$$

or

$$\phi_Y(\xi^\dagger(k, x)) = k,$$

for each $(k, x) \in f^*(X)$, which is clear, since $\xi^\dagger(k, x) \in \phi_Y^{-1}(k)$ by definition.

3. *Naturality I.* We need to show that, given a morphism

$$\alpha: (X, \phi_X) \rightarrow (X', \phi_{X'})$$

of K' -fibred sets, the diagram

$$\begin{array}{ccc} \text{Hom}_{\text{FibSets}(K')}(f^*(X'), Y) & \xrightarrow{\Phi_{X', Y}} & \text{Hom}_{\text{FibSets}(K)}(X', \Pi_f(Y)) \\ f^*(\alpha)^* \downarrow & & \downarrow \alpha^* \\ \text{Hom}_{\text{FibSets}(K')}(f^*(X), Y) & \xrightarrow{\Phi_{X, Y}} & \text{Hom}_{\text{FibSets}(K)}(X, \Pi_f(Y)) \end{array}$$

commutes. Indeed, given a morphism $\xi: f^*(X') \rightarrow Y$ of K' -fibred sets, we have

$$\begin{aligned} [[\Phi_{X, Y} \circ f^*(\alpha)](\xi)](x) &\stackrel{\text{def}}{=} [\Phi_{X, Y}(\xi \circ f^*(\alpha))](x) \\ &\stackrel{\text{def}}{=} ([\xi \circ f^*(\alpha)](k, x))_{k \in f^{-1}(\phi_X(x))} \\ &\stackrel{\text{def}}{=} (\xi(k, \alpha(x)))_{k \in f^{-1}(\phi_X(x))} \\ &\stackrel{\text{def}}{=} \alpha^*\left((\xi(k, x))_{k \in f^{-1}(\phi_X(x))}\right) \\ &\stackrel{\text{def}}{=} \alpha^*\left(\xi^\dagger(x)\right) \\ &\stackrel{\text{def}}{=} [[\alpha^* \circ \Phi_{X, Y}](\xi)](x) \end{aligned}$$

for each $x \in X$.

4. *Naturality II.* We need to show that, given a morphism

$$\beta: (Y, \phi_Y) \rightarrow (Y', \phi_{Y'})$$

of K -fibred sets, the diagram

$$\begin{array}{ccc} \text{Hom}_{\text{FibSets}(K')}(f^*(X), Y) & \xrightarrow{\Phi_{X,Y}} & \text{Hom}_{\text{FibSets}(K)}(X, \Pi_f(Y)) \\ \beta_* \downarrow & & \downarrow \Pi_f(\beta)_* \\ \text{Hom}_{\text{FibSets}(K')}(f^*(X), Y') & \xrightarrow{\Phi_{X,Y'}} & \text{Hom}_{\text{FibSets}(K)}(X, \Pi_f(Y')) \end{array}$$

commutes. Indeed, given a morphism $\xi: X \rightarrow \Pi_f(Y)$ of K -fibred sets, we have

$$\begin{aligned} [[\Phi_{X,Y'} \circ \beta_*](\xi)](x) &\stackrel{\text{def}}{=} [\Phi_{X,Y'}(\beta \circ \xi)](x) \\ &\stackrel{\text{def}}{=} [\Phi_{X,Y'}(\beta \circ \xi)](x) \\ &\stackrel{\text{def}}{=} ([\beta \circ \xi](k, x))_{k \in f^{-1}(\phi_X(x))} \\ &\stackrel{\text{def}}{=} (\beta(\xi(k, x)))_{k \in f^{-1}(\phi_X(x))} \\ &\stackrel{\text{def}}{=} \Pi_f(\beta)_* \left((\xi(k, x))_{k \in f^{-1}(\phi_X(x))} \right) \\ &\stackrel{\text{def}}{=} [\Pi_f(\beta)_* \circ \xi^\dagger](x) \\ &\stackrel{\text{def}}{=} [\Pi_f(\beta)_* \circ \Phi_{X,Y'}(\xi)](x) \end{aligned}$$

for each $x \in X$.

5. *Invertibility I.* We claim that

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \text{id}_{\text{Hom}_{\text{FibSets}(K)}(f^*(X), Y)}.$$

Indeed, given a morphism $\xi: f^*(X') \rightarrow Y$ of K' -fibred sets, we have

$$\begin{aligned} [[\Psi_{X,Y} \circ \Phi_{X,Y}](\xi)](k, x) &\stackrel{\text{def}}{=} [\Psi_{X,Y}(\Phi_{X,Y}(\xi))](k, x) \\ &\stackrel{\text{def}}{=} ([\Phi_{X,Y}(\xi)](x))_k \\ &\stackrel{\text{def}}{=} \left((\xi(k_1, x))_{k_1 \in f^{-1}(\phi_X(x))} \right)_k \\ &\stackrel{\text{def}}{=} \xi(k, x) \end{aligned}$$

for each $(k, x) \in f^*(X)$, and thus the stated equality follows.

6. *Invertibility II.* We claim that

$$\Phi_{X,Y} \circ \Psi_{X,Y} = \text{id}_{\text{Hom}_{\text{FibSets}(K')}(X, \Pi_f(Y))}.$$

Indeed, given a morphism $\xi: X \rightarrow \Pi_f(Y)$ of K -fibred sets, write

$$\xi(x) = (y_k)_{k \in f^{-1}(k'_x)}.$$

We then have

$$\begin{aligned}
 [[\Phi_{X,Y} \circ \Psi_{X,Y}](\xi)](x) &\stackrel{\text{def}}{=} [\Phi_{X,Y}(\Psi_{X,Y}(\xi))](x) \\
 &\stackrel{\text{def}}{=} ([\Psi_{X,Y}(\xi)](k_1, x))_{k_1 \in f^{-1}(\phi_X(x))} \\
 &\stackrel{\text{def}}{=} ((\xi(x))_{k_1})_{k_1 \in f^{-1}(\phi_X(x))} \\
 &\stackrel{\text{def}}{=} \left((y_k)_{k \in f^{-1}(k'_x)} \right)_{k_1 \in f^{-1}(\phi_X(x))} \\
 &\stackrel{\text{def}}{=} (y_{k_1})_{k_1 \in f^{-1}(\phi_X(x))} \\
 &= (y_{k_1})_{k_1 \in f^{-1}(k'_x)} \\
 &= (y_k)_{k \in f^{-1}(k'_x)} \\
 &\stackrel{\text{def}}{=} \xi(x)
 \end{aligned}$$

for each $x \in X$, where the equality $\phi_X(x) = k'_x$ follows from the fact that ξ is a morphism of K' -fibred sets. Thus the stated equality follows.

This finishes the proof. \square

Appendices

9.A Other Chapters

Sets	Category Theory
1. Sets	11. Categories
2. Constructions With Sets	12. Types of Morphisms in Categories
3. Pointed Sets	13. Adjunctions and the Yoneda Lemma
4. Tensor Products of Pointed Sets	14. Constructions With Categories
5. Relations	15. Profunctors
6. Spans	16. Cartesian Closed Categories
7. Posets	17. Kan Extensions
Indexed and Fibred Sets	
7. Indexed Sets	18. Bicategories
8. Fibred Sets	19. Internal Adjunctions
9. Un/Straightening for Indexed and Fibred Sets	Internal Category Theory

20. Internal Categories

33. Hypersemirings and Hyperrings

Cyclic Stuff

21. The Cycle Category

34. Quantales

Cubical Stuff

22. The Cube Category

Near-Rings

Globular Stuff

23. The Globe Category

35. Near-Semirings

Cellular Stuff

24. The Cell Category

Real Analysis

Monoids

25. Monoids

37. Real Analysis in One Variable

26. Constructions With Monoids

38. Real Analysis in Several Variables

Monoids With Zero

27. Monoids With Zero

Measure Theory

28. Constructions With Monoids With
Zero

39. Measurable Spaces

Groups

29. Groups

40. Measures and Integration

30. Constructions With Groups

Probability Theory

Hyper Algebra

31. Hypermonoids

40. Probability Theory

32. Hypergroups

Stochastic Analysis

41. Stochastic Processes, Martingales,
and Brownian Motion

42. Itô Calculus

Differential Geometry

43. Stochastic Differential Equations

44. Topological and Smooth Manifolds

Schemes

45. Schemes

9.2 Other Chapters

Sets	Cyclic Stuff
1. Sets	21. The Cycle Category
2. Constructions With Sets	Cubical Stuff
3. Pointed Sets	22. The Cube Category
4. Tensor Products of Pointed Sets	Globular Stuff
5. Relations	23. The Globe Category
6. Spans	Cellular Stuff
7. Posets	24. The Cell Category
Indexed and Fibred Sets	Monoids
7. Indexed Sets	25. Monoids
8. Fibred Sets	26. Constructions With Monoids
9. Un/Straightening for Indexed and Fibred Sets	Monoids With Zero
Category Theory	27. Monoids With Zero
11. Categories	28. Constructions With Monoids With Zero
12. Types of Morphisms in Categories	Groups
13. Adjunctions and the Yoneda Lemma	29. Groups
14. Constructions With Categories	30. Constructions With Groups
15. Profunctors	Hyper Algebra
16. Cartesian Closed Categories	31. Hypermonoids
17. Kan Extensions	32. Hypergroups
Bicategories	33. Hypersemirings and Hyperrings
18. Bicategories	34. Quantales
19. Internal Adjunctions	Near-Rings
Internal Category Theory	35. Near-Semirings
20. Internal Categories	36. Near-Rings
	Real Analysis
	37. Real Analysis in One Variable

- 38. Real Analysis in Several Variables
- Measure Theory
- 39. Measurable Spaces
- 40. Measures and Integration
- Probability Theory
- 40. Probability Theory
- Stochastic Analysis
- 41. Stochastic Processes, Martingales, and Brownian Motion
- 42. Itô Calculus
- 43. Stochastic Differential Equations
- Differential Geometry
- 44. Topological and Smooth Manifolds
- Schemes
- 45. Schemes

Chapter 10

Un/Straightening for Indexed and Fibred Sets

This chapter contains a discussion of the un/sstraightening equivalence in the context of sets, as well as a general discussion of indexed and fibred sets. In particular, it contains:

1. A discussion of indexed sets (i.e. functors $K_{\text{disc}} \rightarrow \text{Sets}$ with K a set), constructions with them like dependent sums and dependent products, and their properties (????);
2. A discussion of fibred sets (i.e. maps of sets $X \rightarrow K$), constructions with them like dependent sums and dependent products, and their properties (????);
3. A discussion of the un/sstraightening equivalence for indexed and fibred sets ([Section 10.1](#)).

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10.1 Un/Straightening for Indexed and Fibred Sets

10.1.1 Straightening for Fibred Sets

Let K be a set and let (X, ϕ) be a K -fibred set.

Definition 10.1.1.1. The **straightening** of (X, ϕ) is the K -indexed set

$$\text{St}_K(X, \phi) : K_{\text{disc}} \rightarrow \text{Sets}$$

defined by

$$\text{St}_K(X, \phi)_x \stackrel{\text{def}}{=} \phi^{-1}(x)$$

for each $x \in K$.

Proposition 10.1.1.2. Let K be a set.

1. *Functionality.* The assignment $(X, \phi) \mapsto \text{St}_K(X, \phi)$ defines a functor

$$\text{St}_K : \text{FibSets}(K) \rightarrow \text{ISets}(K)$$

- *Action on Objects.* For each $(X, \phi) \in \text{Obj}(\text{FibSets}(K))$, we have

$$[\text{St}_K](X, \phi) \stackrel{\text{def}}{=} \text{St}_K(X, \phi);$$

- *Action on Morphisms.* For each $(X, \phi), (Y, \psi) \in \text{Obj}(\text{FibSets}(K))$, the action on Hom-sets

$$\text{St}_{K|X,Y} : \text{Hom}_{\text{FibSets}(K)}(X, Y) \rightarrow \text{Hom}_{\text{ISets}(K)}(\text{St}_K(X), \text{St}_K(Y))$$

of St_K at (X, Y) is given by sending a morphism

$$f : (X, \phi) \rightarrow (Y, \psi)$$

of K -fibred sets to the morphism

$$\text{St}_K(f) : \text{St}_K(X, \phi) \rightarrow \text{St}_K(Y, \psi)$$

of K -indexed sets defined by

$$\text{St}_K(f) \stackrel{\text{def}}{=} \{f_x^*\}_{x \in K},$$

where f_x^* is the transport map associated to f at $x \in K$ of ??.

2. *Interaction With Change of Base/Indexing.* Let $f : K \rightarrow K'$ be a map of sets. The diagram

$$\begin{array}{ccc} \text{FibSets}(K') & \xrightarrow{f^*} & \text{FibSets}(K) \\ \text{St}_{K'} \downarrow & & \downarrow \text{St}_K \\ \text{ISets}(K') & \xrightarrow{f^*} & \text{ISets}(K) \end{array}$$

commutes.

3. *Interaction With Dependent Sums.* Let $f: K \rightarrow K'$ be a map of sets. The diagram

$$\begin{array}{ccc} \text{FibSets}(K) & \xrightarrow{\Sigma_f} & \text{FibSets}(K') \\ \text{St}_K \downarrow & & \downarrow \text{St}_{K'} \\ \text{ISets}(K) & \xrightarrow{\Sigma_f} & \text{ISets}(K') \end{array}$$

commutes.

4. *Interaction With Dependent Products.* Let $f: K \rightarrow K'$ be a map of sets. The diagram

$$\begin{array}{ccc} \text{Sets}_{/K} & \xrightarrow{\Pi_f} & \text{FibSets}(K') \\ \text{St}_K \downarrow & & \downarrow \text{St}_{K'} \\ \text{ISets}(K) & \xrightarrow{\Pi_f} & \text{ISets}(K') \end{array}$$

commutes.

Proof. **Item 1, Functoriality:** Omitted.

Item 2, Interaction With Change of Base/Indexing: Indeed, we have

$$\begin{aligned} \text{St}_K(f^*(X, \phi))_x &\stackrel{\text{def}}{=} \text{St}_K(K \times_{K'} X)_x \\ &\stackrel{\text{def}}{=} \left(\text{pr}_1^{K \times_{K'} X} \right)^{-1}(x) \\ &= \left\{ (k, y) \in K \times_{K'} X \mid \text{pr}_1^{K \times_{K'} X}(k, y) = x \right\} \\ &= \{(k, y) \in K \times_{K'} X \mid k = x\} \\ &= \{(k, y) \in K \times X \mid k = x \text{ and } f(k) = \phi(y)\} \\ &\cong \{y \in X \mid \phi(y) = f(x)\} \\ &= \phi^{-1}(f(x)) \\ &\stackrel{\text{def}}{=} f^*(\phi^{-1}(x)) \\ &\stackrel{\text{def}}{=} f^*(\text{St}_{K'}(X, \phi)_x) \end{aligned}$$

for each $(X, \phi) \in \text{Obj}(\text{FibSets}(K'))$ and each $x \in K$, and similarly for morphisms.

Item 3, Interaction With Dependent Sums: Indeed, we have

$$\begin{aligned} \text{St}_{K'}(\Sigma_f(X, \phi))_x &\stackrel{\text{def}}{=} \Sigma_f(\phi)^{-1}(x) \\ &\cong \coprod_{\substack{y \in X \\ f(y)=x}} \phi^{-1}(y) \\ &\cong \Sigma_f(\phi^{-1}(x)) \\ &\stackrel{\text{def}}{=} \Sigma_f(\text{St}_K(X, \phi)_x) \end{aligned}$$

for each $(X, \phi) \in \text{Obj}(\text{FibSets}(K))$ and each $x \in K'$, where we have used ?? of ?? for the first bijection, and similarly for morphisms.

Item 4, Interaction With Dependent Products: Indeed, we have

$$\begin{aligned}\text{St}_{K'}(\Pi_f(X, \phi))_x &\stackrel{\text{def}}{=} \Pi_f(\phi)^{-1}(x) \\ &\cong \prod_{\substack{y \in X \\ f(y)=x}} \phi^{-1}(y) \\ &\cong \Pi_f(\phi^{-1}(x)) \\ &\stackrel{\text{def}}{=} \Pi_f(\text{St}_K(X, \phi)_x)\end{aligned}$$

for each $(X, \phi) \in \text{Obj}(\text{FibSets}(K))$ and each $x \in K'$, where we have used ?? of ?? for the first bijection, and similarly for morphisms. \square

10.1.2 Unstraightening for Indexed Sets

Let K be a set and let X be a K -indexed set.

Definition 10.1.2.1.1. The **unstraightening** of X is the K -fibred set

$$\phi_{\text{Un}_K} : \text{Un}_K(X) \rightarrow K$$

consisting of

- *The Underlying Set.* The set $\text{Un}_K(X)$ defined by

$$\text{Un}_K(X) \stackrel{\text{def}}{=} \coprod_{x \in K} X_x;$$

- *The Fibration.* The map of sets

$$\phi_{\text{Un}_K} : \text{Un}_K(X) \rightarrow K$$

defined by sending an element of $\coprod_{x \in K} X_x$ to its index in K .

Proposition 10.1.2.1.2. Let K be a set.

1. *Functionality.* The assignment $X \mapsto \text{Un}_K(X)$ defines a functor

$$\text{Un}_K : \text{ISets}(K) \rightarrow \text{FibSets}(K)$$

- *Action on Objects.* For each $X \in \text{Obj}(\text{ISets}(K))$, we have

$$[\text{Un}_K](X) \stackrel{\text{def}}{=} \text{Un}_K(X);$$

- *Action on Morphisms.* For each $X, Y \in \text{Obj}(\text{ISets}(K))$, the action on Hom-

ssets

$$\text{Un}_{K|X,Y} : \text{Hom}_{\text{ISets}(K)}(X, Y) \rightarrow \text{Hom}_{\text{FibSets}(K)}(\text{Un}_K(X), \text{Un}_K(Y))$$

of Un_K at (X, Y) is defined by

$$\text{Un}_{K|X,Y}(f) \stackrel{\text{def}}{=} \coprod_{x \in K} f_x^*.$$

2. *Interaction With Fibres.* We have a bijection of sets

$$\phi_{\text{Un}_K}^{-1}(x) \cong X_x$$

for each $x \in K$.

3. *As a Pullback.* We have a bijection of sets

$$\begin{array}{ccc} \text{Un}_K(X) & \rightarrow & \text{Sets}_* \\ \downarrow \lrcorner & & \downarrow \bar{\circ} \\ \text{Un}_K(X) \cong K_{\text{disc}} \times_{\text{Sets}} \text{Sets}_* & & \\ \downarrow & & \downarrow \\ K_{\text{disc}} & \xrightarrow[X]{} & \text{Sets}. \end{array}$$

4. *As a Colimit.* We have a bijection of sets

$$\text{Un}_K(X) \cong \text{colim}(X).$$

5. *Interaction With Change of Indexing/Base.* Let $f: K \rightarrow K'$ be a map of sets. The diagram

$$\begin{array}{ccc} \text{ISets}(K') & \xrightarrow{f^*} & \text{ISets}(K) \\ \text{Un}_{K'} \downarrow & & \downarrow \text{Un}_K \\ \text{FibSets}(K') & \xrightarrow[f^*]{} & \text{FibSets}(K) \end{array}$$

commutes.

6. *Interaction With Dependent Sums.* Let $f: K \rightarrow K'$ be a map of sets. The diagram

$$\begin{array}{ccc} \text{ISets}(K) & \xrightarrow{\Sigma_f} & \text{ISets}(K') \\ \text{Un}_K \downarrow & & \downarrow \text{Un}_{K'} \\ \text{FibSets}(K) & \xrightarrow[\Sigma_f]{} & \text{FibSets}(K') \end{array}$$

commutes.

7. *Interaction With Dependent Products.* Let $f: K \rightarrow K'$ be a map of sets. The diagram

$$\begin{array}{ccc} \text{ISets}(K) & \xrightarrow{\Pi_f} & \text{ISets}(K') \\ \text{Un}_K \downarrow & & \downarrow \text{Un}_{K'} \\ \text{FibSets}(K) & \xrightarrow{\Pi_f} & \text{FibSets}(K') \end{array}$$

commutes.

Proof. **Item 1, Functoriality:** Omitted.

Item 2, Interaction With Fibres: Omitted.

Item 3, As a Pullback: Omitted.

Item 4, As a Colimit: Clear.

Item 5, Interaction With Change of Indexing/Base: Indeed, we have

$$\begin{aligned} \text{Un}_K(f^*(X)) &\stackrel{\text{def}}{=} \text{Un}_K(X \circ f) \\ &\stackrel{\text{def}}{=} \coprod_{x \in K} X_{f(x)} \\ &\cong \left\{ (x, (y, a)) \in K \times \coprod_{y \in K'} X_y \mid f(x) = y \right\} \\ &\cong K \times_{K'} \coprod_{y \in K'} X_y \\ &\stackrel{\text{def}}{=} K \times_{K'} \text{Un}_{K'}(X) \\ &\stackrel{\text{def}}{=} f^*(\text{Un}_{K'}(X)) \end{aligned}$$

for each $X \in \text{Obj}(\text{ISets}(K'))$. Similarly, it can be shown that we also have $\text{Un}_K(f^*(\phi)) = f^*(\text{Un}_{K'}(\phi))$ and that $\text{Un}_K \circ f^* = f^* \circ \text{Un}_{K'}$ also holds on morphisms.

Item 6, Interaction With Dependent Sums: Indeed, we have

$$\begin{aligned} \text{Un}_{K'}(\Sigma_f(X)) &\stackrel{\text{def}}{=} \coprod_{x \in K'} \Sigma_f(X)_x \\ &\cong \coprod_{x \in K'} \coprod_{y \in f^{-1}(x)} X_y \\ &\cong \coprod_{y \in K} X_y \\ &\cong \text{Un}_K(X) \\ &\stackrel{\text{def}}{=} \Sigma_f(\text{Un}_K(X)) \end{aligned}$$

for each $X \in \text{Obj}(\text{ISets}(K))$, where we have used ?? of ?? for the first bijection. Similarly, it can be shown that we also have $\text{Un}_{K'}(\Sigma_f(\phi)) = \Sigma_f(\phi_{\text{Un}_K})$ and that $\text{Un}_{K'} \circ \Sigma_f = \Sigma_f \circ \text{Un}_K$ also holds on morphisms.

Item 7, Interaction With Dependent Products: Indeed, we have

$$\begin{aligned} \text{Un}_{K'}(\Pi_f(X)) &\stackrel{\text{def}}{=} \coprod_{x \in K'} \Pi_f(X)_x \\ &\cong \coprod_{x \in K'} \prod_{y \in f^{-1}(x)} X_y \\ &\cong \left\{ (x, h) \in \coprod_{x \in K'} \text{Sets}\left(f^{-1}(x), \phi_{\text{Un}_K}^{-1}(f^{-1}(x))\right) \mid \phi \circ h = \text{id}_{f^{-1}(x)} \right\} \\ &\stackrel{\text{def}}{=} \Pi_f\left(\coprod_{y \in K} X_y\right) \\ &\stackrel{\text{def}}{=} \Pi_f(\text{Un}_K(X)) \end{aligned}$$

for each $X \in \text{Obj}(\text{ISets}(K))$, where we have used ?? of ?? for the first bijection. Similarly, it can be shown that we also have $\text{Un}_{K'}(\Pi_f(\phi)) = \Pi_f(\phi_{\text{Un}_K})$ and that $\text{Un}_{K'} \circ \Pi_f = \Pi_f \circ \text{Un}_K$ also holds on morphisms. \square

10.1.3 The Un/Straightening Equivalence

Theorem 10.1.3.1.1. We have an isomorphism of categories

$$(\text{St}_K \dashv \text{Un}_K): \quad \text{FibSets}(K) \begin{array}{c} \xrightarrow{\text{St}_K} \\ \perp \\ \xleftarrow{\text{Un}_K} \end{array} \text{ISets}(K).$$

Proof. Omitted. \square

10.2 Miscellany

10.2.1 Other Kinds of Un/Straightening

Remark 10.2.1.1.1. There are also other kinds of un/straightening for sets, where Sets is replaced by **Rel** or **Span**:

- *Un/Straightening With **Rel**, I.* We have an isomorphism of sets

$$\text{Rel}(A, B) \cong \text{Sets}(B \times A, \{\text{true}, \text{false}\}).$$

by the definition of a relation from A to B , ??.

- *Un/Straightening With **Rel**, II.* We have an equivalence of categories

$$\text{LaxFun}(K_{\text{disc}}, \text{Rel}) \stackrel{\text{eq.}}{\cong} \text{Cats}_{/K_{\text{disc}}}^{\text{fth}},$$

where $\text{Cats}_{/K_{\text{disc}}}^{\text{fth}}$ is the full subcategory of $\text{Cats}_{/K_{\text{disc}}}$ spanned by the faithful functors; see [Nie04, Theorem 3.1].

- *Un/Straightening With Span, I.* For each $A, B \in \text{Obj}(\text{Sets})$, we have a morphism of sets

$$\text{Span}(A, B) \rightarrow \text{Sets}(A \times B, \mathbb{N} \cup \{\infty\})$$

which assemble into an equivalence of categories between $\text{Span}(\text{Sets})$ and the category MRel of “multirelations”; see ??.

- *Un/Straightening With Span, II.* We have an equivalence of categories

$$\text{LaxFun}(K_{\text{disc}}, \text{Span}) \xrightarrow{\text{eq.}} \text{Cats}_{/K_{\text{disc}}};$$

see [nLa24a, Section 3].

Appendices

10.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets
5. Relations
6. Spans
7. Posets

Indexed and Fibred Sets

7. Indexed Sets
8. Fibred Sets
9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories
12. Types of Morphisms in Categories
13. Adjunctions and the Yoneda Lemma

Constructions With Categories

14. Profunctors
15. Cartesian Closed Categories
16. Kan Extensions

Bicategories

18. Bicategories
19. Internal Adjunctions

Internal Category Theory

20. Internal Categories

Cyclic Stuff

21. The Cycle Category

Cubical Stuff

22. The Cube Category

Globular Stuff

23. The Globe Category

Cellular Stuff

24. The Cell Category

Monoids

- 25. Monoids
- 26. Constructions With Monoids

Monoids With Zero

- 27. Monoids With Zero
- 28. Constructions With Monoids With Zero

Groups

- 29. Groups
- 30. Constructions With Groups

Hyper Algebra

- 31. Hypermonoids
- 32. Hypergroups
- 33. Hypersemirings and Hyperrings
- 34. Quantales

Near-Rings

- 35. Near-Semirings
- 36. Near-Rings

Real Analysis

- 37. Real Analysis in One Variable
- 38. Real Analysis in Several Variables

Measure Theory

- 39. Measurable Spaces
- 40. Measures and Integration

Probability Theory

- 40. Probability Theory

Stochastic Analysis

- 41. Stochastic Processes, Martingales, and Brownian Motion
- 42. Itô Calculus
- 43. Stochastic Differential Equations

Differential Geometry

- 44. Topological and Smooth Manifolds

Schemes

- 45. Schemes

10.2 Other Chapters

Sets

- 1. Sets
- 2. Constructions With Sets
- 3. Pointed Sets
- 4. Tensor Products of Pointed Sets
- 5. Relations
- 6. Spans
- 7. Posets

Indexed and Fibred Sets

- 7. Indexed Sets
- 8. Fibred Sets
- 9. Un/Straightening for Indexed and Fibred Sets

Category Theory

- 11. Categories
- 12. Types of Morphisms in Categories
- 13. Adjunctions and the Yoneda Lemma

- 14. [Constructions With Categories](#)
- 15. [Profunctors](#)
- 16. [Cartesian Closed Categories](#)
- 17. [Kan Extensions](#)
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 - 25. [Monoids](#)
 - 26. [Constructions With Monoids](#)
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 - 27. [Monoids With Zero](#)
 - 28. [Constructions With Monoids With Zero](#)
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 - 29. [Groups](#)
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- Schemes
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Part III

Category Theory

Chapter 11

Categories

Create tags (see [MSE 350788] for some of these):

1. define bicategory $\text{Adj}(C)$
2. internal **Hom** in categories of co/Cartesian fibrations
3. <https://mathoverflow.net/questions/460146/universal-property-of-isbell-duality>
4. <http://www.tac.mta.ca/tac/volumes/36/12/36-12abs.html>
5. justify adjunctions via homs
6. <https://ncatlab.org/nlab/show/enrichment+versus+internalisation>
7. <https://arxiv.org/pdf/2004.08964.pdf>

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11.1 Categories

11.1.1 Foundations

Definition 11.1.1.1.1. A **category** $(C, \circ^C, \mathbb{M}^C)$ consists of^{1,2}

- **Objects.** A class $\text{Obj}(C)$ of **objects**;
- **Morphisms.** For each $A, B \in \text{Obj}(C)$, a class $\text{Hom}_C(A, B)$, called the **class of morphisms of C from A to B** ;
- **Identities.** For each $A \in \text{Obj}(C)$, a map of sets

$$\mathbb{M}_A^C : \text{pt} \rightarrow \text{Hom}_C(A, A),$$

called the **unit map of C at A** , determining a morphism

$$\text{id}_A : A \rightarrow A$$

of C , called the **identity morphism of A** ;

- **Composition.** For each $A, B, C \in \text{Obj}(C)$, a map of sets

$$\circ_{A,B,C}^C : \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) \rightarrow \text{Hom}_C(A, C),$$

called the **composition map of C at (A, B, C)** ;

such that the following conditions are satisfied:

1. **Associativity.** The diagram

$$\begin{array}{ccc}
& \text{Hom}_C(C, D) \times (\text{Hom}_C(B, C) \times \text{Hom}_C(A, B)) & \\
& \nearrow \alpha_{\text{Hom}_C(C,D), \text{Hom}_C(B,C), \text{Hom}_C(A,B)}^{\text{Sets}} & \searrow \text{id}_{\text{Hom}_C(C,D) \times \circ_{A,B,C}^C} \\
(\text{Hom}_C(C, D) \times \text{Hom}_C(B, C)) \times \text{Hom}_C(A, B) & & \text{Hom}_C(C, D) \times \text{Hom}_C(A, C) \\
& \swarrow \circ_{B,C,D}^C \times \text{id}_{\text{Hom}_C(A,B)} & \searrow \circ_{A,C,D}^C \\
& \text{Hom}_C(B, D) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,D}^C} \text{Hom}_C(A, D)
\end{array}$$

¹Further Notation: We also write $C(A, B)$ for $\text{Hom}_C(A, B)$.

²Further Notation: We write $\text{Mor}(C)$ for the class of all morphisms of C .

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

$$\begin{array}{ccc} \text{pt} \times \text{Hom}_\mathcal{C}(A, B) & & \\ \downarrow \mathbb{1}_B^C \times \text{id}_{\text{Hom}_\mathcal{C}(A, B)} & \nearrow \lambda_{\text{Hom}_\mathcal{C}(A, B)}^{\text{Sets}} & \\ \text{Hom}_\mathcal{C}(B, B) \times \text{Hom}_\mathcal{C}(A, B) & \xrightarrow{\circ_{A, B, B}^C} & \text{Hom}_\mathcal{C}(A, B) \end{array}$$

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

$$\begin{array}{ccc} \text{Hom}_\mathcal{C}(A, B) \times \text{pt} & & \\ \downarrow \text{id}_{\text{Hom}_\mathcal{C}(A, B)} \times \mathbb{1}_A^C & \nearrow \rho_{\text{Hom}_\mathcal{C}(A, B)}^{\text{Sets}} & \\ \text{Hom}_\mathcal{C}(A, B) \times \text{Hom}_\mathcal{C}(A, A) & \xrightarrow{\circ_{A, A, B}^C} & \text{Hom}_\mathcal{C}(A, B) \end{array}$$

commutes, i.e. for each morphism $f: A \rightarrow B$ of \mathcal{C} , we have

$$f \circ \text{id}_A = f.$$

Definition 11.1.1.2. 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 $\text{Hom}_\mathcal{C}(A, B)$ is a set.
2. **Locally essentially small** if, for each $A, B \in \text{Obj}(\mathcal{C})$, the class

$$\text{Hom}_\mathcal{C}(A, B)/\{\text{isomorphisms}\}$$

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 $\#\text{Obj}(\mathcal{C}) < \kappa$.

11.1.2 Examples of Categories

Example 11.1.2.1.1. The **punctual category**³ is the category pt where

- *Objects.* We have

$$\text{Obj}(\text{pt}) \stackrel{\text{def}}{=} \{\star\};$$

- *Morphisms.* The unique Hom-set of pt is defined by

$$\text{Hom}_{\text{pt}}(\star, \star) \stackrel{\text{def}}{=} \{\text{id}_\star\};$$

- *Identities.* The unit map

$$\mu_\star^{\text{pt}} : \text{pt} \rightarrow \text{Hom}_{\text{pt}}(\star, \star)$$

of pt at \star is defined by

$$\text{id}_\star^{\text{pt}} \stackrel{\text{def}}{=} \text{id}_\star;$$

- *Composition.* The composition map

$$\circ_{\star, \star, \star}^{\text{pt}} : \text{Hom}_{\text{pt}}(\star, \star) \times \text{Hom}_{\text{pt}}(\star, \star) \rightarrow \text{Hom}_{\text{pt}}(\star, \star)$$

of pt at (\star, \star, \star) is given by the bijection $\text{pt} \times \text{pt} \cong \text{pt}$.

Example 11.1.2.1.2. We have an isomorphism of categories⁴

$$\begin{array}{ccc} \text{Mon} & \longrightarrow & \text{Cats} \\ \downarrow \lrcorner & & \downarrow \text{Obj} \\ \text{Mon} \cong \text{pt} \times_{\text{Sets}} \text{Cats}, & & \\ \downarrow & & \downarrow \\ \text{pt} & \xrightarrow{[\text{pt}]} & \text{Sets} \end{array}$$

via the delooping functor $B : \text{Mon} \rightarrow \text{Cats}$ of ?? of ??.

Proof. Omitted. □

³Further Terminology: Also called the **singleton category**.

⁴This can be enhanced to an isomorphism of 2-categories

$$\begin{array}{ccc} \text{Mon}_{2-\text{disc}} & \rightarrow & \text{Cats}_{2,*} \\ \downarrow \lrcorner & & \downarrow \text{Obj} \\ \text{Mon}_{2-\text{disc}} \cong \text{pt}_{\text{bi}} \times_{\text{Sets}_{2-\text{disc}}} \text{Cats}_{2,*}, & & \\ \downarrow & & \downarrow \\ \text{pt}_{\text{bi}} & \xrightarrow{[\text{pt}]} & \text{Sets}_{2-\text{disc}} \end{array}$$

between the discrete 2-category $\text{Mon}_{2-\text{disc}}$ on Mon and the 2-category of pointed categories with one object.

Example 11.1.2.1.3. 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.

Example 11.1.2.1.4. The **n th ordinal category** is the category \bowtie where⁵

- *Objects.* We have

$$\text{Obj}(\bowtie) \stackrel{\text{def}}{=} \{[0], \dots, [n]\};$$

- *Morphisms.* For each $[i], [j] \in \text{Obj}(\bowtie)$, we have

$$\text{Hom}_{\bowtie}([i], [j]) \stackrel{\text{def}}{=} \begin{cases} \{\text{id}_{[i]}\} & \text{if } [i] = [j], \\ \{[i] \rightarrow [j]\} & \text{if } [j] < [i], \\ \emptyset & \text{if } [j] > [i]; \end{cases}$$

- *Identities.* For each $[i] \in \text{Obj}(\bowtie)$, the unit map

$$\mathbb{1}_{[i]}^{\bowtie} : \text{pt} \rightarrow \text{Hom}_{\bowtie}([i], [i])$$

of \bowtie at $[i]$ is defined by

$$\text{id}_{[i]}^{\bowtie} \stackrel{\text{def}}{=} \text{id}_{[i]};$$

⁵In other words, \bowtie is the category associated to the poset

$$[0] \rightarrow [1] \rightarrow \dots \rightarrow [n-1] \rightarrow [n].$$

The category \bowtie for $n \geq 2$ may also be defined in terms of \vee and joins: we have isomorphisms of categories

$$\begin{aligned} \mathbb{1} &\cong \mathbb{1} \star \mathbb{1}, \\ \mathbb{1} &\cong \mathbb{1} \star \mathbb{1} \\ &\cong (\mathbb{1} \star \mathbb{1}) \star \mathbb{1}, \\ \mathbb{1} &\cong \mathbb{1} \star \mathbb{1} \\ &\cong (\mathbb{1} \star \mathbb{1}) \star \mathbb{1} \\ &\cong ((\mathbb{1} \star \mathbb{1}) \star \mathbb{1}) \star \mathbb{1}, \\ \mathbb{1} &\cong \mathbb{1} \star \mathbb{1} \\ &\cong (\mathbb{1} \star \mathbb{1}) \star \mathbb{1} \\ &\cong ((\mathbb{1} \star \mathbb{1}) \star \mathbb{1}) \star \mathbb{1} \\ &\cong (((\mathbb{1} \star \mathbb{1}) \star \mathbb{1}) \star \mathbb{1}) \star \mathbb{1}, \end{aligned}$$

and so on.

- *Composition.* For each $[i], [j], [k] \in \text{Obj}(\bowtie)$, the composition map

$$\circ_{[i],[j],[k]}^{\bowtie} : \text{Hom}_{\bowtie}([j], [k]) \times \text{Hom}_{\bowtie}([i], [j]) \rightarrow \text{Hom}_{\bowtie}([i], [k])$$

of \bowtie at $([i], [j], [k])$ is defined by

$$\begin{aligned} \text{id}_{[i]} \circ \text{id}_{[i]} &= \text{id}_{[i]}, \\ ([j] \rightarrow [k]) \circ ([i] \rightarrow [j]) &= ([i] \rightarrow [k]). \end{aligned}$$

Example 11.1.2.1.5. Here we list all the other categories that appear throughout this work.

- The category Sets_* of pointed sets of ??.
- The category Rel of sets and relations of ??.
- The category $\text{Span}(A, B)$ of spans from a set A to a set B of ??.
- The category $\text{ISets}(K)$ of K -indexed sets of ??.
- The category ISets of indexed sets of ??.
- The category $\text{FibSets}(K)$ of K -fibred sets of ??.
- The category FibSets of fibred sets of ??.

11.1.3 Subcategories

Let C be a category.

Definition 11.1.3.1.1. 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 11.1.3.1.2. 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 11.1.3.1.3. 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.⁶

Definition 11.1.3.1.4. A subcategory \mathcal{A} of C is **wide**⁷ if $\text{Obj}(\mathcal{A}) = \text{Obj}(C)$.

11.1.4 Skeletons of Categories

Definition 11.1.4.1.1. A⁸ **skeleton** of a category C is a full subcategory $\text{Sk}(C)$ with one object from each isomorphism class of objects of C .

Definition 11.1.4.1.2. A category C is **skeletal** if $C \cong \text{Sk}(C)$.⁹

Proposition 11.1.4.1.3. Let C be a category.

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. □

⁶That is, given $A \in \text{Obj}(\mathcal{A})$ and $C \in \text{Obj}(C)$, if $C \cong A$, then $C \in \text{Obj}(\mathcal{A})$.

⁷Further Terminology: Also called **lluf**.

⁸Due to Item 3 of Proposition 11.1.4.1.3, we often refer to any such full subcategory $\text{Sk}(C)$ of C as *the* skeleton of C .

⁹That is, C is **skeletal** if isomorphic objects of C are equal.

11.1.5 Precomposition and Postcomposition

Let C be a category and let $A, B, C \in \text{Obj}(C)$.

Definition 11.1.5.1.1. Let $f: A \rightarrow B$ and $g: B \rightarrow C$ be morphisms of C .

- 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 $\phi \in \text{Hom}_C(B, C)$.

- 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 11.1.5.1.2. 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

$$\begin{array}{ccc} \text{Hom}_C(X, A) & \xrightarrow{f_*} & \text{Hom}_C(X, B) \\ (g \circ f)^* = f^* \circ g^*, & \searrow (gof)_* & \downarrow g_* \\ & & \text{Hom}_C(X, C), \\ \text{Hom}_C(C, X) & \xrightarrow{g^*} & \text{Hom}_C(B, X) \\ (g \circ f)_* = g_* \circ f_*, & \searrow (gof)^* & \downarrow f^* \\ & & \text{Hom}_C(A, X). \end{array}$$

3. *Interaction With Composition II.* We have

$$\begin{array}{ccc} \text{pt} & \xrightarrow{[f]} & \text{Hom}_C(A, B) \\ & \searrow [g \circ f] & \downarrow g^* \\ & & \text{Hom}_C(A, C) \end{array} \quad [g \circ f] = g_* \circ [f], \quad [g \circ f] = f^* \circ [g],$$

$$\begin{array}{ccc} \text{pt} & \xrightarrow{[g]} & \text{Hom}_C(B, C) \\ & \searrow [g \circ f] & \downarrow f^* \\ & & \text{Hom}_C(A, C). \end{array}$$

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. \square

11.2 The Quadruple Adjunction With Sets

11.2.1 Statement

Let C be a category.

Proposition 11.2.1.1.1. We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}): \text{Sets} \rightleftarrows \text{Cats},$$

π_0
 \perp
 $(-)_{\text{disc}}$
 \perp
 Obj
 \perp
 $(-)_{\text{indisc}}$

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 11.2.3.1.1](#).

- The functor

$$(-)_{\text{disc}}: \text{Sets} \rightarrow \text{Cats},$$

the **discrete category functor**, is the functor sending a set to its associated discrete category of [Definition 11.2.5.1.1](#).

- 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 [Definition 11.2.6.1.1](#).

Proof. Omitted. □

11.2.2 Connected Components of Categories

Let C be a category.

Definition 11.2.2.1.1. A **connected component** of C is a full subcategory \mathcal{I} of C satisfying the following conditions.¹⁰

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} .

¹⁰In other words, a **connected component** of C is an element of the set $\text{Obj}(C)/\sim$ 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 .

11.2.3 Sets of Connected Components of Categories

Let C be a category.

Definition 11.2.3.1.1. The **set of connected components** of C is the set $\pi_0(C)$ whose elements are the connected components of C .

Proposition 11.2.3.1.2. 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

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}) : \text{Sets} \rightleftarrows \text{Cats.}$$

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

$$\left(\pi_0, \pi_0^{\coprod}, \pi_{0|*}^{\coprod}\right) : (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Sets}, \coprod, \emptyset),$$

being equipped with isomorphisms

$$\begin{aligned} \pi_{0|C,\mathcal{D}}^{\coprod} : \pi_0(C) \coprod \pi_0(\mathcal{D}) &\xrightarrow{\cong} \pi_0(C \coprod \mathcal{D}), \\ \pi_{0|*}^{\coprod} : \emptyset &\xrightarrow{\cong} \pi_0(\emptyset_{\text{cat}}), \end{aligned}$$

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

$$\left(\pi_0, \pi_0^\otimes, \pi_{0|k}^\otimes \right) : (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Sets}, \times, \text{pt}),$$

being equipped with isomorphisms

$$\begin{aligned} \pi_{0|C,D}^\otimes : \pi_0(C) \times \pi_0(D) &\xrightarrow{\cong} \pi_0(C \times D), \\ \pi_{0|k}^\otimes : \text{pt} &\xrightarrow{\cong} \pi_0(\text{pt}), \end{aligned}$$

natural in $C, D \in \text{Obj}(\text{Cats})$.

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

[Item 2](#), *Adjointness:* This is proved in [Proposition 11.2.1.1.1](#).

[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:* Omitted.

[Item 6](#), *Symmetric Strong Monoidality With Respect to Products:* Omitted. □

11.2.4 Connected Categories

Definition 11.2.4.1.1. A category C is **connected** if $\pi_0(C) \cong \text{pt}$.^{11,12}

11.2.5 Discrete Categories

Let X be a set.

Definition 11.2.5.1.1. The **discrete category on a set 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

$$\text{id}_A^{X_{\text{disc}}} \stackrel{\text{def}}{=} \text{id}_A;$$

¹¹Further Terminology: A category is **disconnected** if it is not connected.

¹²Example: A groupoid is connected iff any two of its objects are isomorphic.

- *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

$$\text{id}_A \circ \text{id}_A \stackrel{\text{def}}{=} \text{id}_A.$$

Proposition 11.2.5.1.2. Let X be a set.

1. *Functoriality.* The assignment $X \mapsto X_{\text{disc}}$ defines a functor

$$(-)_{\text{disc}} : \text{Sets} \rightarrow \text{Cats}.$$

2. *Adjointness.* We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}) : \text{Sets} \rightleftarrows \text{Cats.}$$

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

$$((-)_{\text{disc}}, (-)_{\text{disc}}^{\coprod}, (-)_{\text{disc}|\wp}^{\coprod}) : (\text{Sets}, \coprod, \emptyset) \rightarrow (\text{Cats}, \coprod, \emptyset_{\text{cat}}),$$

being equipped with isomorphisms

$$(-)_{\text{disc}|X,Y}^{\coprod} : X_{\text{disc}} \coprod Y_{\text{disc}} \xrightarrow{\cong} (X \coprod Y)_{\text{disc}},$$

$$(-)_{\text{disc}|\wp}^{\coprod} : \emptyset_{\text{cat}} \xrightarrow{\cong} \emptyset_{\text{disc}},$$

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

4. *Symmetric Strong Monoidality With Respect to Products.* The functor of [Item 1](#) has a symmetric strong monoidal structure

$$((-)_{\text{disc}}, (-)_{\text{disc}}^{\otimes}, (-)_{\text{disc}|\wp}^{\otimes}) : (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Cats}, \times, \text{pt}),$$

being equipped with isomorphisms

$$(-)_{\text{disc}|X,Y}^{\otimes} : X_{\text{disc}} \times Y_{\text{disc}} \xrightarrow{\cong} (X \times Y)_{\text{disc}},$$

$$(-)_{\text{disc}|\wp}^{\otimes} : \text{pt} \xrightarrow{\cong} \text{pt}_{\text{disc}},$$

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

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

[Item 2](#), *Adjointness:* This is proved in [Proposition 11.2.1.1.1](#).

[Item 3](#), *Symmetric Strong Monoidality With Respect to Coproducts:* Omitted.

[Item 4](#), *Symmetric Strong Monoidality With Respect to Products:* Omitted. □

11.2.6 Indiscrete Categories

Definition 11.2.6.1.1. The **indiscrete category on a set** X^{13} 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

$$\text{Hom}_{X_{\text{disc}}}(A, B) \stackrel{\text{def}}{=} \{[A] \rightarrow [B]\};$$

- *Identities.* For each $A \in \text{Obj}(X_{\text{indisc}})$, the unit map

$$\mu_A^{X_{\text{indisc}}} : \text{pt} \rightarrow \text{Hom}_{X_{\text{indisc}}}(A, A)$$

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

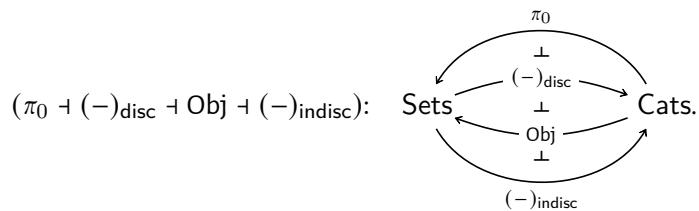
$$([B] \rightarrow [C]) \circ ([A] \rightarrow [B]) \stackrel{\text{def}}{=} ([A] \rightarrow [C]).$$

Proposition 11.2.6.1.2. Let X be a set.

1. *Functionality.* The assignment $X \mapsto X_{\text{indisc}}$ defines a functor

$$(-)_{\text{indisc}} : \text{Sets} \rightarrow \text{Cats}.$$

2. *Adjointness.* We have a quadruple adjunction



¹³Further Terminology: Also 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

$$\left((-)_{\text{indisc}}, (-)_{\text{indisc}}^{\otimes}, (-)_{\text{indisc}|_{\mathbb{P}}}^{\otimes} \right): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Cats}, \times, \text{pt}),$$

being equipped with isomorphisms

$$\begin{aligned} (-)_{\text{indisc}|_{X,Y}}^{\otimes}: X_{\text{indisc}} \times Y_{\text{indisc}} &\xrightarrow{\cong} (X \times Y)_{\text{indisc}}, \\ (-)_{\text{indisc}|_{\mathbb{P}}}^{\otimes}: \text{pt} &\xrightarrow{\cong} \text{pt}_{\text{indisc}}, \end{aligned}$$

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

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

[Item 2](#), *Adjointness:* This is proved in [Proposition 11.2.1.1.1](#).

[Item 3](#), *Symmetric Strong Monoidality With Respect to Products:* Omitted. □

11.3 Groupoids

11.3.1 Foundations

Let C be a category.

Definition 11.3.1.1.1. 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

$$\begin{aligned} f \circ f^{-1} &= \text{id}_B, \\ f^{-1} \circ f &= \text{id}_A. \end{aligned}$$

Definition 11.3.1.1.2. A **groupoid** is a category in which every morphism is an isomorphism.

11.3.2 The Groupoid Completion of a Category

Let C be a category.

Definition 11.3.2.1.1. The **groupoid completion** of C ¹⁴ is the pair $(K_0(C), \iota_C)$ consisting of

- A groupoid $K_0(C)$;
- A functor $\iota_C: C \rightarrow K_0(C)$;

¹⁴Further Terminology: Also called the **Grothendieck groupoid** of C or the **Grothendieck groupoid completion** of C .

satisfying the following universal property:¹⁵

(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.

Proposition 11.3.2.1.2. Let C be a category.

1. *Functoriality.* The assignment $C \mapsto K_0(C)$ defines a functor

$$K_0: \text{Cats} \rightarrow \text{Grpd}.$$

2. *2-Functoriality.* The assignment $C \mapsto K_0(C)$ defines a 2-functor

$$K_0: \text{Cats}_2 \rightarrow \text{Grpd}_2.$$

3. *Adjointness.* We have an adjunction

$$(K_0 \dashv \iota): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp \\ \xleftarrow{\iota} \end{array} \text{Grpd},$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Grpd}}(K_0(C), \mathcal{G}) \cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}),$$

natural in $C \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$, forming, together with the functor *Core* of Item 1 of Proposition 11.3.3.1.3, a triple adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp \\ \xleftarrow{\iota} \\ \perp \\ \xleftarrow{\text{Core}} \end{array} \text{Grpd},$$

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 $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

¹⁵See Item 5 of Proposition 11.3.2.1.2 for an explicit construction.

4. *2-Adjointness.* We have a 2-adjunction

$$(K_0 \dashv \iota): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \xleftarrow[\iota]{} \end{array} \text{Grpd},$$

witnessed by an isomorphism of categories

$$\text{Fun}(K_0(C), \mathcal{G}) \cong \text{Fun}(C, \mathcal{G}),$$

natural in $C \in \text{Obj}(\text{Cats})$ and $\mathcal{G} \in \text{Obj}(\text{Grpd})$, forming, together with the 2-functor Core of Item 2 of Proposition 11.3.3.1.3, a triple 2-adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \xleftarrow[\iota]{} \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

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. *Interaction With Classifying Spaces.* We have an isomorphism of groupoids

$$K_0(C) \cong \Pi_{\leq 1}(|N_\bullet(C)|),$$

natural in $C \in \text{Obj}(\text{Cats})$; i.e. the diagram

$$\begin{array}{ccc} \text{Cats} & \xrightarrow{K_0} & \text{Grp} \\ N_\bullet \downarrow & \Downarrow \gamma & \uparrow \Pi_{\leq 1} \\ \text{sSets} & \xrightarrow{|-|} & \text{Top} \end{array}$$

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

$$\left(K_0, K_0^{\coprod}, K_{0|\mathbb{1}}^{\coprod}\right): (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Grpd}, \coprod, \emptyset_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned} K_{0|C,D}^{\coprod}: K_0(C) \coprod K_0(D) &\xrightarrow{\cong} K_0(C \coprod D), \\ K_{0|\mathbb{1}}^{\coprod}: \emptyset_{\text{cat}} &\xrightarrow{\cong} K_0(\emptyset_{\text{cat}}), \end{aligned}$$

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

$$\left(K_0, K_0^\times, K_{0|k}^\times \right) : (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned} K_{0|C,D}^\times : K_0(C) \times K_0(D) &\xrightarrow{\cong} K_0(C \times D), \\ K_{0|k}^\times : \text{pt} &\xrightarrow{\cong} K_0(\text{pt}), \end{aligned}$$

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. □

11.3.3 The Core of a Category

Let C be a category.

Definition 11.3.3.1.1. The **core** of C is the pair $(\text{Core}(C), \iota_C)$ ¹⁶ consisting of

1. A groupoid $\text{Core}(C)$;
2. A functor $\iota_C : \text{Core}(C) \hookrightarrow C$;

satisfying the following universal property:

(UP) Given another such pair (G, i) , there exists a unique functor $G \xrightarrow{\exists!} \text{Core}(C)$ making the diagram

$$\begin{array}{ccc} & \text{Core}(C) & \\ & \swarrow \exists! & \downarrow \iota_C \\ G & \xrightarrow{i} & C \end{array}$$

commute.

¹⁶Further Notation: Also written C^\simeq .

Construction 11.3.3.1.2. The core of C is the wide subcategory of C spanned by the isomorphisms of C , i.e. the category $\text{Core}(C)$ where¹⁷

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. \square

Proposition 11.3.3.1.3. Let C be a category.

1. *Functoriality.* The assignment $C \mapsto \text{Core}(C)$ defines a functor

$$\text{Core}: \text{Cats} \rightarrow \text{Grpd}.$$

2. *2-Functoriality.* The assignment $C \mapsto \text{Core}(C)$ defines a 2-functor

$$\text{Core}: \text{Cats}_2 \rightarrow \text{Grpd}_2.$$

3. *Adjointness.* We have an adjunction

$$(\iota \dashv \text{Core}): \text{Grpd} \begin{array}{c} \xrightarrow{\iota} \\ \perp \\ \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) \cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

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 11.3.2.1.2, a triple adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \text{Cats} \begin{array}{c} \xleftarrow{K_0} \\ \perp \\ \xrightarrow{\iota} \\ \perp \\ \xleftarrow{\text{Core}} \end{array} \text{Grpd},$$

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 $\mathcal{G} \in \text{Obj}(\text{Grpd})$.

¹⁷*Slogan:* The groupoid $\text{Core}(C)$ is the maximal subgroupoid of C .

4. *2-Adjointness.* We have an adjunction

$$(\iota \dashv \text{Core}): \text{Grpd} \begin{array}{c} \xrightarrow{\iota} \\ \perp_2 \\ \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

witnessed by an isomorphism of categories

$$\text{Fun}(\mathcal{G}, \mathcal{D}) \cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

natural in $\mathcal{G} \in \text{Obj}(\text{Grpd})$ and $\mathcal{D} \in \text{Obj}(\text{Cats})$, forming, together with the 2-functor K_0 of Item 2 of Proposition 11.3.2.1.2, a triple 2-adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \text{Cats} \begin{array}{c} \xleftarrow{K_0} \\ \perp_2 \\ \xleftarrow{\iota} \xrightarrow{\text{Core}} \\ \perp_2 \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

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

$$(\text{Core}, \text{Core}^\times, \text{Core}_\times^\times): (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned} \text{Core}_{C,D}^\times: \text{Core}(C) \times \text{Core}(D) &\xrightarrow{\cong} \text{Core}(C \times D), \\ \text{Core}_\times^\times: \text{pt} &\xrightarrow{\cong} \text{Core}(\text{pt}), \end{aligned}$$

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

$$(\text{Core}, \text{Core}^{\coprod}, \text{Core}_\times^{\coprod}): (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Grpd}, \coprod, \emptyset_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned} \text{Core}_{C,D}^{\coprod}: \text{Core}(C) \coprod \text{Core}(D) &\xrightarrow{\cong} \text{Core}(C \coprod D), \\ \text{Core}_\times^{\coprod}: \emptyset_{\text{cat}} &\xrightarrow{\cong} \text{Core}(\emptyset_{\text{cat}}), \end{aligned}$$

natural in $C, D \in \text{Obj}(\text{Cats})$.

Proof. **Item 1, Functoriality:** Omitted.

Item 2, 2-Functoriality: Omitted.

Item 3, Adjointness: The adjunction $(K_0 \dashv \iota)$ follows from the universal property of the Gabriel–Zisman localisation of a category with respect to a class of morphisms (??), while the adjunction $(\iota \dashv \text{Core})$ is a reformulation of the universal property of the core of a category (Definition 11.3.3.1.1).¹⁸

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

11.4 Functors

11.4.1 Foundations

Let C and \mathcal{D} be categories.

Definition 11.4.1.1.1. A **functor** $F: C \rightarrow \mathcal{D}$ from C to \mathcal{D} ¹⁹ consists of²⁰

1. *Action on Objects.* A map of sets

$$F: \text{Obj}(C) \rightarrow \text{Obj}(\mathcal{D}),$$

called the **action on objects** of F ;

2. *Action on Morphisms.* For each $A, B \in \text{Obj}(C)$, a map

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B),$$

called the **action on morphisms** of F at (A, B) ²¹;

satisfying the following conditions:

1. *Preservation of Identities.* For each $A \in \text{Obj}(C)$, the diagram

$$\begin{array}{ccc} & \text{pt} & \\ & \downarrow \kappa_A^C & \searrow \kappa_{F_A}^{\mathcal{D}} \\ \text{Hom}_C(A, A) & \xrightarrow{F_{A,A}} & \text{Hom}_{\mathcal{D}}(F_A, F_A) \end{array}$$

commutes, i.e. we have

$$F(\text{id}_A) = \text{id}_{F_A}.$$

¹⁸Reference: [Rie17, Example 4.1.15]

¹⁹Further Terminology: Also called a **covariant functor**.

²⁰Further Notation: Given functors $F: C \rightarrow \mathcal{D}$ and $G: C^{\text{op}} \rightarrow \mathcal{D}$, we will sometimes write F_A for $F(A)$ (resp. G^A for $G(A)$) and F_f for $F(f)$ (resp. G^f for $G(f)$). This has been called Einstein notation in the literature.

²¹Further Terminology: Also called **action on Hom-sets** of F at (A, B) .

2. *Preservation of Composition.* For each $A, B, C \in \text{Obj}(C)$, the diagram

$$\begin{array}{ccc} \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_C(A, C) \\ F_{B,C} \times F_{A,B} \downarrow & & \downarrow F_{A,C} \\ \text{Hom}_{\mathcal{D}}(F_B, F_C) \times \text{Hom}_{\mathcal{D}}(F_A, F_B) & \xrightarrow{\circ_{F_A, F_B, F_C}^{\mathcal{D}}} & \text{Hom}_{\mathcal{D}}(F_A, F_C) \end{array}$$

commutes, i.e. for each composable pair (g, f) of morphisms of C , we have

$$F(g \circ f) = F(g) \circ F(f).$$

Example 11.4.1.1.2. The **identity functor** of a category C is the functor $\text{id}_C : C \rightarrow C$ where

1. *Action on Objects.* For each $A \in \text{Obj}(C)$, we have

$$\text{id}_C(A) \stackrel{\text{def}}{=} A;$$

2. *Action on Morphisms.* For each $A, B \in \text{Obj}(C)$, the action on morphisms map

$$(\text{id}_C)_{A,B} : \text{Hom}_C(A, B) \rightarrow \underbrace{\text{Hom}_C(\text{id}_C(A), \text{id}_C(B))}_{\stackrel{\text{def}}{=} \text{Hom}_C(A, B)}$$

of id_C at (A, B) is defined by

$$(\text{id}_C)_{A,B} \stackrel{\text{def}}{=} \text{id}_{\text{Hom}_C(A, B)}.$$

Proof. Preservation of Identities: We have $\text{id}_C(\text{id}_A) \stackrel{\text{def}}{=} \text{id}_A$ for each $A \in \text{Obj}(C)$ by definition.

Preservation of Compositions: For each composable pair $A \xrightarrow{f} B \xrightarrow{g} C$ of morphisms of C , we have

$$\begin{aligned} \text{id}_C(g \circ f) &\stackrel{\text{def}}{=} g \circ f \\ &\stackrel{\text{def}}{=} \text{id}_C(g) \circ \text{id}_C(f). \end{aligned}$$

This finishes the proof. □

Definition 11.4.1.1.3. The **composition** of two functors $F : C \rightarrow \mathcal{D}$ and $G : \mathcal{D} \rightarrow \mathcal{E}$ is the functor $G \circ F$ where

· *Action on Objects.* For each $A \in \text{Obj}(C)$, we have

$$[G \circ F](A) \stackrel{\text{def}}{=} G(F(A));$$

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

$$(G \circ F)_{A,B} : \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{E}}(G_{F_A}, G_{F_B})$$

of $G \circ F$ at (A, B) is defined by

$$[G \circ F](f) \stackrel{\text{def}}{=} G(F(f)).$$

Proof. Preservation of Identities: For each $A \in \text{Obj}(C)$, we have

$$\begin{aligned} G_{F_{\text{id}_A}} &= G_{\text{id}_{F_A}} && \text{(functoriality of } F\text{)} \\ &= \text{id}_{G_{F_A}}. && \text{(functoriality of } G\text{)} \end{aligned}$$

Preservation of Composition: For each composable pair (g, f) of morphisms of C , we have

$$\begin{aligned} G_{F_{g \circ f}} &= G_{F_g \circ F_f} && \text{(functoriality of } F\text{)} \\ &= G_{F_g} \circ G_{F_f}. && \text{(functoriality of } G\text{)} \end{aligned}$$

This finishes the proof. □

Proposition 11.4.1.1.4. Let $F: C \rightarrow \mathcal{D}$ be a functor.

1. *Preservation of Isomorphisms.* If f is an isomorphism in C , then $F(f)$ is an isomorphism in \mathcal{D} .²²

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

$$\begin{aligned} F(f) \circ F(f)^{-1} &= F(f \circ f^{-1}) \\ &= F(\text{id}_A) \\ &= \text{id}_{F(A)}, \end{aligned}$$

showing $F(f)$ to be an isomorphism. □

²²When the converse holds, we call F *conservative*, see [Definition 11.4.6.1.1](#).

11.4.2 Faithful Functors

Let C and \mathcal{D} be categories.

Definition 11.4.2.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **faithful** if, for each $A, B \in \text{Obj}(C)$, the action on morphisms map

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is injective.

Proposition 11.4.2.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor $F: C \rightarrow \mathcal{D}$ is faithful.
- (b) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is faithful.

- (c) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is faithful.

Proof. **Item 1, Characterisations:** Omitted. □

11.4.3 Full Functors

Let C and \mathcal{D} be categories.

Definition 11.4.3.1.1. A functor $F: C \rightarrow \mathcal{D}$ is **full** if, for each $A, B \in \text{Obj}(C)$, the action on morphisms map

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is surjective.

Proposition 11.4.3.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor $F: C \rightarrow \mathcal{D}$ is full.
- (b) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is full.

- (c) For each $\mathcal{X} \in \text{Obj}(\text{Cats})$, the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is full.

Proof. **Item 1, Characterisations:** Omitted. □

11.4.4 Fully Faithful Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 11.4.4.1.1. 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 map

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of F at (A, B) is bijective.

Proposition 11.4.4.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor

1. *Characterisations.* 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 precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is fully faithful.

- (c) 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.

2. *Conservativity.* If F is fully faithful, then F is conservative.

Proof. Item 1, *Characterisations:* Omitted.

Item 2, *Conservativity:* This is proved in Item 2 of Proposition 11.4.6.1.2. □

11.4.5 Essentially Surjective Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 11.4.5.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **essentially surjective** if, for each $D \in \text{Obj}(\mathcal{D})$, there exists some object A of \mathcal{C} with $F(A) \cong D$.

11.4.6 Conservative Functors

Let \mathcal{C} and \mathcal{D} be categories.

Definition 11.4.6.1.1. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is **conservative** if it satisfies the following condition:

- (★) 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 11.4.6.1.2. 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.

Proof. **Item 1, Characterisations:** This follows from **Item 1** of [Proposition 11.4.1.1.4](#).

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

11.4.7 Equivalences of Categories

Definition 11.4.7.1.1. Let \mathcal{C} and \mathcal{D} be categories.

- 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

$$\begin{aligned} \eta: \text{id}_{\mathcal{C}} &\xrightarrow{\cong} G \circ F, \\ \epsilon: F \circ G &\xrightarrow{\cong} \text{id}_{\mathcal{D}}. \end{aligned}$$

- 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 11.4.7.1.2. Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

1. *Characterisations.* If C and \mathcal{D} are small²³, then the following conditions are equivalent:²⁴

- (a) The functor F is an equivalence of categories.
- (b) The functor F is fully faithful and essentially surjective.
- (c) The induced functor

$$\upharpoonright F\text{Sk}(C) : \text{Sk}(C) \rightarrow \text{Sk}(\mathcal{D})$$

is an *isomorphism* of categories.

2. *Two-Out-of-Three.* Let

$$\begin{array}{ccc} C & \xrightarrow{G \circ F} & \mathcal{E} \\ F \searrow & \nearrow G & \\ \mathcal{D} & & \end{array}$$

be a diagram in Cats . If two out of the three functors among F , G , and $G \circ F$ are equivalences of categories, then so is the third.

3. *Stability Under Composition.* Let

$$\begin{array}{ccccc} C & \xleftarrow[F]{G} & \mathcal{D} & \xleftarrow[F']{G'} & \mathcal{E} \end{array}$$

be a diagram in Cats . If (F, G) and (F', G') are equivalences of categories, then so is their composite $(F' \circ F, G' \circ G)$.

4. *Equivalences vs. Adjoint Equivalences.* Every equivalence of categories can be promoted to an adjoint equivalence.²⁵

5. *Interaction With Groupoids.* If 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:

²³Otherwise there will be size issues. One can also work with large categories and universes, or require F to be *constructively* essentially surjective; see [[MSE1465107](#)].

²⁴In ZFC, the equivalence between [Item 1a](#) and [Item 1b](#) is equivalent to the axiom of choice; see [[MO119454](#)].

In Univalent Foundations, this is true without requiring neither the axiom of choice nor the law of the excluded middle.

²⁵More 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 **1c** 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 $\eta: \text{id}_{\mathcal{D}} \xrightarrow{\cong} F \circ j$, with a similar natural isomorphism $\epsilon: \text{id}_{\mathcal{C}} \xrightarrow{\cong} j \circ F$. Hence F is an equivalence.

3. **Item 1a** \implies **Item 1c**. This follows from ??.

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 [nLa24b, Proposition 4.4]. □

11.4.8 Isomorphisms of Categories

Definition 11.4.8.1.1. An **isomorphism of categories** is a pair of functors

$$F: \mathcal{C} \rightarrow \mathcal{D},$$

$$G: \mathcal{D} \rightarrow \mathcal{C}$$

such that we have

$$G \circ F = \text{id}_{\mathcal{C}},$$

$$F \circ G = \text{id}_{\mathcal{D}}.$$

Example 11.4.8.1.2. 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 11.4.8.1.3. 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 a bijection on objects.

Proof. **Item 1, Characterisations:** Omitted, but similar to Item 1 of Proposition 11.4.7.1.2. \square

11.4.9 The Natural Transformation Associated to a Functor

Definition 11.4.9.1.1. Every functor $F: \mathcal{C} \rightarrow \mathcal{D}$ defines a natural transformation²⁶

$$\begin{array}{ccc} \mathcal{C}^{\text{op}} \times \mathcal{C} & \xrightarrow{F^{\text{op}} \times F} & \mathcal{D}^{\text{op}} \times \mathcal{D} \\ F^{\dagger}: \text{Hom}_{\mathcal{C}} \Rightarrow \text{Hom}_{\mathcal{D}} \circ (F^{\text{op}} \times F), & \swarrow \cong_{F^{\dagger}} \searrow & \swarrow \text{Hom}_{\mathcal{D}} \\ \text{Hom}_{\mathcal{C}} & & \text{Sets}, \end{array}$$

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

$$\begin{array}{ccc} \text{Hom}_{\mathcal{C}}(X, Y) & \xrightarrow{\phi^* \circ \psi_* = \psi_* \circ \phi^*} & \text{Hom}_{\mathcal{C}}(A, B) \\ F_{X,Y} \downarrow & & \downarrow F_{A,B} \\ \text{Hom}_{\mathcal{D}}(F_X, F_Y) & \xrightarrow{F(\phi)^* \circ F(\psi)_* = F(\psi)_* \circ F(\phi)^*} & \text{Hom}_{\mathcal{D}}(F_A, F_B), \end{array}$$

²⁶This is the 1-categorical version of ?? of ??.

acting on elements as

$$\begin{array}{ccc} f & \xrightarrow{\quad} & \psi \circ f \circ \phi \\ \downarrow & & \downarrow \\ F(f) & \longmapsto & F(\psi) \circ F(f) \circ F(\phi) = F(\psi \circ f \circ \phi) \end{array}$$

commutes, which follows from the functoriality of F . \square

Proposition 11.4.9.1.2. Let $F: C \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{E}$ be functors.

1. *Interaction With Natural Isomorphisms.* The following conditions are equivalent:

- (a) The natural transformation $F^\dagger: \text{Hom}_C \Rightarrow \text{Hom}_{\mathcal{D}} \circ (F^{\text{op}} \times F)$ 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

$$\begin{array}{ccc} C^{\text{op}} \times C & \xrightarrow{F^{\text{op}} \times F} & \mathcal{D}^{\text{op}} \times \mathcal{D} & \xrightarrow{G^{\text{op}} \times G} & \mathcal{E}^{\text{op}} \times \mathcal{E} \\ \searrow \text{Hom}_C & \nearrow \cong_{F^\dagger} & \downarrow \text{Hom}_{\mathcal{D}} & \nearrow \cong_{G^\dagger} & \searrow \text{Hom}_{\mathcal{E}} \\ & & \text{Sets} & & \end{array} = \begin{array}{ccc} C^{\text{op}} \times C & \xrightarrow{(G \circ F)^{\text{op}} \times (G \circ F)} & \mathcal{E}^{\text{op}} \times \mathcal{E}, \\ \searrow \text{Hom}_C & \nearrow \cong_{(G \circ F)^\dagger} & \searrow \text{Hom}_{\mathcal{E}} \\ & & \text{Sets} \end{array}$$

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

$$\text{id}_C^\dagger = \text{id}_{\text{Hom}_C(-1, -2)},$$

i.e. the natural transformation associated to id_C is the identity natural transformation of the functor $\text{Hom}_C(-1, -2)$.

Proof. **Item 1, Interaction With Natural Isomorphisms:** Clear.

Item 2, Interaction With Composition: Clear.

Item 3, Interaction With Identities: Clear. \square

11.5 Natural Transformations

11.5.1 Foundations

Let C and \mathcal{D} be categories and $F, G: C \Rightarrow \mathcal{D}$ be functors.

Definition 11.5.1.1.1. A **transformation**^{27,28} $\alpha: F \xrightarrow{\text{unnat}} G$ from F to G is a collection

$$\{\alpha_A: F(A) \rightarrow G(A)\}_{A \in \text{Obj}(C)}$$

of morphisms of \mathcal{D} .

Definition 11.5.1.1.2. A **natural transformation**²⁹ $\alpha: F \Rightarrow G$ 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.^{30,31}

Example 11.5.1.1.3. 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 morphism $f: A \rightarrow B$ of C , the diagram

$$\begin{array}{ccc} F(A) & \xrightarrow{F(f)} & F(B) \\ \text{id}_{F(A)} \downarrow & & \downarrow \text{id}_{F(B)} \\ F(A) & \xrightarrow{F(f)} & F(B) \end{array}$$

commutes, which follows from unitality of the composition of C . □

Definition 11.5.1.1.4. Two natural transformations $\alpha, \beta: F \Rightarrow G$ are **equal** if we have

$$\alpha_A = \beta_A$$

for each $A \in \text{Obj}(C)$.

²⁷Further Terminology: Also called an **unnatural transformation** for emphasis.

²⁸Further Notation: We write $\text{UnNat}(F, G)$ for the set of unnatural transformations from F to G .

²⁹Pictured in diagrams as

$$\begin{array}{ccc} C & \begin{array}{c} \xrightarrow{F} \\ \Downarrow \alpha \\ \xrightarrow{G} \end{array} & \mathcal{D}. \end{array}$$

³⁰Further Terminology: The morphism $\alpha_A: F_A \rightarrow G_A$ is called the **component of α at A** .

³¹Further Notation: We write $\text{Nat}(F, G)$ for the set of natural transformations from F to G .

11.5.2 Vertical Composition of Natural Transformations

Definition 11.5.2.1.1. The **vertical composition** of two natural transformations $\alpha: F \Rightarrow G$ and $\beta: G \Rightarrow H$ as in the diagram

$$\begin{array}{ccc} & F & \\ C & \xrightarrow{\quad G \quad} & \mathcal{D} \\ & \beta \Downarrow & \\ & H & \end{array}$$

is the natural transformation $\beta \circ \alpha: F \Rightarrow H$ consisting of the collection

$$\{(\beta \circ \alpha)_A: F(A) \rightarrow H(A)\}_{A \in \text{Obj}(C)}$$

with

$$(\beta \circ \alpha)_A \stackrel{\text{def}}{=} \beta_A \circ \alpha_A$$

for each $A \in \text{Obj}(C)$.

Proof. The naturality condition for $\beta \circ \alpha$ is the requirement that the boundary of the diagram

$$\begin{array}{ccc} F(A) & \xrightarrow{F(f)} & F(B) \\ \alpha_A \downarrow & (1) & \downarrow \alpha_B \\ G(A) & \xrightarrow{G(f)} & G(B) \\ \beta_A \downarrow & (2) & \downarrow \beta_B \\ H(A) & \xrightarrow{H(f)} & H(B) \end{array}$$

commutes. Since

1. Subdiagram (1) commutes by the naturality of α ;
2. Subdiagram (2) commutes by the naturality of β ;

so does the boundary diagram. Hence $\beta \circ \alpha$ is a natural transformation. \square

Proposition 11.5.2.1.2. 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

$$\begin{array}{ccccc}
& & \text{Nat}(H, K) \times (\text{Nat}(G, H) \times \text{Nat}(F, G)) & & \\
& \nearrow \alpha^{\text{Sets}}_{\text{Nat}(H, K), \text{Nat}(G, H), \text{Nat}(F, G)} & & \searrow \text{id}_{\text{Nat}(H, K) \times \text{Nat}(F, G)} & \\
(\text{Nat}(H, K) \times \text{Nat}(G, H)) \times \text{Nat}(F, G) & & & \text{Nat}(H, K) \times \text{Nat}(F, H) & \\
\downarrow \circ_{G, H, K} \times \text{id}_{\text{Nat}(F, G)} & & & \downarrow \circ_{F, H, K} & \\
\text{Nat}(G, K) \times \text{Nat}(F, G) & \xrightarrow[\circ_{F, G, K}]{} & \text{Nat}(F, K) & &
\end{array}$$

commutes, i.e. given natural transformations

$$\begin{aligned}
\alpha : F &\Longrightarrow G, \\
\beta : G &\Longrightarrow H, \\
\gamma : H &\Longrightarrow K,
\end{aligned}$$

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

$$\begin{array}{ccc}
\text{pt} \times \text{Nat}(F, G) & & \\
\downarrow [\text{id}_G] \times \text{id}_{\text{Nat}(F, G)} & \searrow \lambda^{\text{Sets}}_{\text{Nat}(F, G)} & \\
\text{Nat}(G, G) \times \text{Nat}(F, G) & \xrightarrow[\circ_{F, G, G}]{} & \text{Nat}(F, G)
\end{array}$$

commutes, i.e. given a natural transformation $\alpha : F \Longrightarrow G$, we have

$$\text{id}_G \circ \alpha = \alpha.$$

(b) *Right Unitality.* The diagram

$$\begin{array}{ccc}
\text{Nat}(F, G) \times \text{pt} & & \\
\downarrow \text{id}_{\text{Nat}(F, G)} \times [\text{id}_F] & \searrow \rho^{\text{Sets}}_{\text{Nat}(F, G)} & \\
\text{Nat}(F, G) \times \text{Nat}(F, F) & \xrightarrow[\circ_{F, F, G}^{\mathcal{C}}]{} & \text{Nat}(F, G)
\end{array}$$

commutes, i.e. given a natural transformation $\alpha : F \Rightarrow G$, we have

$$\alpha \circ \text{id}_F = \alpha.$$

4. *Middle Four Exchange*. Let $F_1, F_2, F_3 : C \rightarrow \mathcal{D}$ and $G_1, G_2, G_3 : \mathcal{D} \rightarrow \mathcal{E}$ be functors. The diagram

$$\begin{array}{ccc}
(\text{Nat}(G_2, G_3) \times \text{Nat}(G_1, G_2)) \times (\text{Nat}(F_2, F_3) \times \text{Nat}(F_1, F_2)) & \xleftarrow{\sim} & (\text{Nat}(G_2, G_3) \times \text{Nat}(F_2, F_3)) \times (\text{Nat}(G_1, G_2) \times \text{Nat}(F_1, F_2)) \\
\downarrow^{\circ_{G_1, G_2, G_3} \times \circ_{F_1, F_2, F_3}} & & \downarrow^{\star_{F_2, F_3, G_2, G_3} \times \star_{F_1, F_2, G_1, G_2}} \\
\text{Nat}(G_1, G_3) \times \text{Nat}(F_1, F_3) & & \text{Nat}(G_2 \circ F_2, G_3 \circ F_3) \times \text{Nat}(G_1 \circ F_1, G_2 \circ F_2) \\
& \searrow^{\star_{F_1, F_3, G_1, G_3}} & \swarrow^{\circ_{G_1 \circ F_1, G_2 \circ F_2, G_3 \circ F_3}} \\
& \text{Nat}(G_1 \circ F_1, G_3 \circ F_3) &
\end{array}$$

commutes, i.e. given a diagram

$$\begin{array}{ccccc}
& \overset{F_1}{\curvearrowright} & & \overset{G_1}{\curvearrowright} & \\
C & \xrightarrow{F_2} & \mathcal{D} & \xrightarrow{G_2} & \mathcal{E} \\
\downarrow^{\alpha} \quad \downarrow^{\beta} & & \downarrow^{\alpha'} \quad \downarrow^{\beta'} & & \downarrow^{\beta''} \\
F_3 & & G_3 & &
\end{array}$$

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

$$\begin{aligned}
((\gamma \circ \beta) \circ \alpha)_A &= (\gamma_A \circ \beta_A) \circ \alpha_A \\
&= \gamma_A \circ (\beta_A \circ \alpha_A) \\
&= (\gamma \circ (\beta \circ \alpha))_A
\end{aligned}$$

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 11.5.3.1.2](#). \square

11.5.3 Horizontal Composition of Natural Transformations

Definition 11.5.3.1.1. The **horizontal composition**^{32,33} of two natural transformations $\alpha: F \Rightarrow G$ and $\beta: H \Rightarrow K$ as in the diagram

$$\begin{array}{ccc} C & \xrightarrow[F]{\alpha \Downarrow} & \mathcal{D} \\ & \Downarrow G & \\ & \xrightarrow[H]{\beta \Downarrow} & \mathcal{E} \\ & \Downarrow K & \end{array}$$

of α and β is the natural transformation

$$\beta \star \alpha: (H \circ F) \Rightarrow (K \circ G),$$

as in the diagram

$$\begin{array}{ccc} C & \xrightarrow[H \circ F]{\beta \star \alpha \Downarrow} & \mathcal{E}, \\ & \Downarrow K \circ G & \end{array}$$

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

$$\begin{aligned} (\beta \star \alpha)_A &\stackrel{\text{def}}{=} \beta_{G(A)} \circ H(\alpha_A) \\ &= K(\alpha_A) \circ \beta_{F(A)}, \end{aligned} \quad \begin{array}{ccc} H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\ \beta_{F(A)} \downarrow & & \downarrow \beta_{G(A)} \\ K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)). \end{array}$$

Proof. First, we claim that we indeed have

$$\begin{array}{ccc} H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\ \beta_{G(A)} \circ H(\alpha_A) = K(\alpha_A) \circ \beta_{F(A)} \downarrow & & \downarrow \beta_{G(A)} \\ K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)). \end{array}$$

³²Further Terminology: Also called the **Codement product** of α and β .

³³Horizontal composition forms a map

$$\star_{(F,H),(G,K)}: \text{Nat}(H, K) \times \text{Nat}(F, G) \rightarrow \text{Nat}(H \circ F, K \circ G).$$

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.³⁴

□

Proposition 11.5.3.1.2. 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 Cats_2 . The diagram

$$\begin{array}{ccc}
 \text{Nat}(F_3, G_3) \times \text{Nat}(F_2, G_2) \times \text{Nat}(F_1, G_1) & \xrightarrow{\star_{(F_2, G_2), (F_3, G_3)} \times \text{id}} & \text{Nat}(F_3 \circ F_2, G_3 \circ G_2) \times \text{Nat}(F_1, G_1) \\
 \downarrow \text{id} \times \star_{(F_1, G_1), (F_2, G_2)} & & \downarrow \star_{(F_3 \circ F_2), (G_3 \circ G_2, F_1, G_1)} \\
 \text{Nat}(F_3, G_3) \times \text{Nat}(F_2 \circ F_1, G_2 \circ G_1) & \xrightarrow{\star_{(F_2 \circ F_1), (G_2 \circ G_1, F_3, G_3)}} & \text{Nat}(F_3 \circ F_2 \circ F_1, G_3 \circ G_2 \circ G_1)
 \end{array}$$

³⁴Reference: [Bor94, Proposition 1.3.4].

commutes, i.e. given natural transformations

$$\begin{array}{ccccc} & F_1 & & F_2 & & F_3 \\ C & \xrightarrow{\alpha \Downarrow} & \mathcal{D} & \xrightarrow{\beta \Downarrow} & \mathcal{E} & \xrightarrow{\gamma \Downarrow} \mathcal{F}, \\ & G_1 & & G_2 & & G_3 \end{array}$$

we have

$$(\gamma \star \beta) \star \alpha = \gamma \star (\beta \star \alpha).$$

3. *Interaction With Identities.* Let $F: C \rightarrow \mathcal{D}$ and $G: \mathcal{D} \rightarrow \mathcal{E}$ be functors. The diagram

$$\begin{array}{ccc} \text{pt} \times \text{pt} & \xrightarrow{[\text{id}_G] \times [\text{id}_F]} & \text{Nat}(G, G) \times \text{Nat}(F, F) \\ \uparrow \downarrow \vdots & & \downarrow \star_{(F,F),(G,G)} \\ \text{pt} & \xrightarrow{[\text{id}_{G \circ F}]} & \text{Nat}(G \circ F, G \circ F) \end{array}$$

commutes, i.e. we have

$$\text{id}_G \star \text{id}_F = \text{id}_{G \circ F}.$$

4. *Middle Four Exchange.* Let $F_1, F_2, F_3: C \rightarrow \mathcal{D}$ and $G_1, G_2, G_3: \mathcal{D} \rightarrow \mathcal{E}$ be functors. The diagram

$$\begin{array}{ccc} (\text{Nat}(G_2, G_3) \times \text{Nat}(G_1, G_2)) \times (\text{Nat}(F_2, F_3) \times \text{Nat}(F_1, F_2)) & \xleftarrow{\sim} & (\text{Nat}(G_2, G_3) \times \text{Nat}(F_2, F_3)) \times (\text{Nat}(G_1, G_2) \times \text{Nat}(F_1, F_2)) \\ \downarrow \circ_{G_1, G_2, G_3} \times \circ_{F_1, F_2, F_3} & & \downarrow \star_{F_2, F_3, G_2, G_3} \times \star_{F_1, F_2, G_1, G_2} \\ \text{Nat}(G_1, G_3) \times \text{Nat}(F_1, F_3) & & \text{Nat}(G_2 \circ F_2, G_3 \circ F_3) \times \text{Nat}(G_1 \circ F_1, G_2 \circ F_2) \\ \searrow \star_{F_1, F_3, G_1, G_3} & & \swarrow \circ_{G_1 \circ F_1, G_2 \circ F_2, G_3 \circ F_3} \\ \text{Nat}(G_1 \circ F_1, G_3 \circ F_3) & & \end{array}$$

commutes, i.e. given a diagram

$$\begin{array}{ccccc} & F_1 & & G_1 & \\ C & \xrightarrow{\alpha \Downarrow} & \mathcal{D} & \xrightarrow{\beta \Downarrow} & \mathcal{E} \\ \xrightarrow{F_2} & \longrightarrow & \xrightarrow{G_2} & \longrightarrow & \\ \alpha' \Downarrow & & \beta' \Downarrow & & \\ F_3 & & G_3 & & \end{array}$$

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: Omitted.

Item 3, Interaction With Identities: We have

$$\begin{aligned} (\text{id}_G \star \text{id}_F)_A &\stackrel{\text{def}}{=} (\text{id}_G)_{F_A} \circ G_{(\text{id}_F)_A} \\ &\stackrel{\text{def}}{=} \text{id}_{G_{F_A}} \circ G_{\text{id}_{F_A}} \\ &= \text{id}_{G_{F_A}} \circ \text{id}_{G_{F_A}} \\ &= \text{id}_{G_{F_A}} \\ &\stackrel{\text{def}}{=} (\text{id}_{G \circ F})_A \end{aligned}$$

for each $A \in \text{Obj}(C)$, showing the desired equality.

Item 4, Middle Four Exchange: Let $A \in \text{Obj}(C)$ and consider the diagram

$$\begin{array}{ccccc} & & G_{F''_A} & & \\ & \nearrow G_{\alpha'_A} & & \searrow \beta_{F''_A} & \\ G_{F_A} & \xrightarrow{G_{\alpha_A}} & G_{F'_A} & (1) & G''_{F''_A} \xrightarrow{\beta'_{F''_A}} G''_{F'_A} \\ & \searrow \beta_{F'_A} & & \nearrow G'_{\alpha'_A} & \\ & & G'_{F'_A} & & \end{array}$$

The top composition is $((\beta' \circ \beta) \star (\alpha' \circ \alpha))_A$ and the bottom composition is $((\beta' \star \alpha') \circ (\beta \star \alpha))_A$. Since Subdiagram (1) commutes, they are equal. \square

11.5.4 Properties of Natural Transformations

Proposition 11.5.4.1.1. Let $F, G: C \Rightarrow \mathcal{D}$ be functors. The following data are equivalent:³⁵

1. A natural transformation $\alpha: F \Rightarrow G$.
2. A functor $[\alpha]: C \rightarrow \mathcal{D}^k$ filling the diagram

$$\begin{array}{ccc} & \mathcal{D} & \\ F \swarrow & \uparrow \text{ev}_0 & \\ C & \xrightarrow{[\alpha]} & \mathcal{D}^k \\ & \searrow G & \downarrow \text{ev}_1 \\ & & \mathcal{D} \end{array}$$

³⁵Taken from [MO 64365].

3. A functor $[\alpha]: C \times \mathbb{1} \rightarrow \mathcal{D}$ filling the diagram

$$\begin{array}{ccc}
 & C & \\
 \text{ev}_0 \uparrow & \searrow F & \\
 C \times \mathbb{1} - [\alpha] \rightarrow \mathcal{D}. & & \\
 \text{ev}_1 \downarrow & \nearrow G & \\
 & C &
 \end{array}$$

Proof. From Item 1 to Item 2 and Back: We may identify \mathcal{D}^* with $\text{Arr}(\mathcal{D})$. Given a natural transformation $\alpha: F \Rightarrow G$, we have a functor

$$\begin{aligned}
 [\alpha]: C &\longrightarrow \mathcal{D}^* \\
 A &\longmapsto \alpha_A \\
 (f: A \rightarrow B) &\longmapsto \left(\begin{array}{ccc} F_A & \xrightarrow{F_f} & F_B \\ \alpha_A \downarrow & & \downarrow \alpha_B \\ G_A & \xrightarrow{G_f} & G_B \end{array} \right)
 \end{aligned}$$

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 11.6.1.1.2](#). \square

11.5.5 Natural Isomorphisms

Definition 11.5.5.1.1. A natural transformation $\alpha: F \Rightarrow G$ between functors $F, G: C \rightarrow \mathcal{D}$ between categories C and \mathcal{D} 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 11.5.5.1.2. 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 $A \in \text{Obj}(C)$, the morphism $\alpha_A: F_A \rightarrow G_A$ is an isomorphism.
2. *Componentwise Inverses of Natural Transformations Assemble Into Natural Transformations.*

tions. Let $\alpha^{-1}: G \Rightarrow F$ be a transformation such that, for each $A \in \text{Obj}(C)$, we have

$$\begin{aligned}\alpha_A^{-1} \circ \alpha_A &= \text{id}_{F(A)}, \\ \alpha_A \circ \alpha_A^{-1} &= \text{id}_{G(A)}.\end{aligned}$$

Then α^{-1} is a natural transformation.

Proof. **Item 1, Characterisations:** The implication **Item 1a** \Rightarrow **Item 1b** is clear, whereas the implication **Item 1b** \Rightarrow **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

$$\begin{array}{ccccc} G(A) & \xrightarrow{G(f)} & G(B) & & \\ \alpha_A^{-1} \downarrow & (1) & \downarrow \alpha_B^{-1} & & \\ F(A) & \xrightarrow{F(f)} & F(B) & & \\ \alpha_A \downarrow & (2) & \downarrow \alpha_B & & \\ G(A) & \xrightarrow{G(f)} & G(B), & & \end{array}$$

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

11.6 Categories of Categories

11.6.1 Functor Categories

Let C be a category and \mathcal{D} be a small category.

Definition 11.6.1.1.1. The **category of functors from C to \mathcal{D}** ³⁶ is the category $\text{Fun}(C, \mathcal{D})$ ³⁷ where

- *Objects.* The objects of $\text{Fun}(C, \mathcal{D})$ are functors from C to \mathcal{D} ;
- *Morphisms.* For each $F, G \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$, we have

$$\text{Hom}_{\text{Fun}(C, \mathcal{D})}(F, G) \stackrel{\text{def}}{=} \text{Nat}(F, G);$$

- *Identities.* For each $F \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$, the unit map

$$\text{id}_F^{\text{Fun}(C, \mathcal{D})} : \text{pt} \rightarrow \text{Nat}(F, F)$$

of $\text{Fun}(C, \mathcal{D})$ at F is given by

$$\text{id}_F^{\text{Fun}(C, \mathcal{D})} \stackrel{\text{def}}{=} \text{id}_F,$$

where $\text{id}_F : F \Rightarrow F$ is the identity natural transformation of F of [Example 11.5.1.3](#);

- *Composition.* For each $F, G, H \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$, the composition map

$$\circ_{F,G,H}^{\text{Fun}(C, \mathcal{D})} : \text{Nat}(G, H) \times \text{Nat}(F, G) \rightarrow \text{Nat}(F, H)$$

of $\text{Fun}(C, \mathcal{D})$ at (F, G, H) is given by

$$\beta \circ_{F,G,H}^{\text{Fun}(C, \mathcal{D})} \alpha \stackrel{\text{def}}{=} \beta \circ \alpha,$$

where $\beta \circ \alpha$ is the vertical composition of α and β of [Item 1 of Proposition 11.5.2.1.2](#).

Proposition 11.6.1.2. Let C and \mathcal{D} be categories and let $F : C \rightarrow \mathcal{D}$ be a functor.

1. *Functionality.* The assignments $C, \mathcal{D}, (C, \mathcal{D}) \mapsto \text{Fun}(C, \mathcal{D})$ define functors

$$\begin{aligned} \text{Fun}(C, -_2) &: \text{Cats} \rightarrow \text{Cats}, \\ \text{Fun}(-_1, \mathcal{D}) &: \text{Cats}^{\text{op}} \rightarrow \text{Cats}, \\ \text{Fun}(-_1, -_2) &: \text{Cats}^{\text{op}} \times \text{Cats} \rightarrow \text{Cats}. \end{aligned}$$

³⁶Further Terminology: Also called the **functor category** $\text{Fun}(C, \mathcal{D})$.

³⁷Further Notation: Also written \mathcal{D}^C and $[C, \mathcal{D}]$.

2. *2-Functionality.* The assignments $C, \mathcal{D}, (C, \mathcal{D}) \mapsto \text{Fun}(C, \mathcal{D})$ define 2-functors

$$\begin{aligned}\text{Fun}(C, -_2) &: \text{Cats}_2 \rightarrow \text{Cats}_2, \\ \text{Fun}(-_1, \mathcal{D}) &: \text{Cats}_2^{\text{op}} \rightarrow \text{Cats}_2, \\ \text{Fun}(-_1, -_2) &: \text{Cats}_2^{\text{op}} \times \text{Cats}_2 \rightarrow \text{Cats}_2.\end{aligned}$$

3. *Adjointness.* We have adjunctions

$$\begin{aligned}(C \times - \dashv \text{Fun}(C, -)) : \quad \text{Cats} &\begin{array}{c} \xrightarrow{C \times -} \\ \perp \\ \xleftarrow{\text{Fun}(C, -)} \end{array} \text{Cats}, \\ (- \times \mathcal{D} \dashv \text{Fun}(\mathcal{D}, -)) : \quad \text{Cats} &\begin{array}{c} \xrightarrow{- \times \mathcal{D}} \\ \perp \\ \xleftarrow{\text{Fun}(\mathcal{D}, -)} \end{array} \text{Cats},\end{aligned}$$

witnessed by bijections of sets

$$\begin{aligned}\text{Hom}_{\text{Cats}}(C \times \mathcal{D}, \mathcal{E}) &\cong \text{Hom}_{\text{Cats}}(\mathcal{D}, \text{Fun}(C, \mathcal{E})), \\ \text{Hom}_{\text{Cats}}(C \times \mathcal{D}, \mathcal{E}) &\cong \text{Hom}_{\text{Cats}}(C, \text{Fun}(\mathcal{D}, \mathcal{E})),\end{aligned}$$

natural in $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$.

4. *2-Adjointness.* We have 2-adjunctions

$$\begin{aligned}(C \times - \dashv \text{Fun}(C, -)) : \quad \text{Cats}_2 &\begin{array}{c} \xrightarrow{C \times -} \\ \perp_2 \\ \xleftarrow{\text{Fun}(C, -)} \end{array} \text{Cats}_2, \\ (- \times \mathcal{D} \dashv \text{Fun}(\mathcal{D}, -)) : \quad \text{Cats}_2 &\begin{array}{c} \xrightarrow{- \times \mathcal{D}} \\ \perp_2 \\ \xleftarrow{\text{Fun}(\mathcal{D}, -)} \end{array} \text{Cats}_2,\end{aligned}$$

witnessed by isomorphisms of categories

$$\begin{aligned}\text{Fun}(C \times \mathcal{D}, \mathcal{E}) &\cong \text{Fun}(\mathcal{D}, \text{Fun}(C, \mathcal{E})), \\ \text{Fun}(C \times \mathcal{D}, \mathcal{E}) &\cong \text{Fun}(C, \text{Fun}(\mathcal{D}, \mathcal{E})),\end{aligned}$$

natural in $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats}_2)$.

5. *Trivial Functor 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

$$D: \mathcal{I} \rightarrow \text{Fun}(\mathcal{C}, \mathcal{D})$$

be a diagram in $\text{Fun}(\mathcal{C}, \mathcal{D})$. 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 $A \in \text{Obj}(\mathcal{C})$.

7. *Bicompleteness.* If \mathcal{E} is co/complete, then so is $\text{Fun}(\mathcal{C}, \mathcal{E})$.

8. *Abelianness.* If \mathcal{E} is abelian, then so is $\text{Fun}(\mathcal{C}, \mathcal{E})$.

9. *Monomorphisms and Epimorphisms.* Let $\alpha: F \Rightarrow G$ be a morphism of $\text{Fun}(\mathcal{C}, \mathcal{D})$. The following conditions are equivalent:

(a) The natural transformation

$$\alpha: F \Rightarrow G$$

is a monomorphism (resp. epimorphism) in $\text{Fun}(\mathcal{C}, \mathcal{D})$.

(b) 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, Trivial Functor Categories: Omitted.

Item 6, Objectwise Computation of Co/Limits: Omitted.

Item 7, Bicompleteness: This follows from ??.

Item 8, Abelianness: Omitted.

Item 9, Monomorphisms and Epimorphisms: Omitted. □

11.6.2 The Category of Categories and Functors

Definition 11.6.2.1.1. The **category of (small) categories and functors** is the category Cats where

- *Objects.* The objects of Cats are small categories;

- *Morphisms.* For each $C, \mathcal{D} \in \text{Obj}(\text{Cats})$, we have

$$\text{Hom}_{\text{Cats}}(C, \mathcal{D}) \stackrel{\text{def}}{=} \text{Obj}(\text{Fun}(C, \mathcal{D}));$$

- *Identities.* For each $C \in \text{Obj}(\text{Cats})$, the unit map

$$\mathbb{1}_C^{\text{Cats}} : \text{pt} \rightarrow \text{Hom}_{\text{Cats}}(C, C)$$

of Cats at C is defined by

$$\text{id}_C^{\text{Cats}} \stackrel{\text{def}}{=} \text{id}_C,$$

where $\text{id}_C : C \rightarrow C$ is the identity functor of C of [Example 11.4.1.1.2](#);

- *Composition.* For each $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$, the composition map

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\text{Cats}} : \text{Hom}_{\text{Cats}}(\mathcal{D}, \mathcal{E}) \times \text{Hom}_{\text{Cats}}(C, \mathcal{D}) \rightarrow \text{Hom}_{\text{Cats}}(C, \mathcal{E})$$

of Cats at $(C, \mathcal{D}, \mathcal{E})$ is given by

$$G \circ_{C, \mathcal{D}, \mathcal{E}}^{\text{Cats}} F \stackrel{\text{def}}{=} G \circ F,$$

where $G \circ F : C \rightarrow \mathcal{E}$ is the composition of F and G of [Definition 11.4.1.1.3](#).

Proposition 11.6.2.1.2. Let 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:](#) This follows from

[Item 2, Cartesian Monoidal Structure:](#) Omitted. □

11.6.3 The 2-Category of Categories, Functors, and Natural Transformations

Definition 11.6.3.1.1. The **2-category of (small) categories, functors, and natural transformations** is the 2-category Cats_2 where

- *Objects.* The objects of Cats_2 are small categories;
- *Hom-Categories.* For each $C, \mathcal{D} \in \text{Obj}(\text{Cats}_2)$, we have

$$\text{Hom}_{\text{Cats}_2}(C, \mathcal{D}) \stackrel{\text{def}}{=} \text{Fun}(C, \mathcal{D});$$

- *Identities.* For each $C \in \text{Obj}(\text{Cats}_2)$, the unit functor

$$\mathbb{1}_C^{\text{Cats}_2} : \text{pt} \rightarrow \text{Fun}(C, C)$$

of Cats_2 at C is the functor picking the identity functor $\text{id}_C : C \rightarrow C$ of C ;

- *Composition.* For each $C, D, E \in \text{Obj}(\text{Cats}_2)$, the composition bifunctor

$$\circ_{C,D,E}^{\text{Cats}_2} : \text{Hom}_{\text{Cats}_2}(D, E) \times \text{Hom}_{\text{Cats}_2}(C, D) \rightarrow \text{Hom}_{\text{Cats}_2}(C, E)$$

of Cats_2 at (C, D, E) is the functor where

- *Action on Objects.* For each object $(G, F) \in \text{Obj}(\text{Hom}_{\text{Cats}_2}(D, E) \times \text{Hom}_{\text{Cats}_2}(C, D))$, we have

$$\circ_{C,D,E}^{\text{Cats}_2}(G, F) \stackrel{\text{def}}{=} G \circ F;$$

- *Action on Morphisms.* For each morphism $(\beta, \alpha) : (K, H) \Rightarrow (G, F)$ of $\text{Hom}_{\text{Cats}_2}(D, E) \times \text{Hom}_{\text{Cats}_2}(C, D)$, we have

$$\circ_{C,D,E}^{\text{Cats}_2}(\beta, \alpha) \stackrel{\text{def}}{=} \beta \star \alpha,$$

where $\beta \star \alpha$ is the horizontal composition of α and β of [Definition 11.5.3.1.1](#).

Proposition 11.6.3.1.2. Let 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:](#) This follows from □

11.6.4 The Category of Groupoids

Definition 11.6.4.1.1. The **category of (small) groupoids** is the full subcategory Grpd of Cats spanned by the groupoids.

11.6.5 The 2-Category of Groupoids

Definition 11.6.5.1.1. The **2-category of (small) groupoids** is the full sub-2-category Grpd_2 of Cats_2 spanned by the groupoids.

11.7 Miscellany

11.7.1 Concrete Categories

Definition 11.7.1.1.1. A category C is **concrete** if there exists a faithful functor $F : C \rightarrow \text{Sets}$.

11.7.2 Balanced Categories

Definition 11.7.2.1.1. A category is **balanced** if every morphism which is both a monomorphism and an epimorphism is an isomorphism.

11.7.3 Monoid Actions on Objects of Categories

Let A be a monoid, let C be a category, and let $X \in \text{Obj}(C)$.

Definition 11.7.3.1.1. An A -action on X is a functor $\lambda: BA \rightarrow C$ with $\lambda(\star) = X$.

Remark 11.7.3.1.2. In detail, an A -action on X is an A -action on $\text{End}_C(X)$, consisting of a morphism

$$\lambda: A \rightarrow \underbrace{\text{End}_C(X)}_{\stackrel{\text{def}}{=} \text{Hom}_C(X, X)}$$

satisfying the following conditions:

1. *Preservation of Identities.* We have

$$\lambda_{1_A} = \text{id}_X.$$

2. *Preservation of Composition.* For each $a, b \in A$, we have

$$\begin{array}{ccc} X & \xrightarrow{\lambda_a} & X \\ \lambda_b \circ \lambda_a = \lambda_{ab}, & \searrow \lambda_{ab} & \downarrow \lambda_b \\ & & X. \end{array}$$

11.7.4 Group Actions on Objects of Categories

Let G be a group, let C be a category, and let $X \in \text{Obj}(C)$.

Definition 11.7.4.1.1. A G -action on X is a functor $\lambda: BG \rightarrow C$ with $\lambda(\star) = X$.

Remark 11.7.4.1.2. In detail, a G -action on X is a G -action on $\text{Aut}_C(X)$, consisting of a morphism

$$\lambda: G \rightarrow \underbrace{\text{End}_C(X)}_{\stackrel{\text{def}}{=} \text{Hom}_C(X, X)}$$

satisfying the following conditions:

1. *Preservation of Identities.* We have

$$\lambda_{1_A} = \text{id}_X.$$

2. *Preservation of Composition.* For each $a, b \in A$, we have

$$\begin{array}{ccc} X & \xrightarrow{\lambda_a} & X \\ \lambda_b \circ \lambda_a = \lambda_{ab}, & \searrow \lambda_{ab} & \downarrow \lambda_b \\ & & X. \end{array}$$

Appendices

11.A Other Chapters

Sets

1. Sets
2. Constructions With Sets
3. Pointed Sets
4. Tensor Products of Pointed Sets
5. Relations
6. Spans
7. Posets

Indexed and Fibred Sets

7. Indexed Sets
8. Fibred Sets
9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories
12. Types of Morphisms in Categories
13. Adjunctions and the Yoneda Lemma
14. Constructions With Categories
15. Profunctors
16. Cartesian Closed Categories
17. Kan Extensions

Bicategories

18. Bicategories
19. Internal Adjunctions

Internal Category Theory

20. Internal Categories

Cyclic Stuff

21. The Cycle Category

Cubical Stuff

22. The Cube Category

Globular Stuff

23. The Globe Category

Cellular Stuff

24. The Cell Category

Monoids

25. Monoids

26. Constructions With Monoids

Monoids With Zero

27. Monoids With Zero

28. Constructions With Monoids With Zero

Groups

29. Groups

30. Constructions With Groups

Hyper Algebra

31. Hypermonoids

32. Hypergroups

33. Hypersemirings and Hyperrings

34. Quantales

Near-Rings

35. Near-Semirings

36. Near-Rings

Real Analysis

37. Real Analysis in One Variable

38. Real Analysis in Several Variables

41. Stochastic Processes, Martingales, and Brownian Motion

Measure Theory

39. Measurable Spaces

42. Itô Calculus

40. Measures and Integration

43. Stochastic Differential Equations

Probability Theory

40. Probability Theory

Differential Geometry

44. Topological and Smooth Manifolds

Stochastic Analysis

Schemes

45. Schemes

11.2 Other Chapters

Sets

15. Profunctors

1. Sets

16. Cartesian Closed Categories

2. Constructions With Sets

17. Kan Extensions

3. Pointed Sets

Bicategories

4. Tensor Products of Pointed Sets

18. Bicategories

5. Relations

19. Internal Adjunctions

6. Spans

Internal Category Theory

7. Posets

20. Internal Categories

Indexed and Fibred Sets

Cyclic Stuff

7. Indexed Sets

21. The Cycle Category

8. Fibred Sets

Cubical Stuff

9. Un/Straightening for Indexed and Fibred Sets

22. The Cube Category

Category Theory

Globular Stuff

11. Categories

23. The Globe Category

12. Types of Morphisms in Categories

Cellular Stuff

13. Adjunctions and the Yoneda Lemma

24. The Cell Category

14. Constructions With Categories

Monoids

25. Monoids

26. Constructions With Monoids

Monoids With Zero	37. Real Analysis in One Variable
27. Monoids With Zero	38. Real Analysis in Several Variables
28. Constructions With Monoids With Zero	Measure Theory
Groups	39. Measurable Spaces
29. Groups	40. Measures and Integration
30. Constructions With Groups	Probability Theory
Hyper Algebra	40. Probability Theory
31. Hypermonoids	Stochastic Analysis
32. Hypergroups	41. Stochastic Processes, Martingales, and Brownian Motion
33. Hypersemirings and Hyperrings	42. Itô Calculus
34. Quantales	43. Stochastic Differential Equations
Near-Rings	Differential Geometry
35. Near-Semirings	44. Topological and Smooth Manifolds
36. Near-Rings	Schemes
Real Analysis	45. Schemes

Chapter 12

Types of Morphisms in Categories

Create tags (see [MSE 350788] for some of these):

1. ??
2. ??
3. ??
4. ??
5. write material on sections and retractions

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12.1 Monomorphisms

12.1.1 Foundations

Let \mathcal{C} be a category.

Definition 12.1.1.1.1. A morphism $m: A \rightarrow B$ of C is a **monomorphism** if, for each diagram of the form

$$m \circ f = m \circ g, \quad X \xrightarrow[g]{f} A \xrightarrow{m} B$$

in Cats , we have $f = g$.

Example 12.1.1.1.2. Here are some examples of monomorphisms.

1. *Monomorphisms in Sets.* The monomorphisms in Sets are precisely the injections.

Proof. **Item 1, Monomorphisms in Sets:** Let $f: A \rightarrow B$ be a morphism in Sets. Suppose that f is a monomorphism and consider the diagram

$$\{\ast\} \xrightarrow[\{y\}]{} A \xrightarrow{f} B,$$

where $[x]$ and $[y]$ are the morphisms picking the elements x and y of A . If $f(x) = f(y)$, then $f \circ [x] = f \circ [y]$, and thus $[x] = [y]$ since f is a monomorphism. Hence $x = y$ and we see that f is injective.

Conversely, suppose that f is injective. Proceeding by contrapositive, we claim that given a pair of maps $g, h: X \Rightarrow A$ such that $g \neq h$, then $f \circ g \neq f \circ h$. Indeed, as g and h are different maps, there must exist at least one element $x \in X$ such that $g(x) \neq h(x)$. But then we have $f(g(x)) \neq f(h(x))$, since f is injective. Thus $f \circ g \neq f \circ h$, and we are done, having showed that f is a monomorphism. \square

Proposition 12.1.1.1.3. Let $f: A \rightarrow B$ be a morphism of C .

1. *Characterisations.* The following conditions are equivalent:
 - (a) The morphism f is a monomorphism.
 - (b) For each $X \in \text{Obj}(C)$, the map of sets

$$f_*: \text{Hom}_{\text{Sets}}(X, A) \rightarrow \text{Hom}_{\text{Sets}}(X, B)$$

is injective.

- (c) The kernel pair of f is trivial, i.e. we have

$$\begin{array}{ccc} A & \xrightarrow{\text{id}_A} & A \\ A \times_B A \cong A, & \downarrow \text{id}_A & \downarrow f \\ A & \xrightarrow{f} & B. \end{array}$$

2. *Duality.* The following conditions are equivalent:

- (a) The morphism $f: A \rightarrow B$ is a monomorphism in C .
- (b) The morphism $f^\dagger: B \rightarrow A$ is an epimorphism in C^{op} .

3. *Monomorphisms vs. Injective Maps.* Let

- C be a concrete category as in ??;
- $\mathfrak{U}_C: C \rightarrow \text{Sets}$ be the forgetful functor from C to Sets ;
- $f: A \rightarrow B$ be a morphism of C .

If \mathfrak{U}_C preserves pullbacks, then the following conditions are equivalent:

- (a) The morphism f is a monomorphism.
- (b) The morphism $\mathfrak{U}(f)_C$ is injective.

4. *Stability Properties.* The class of all monomorphisms of C is stable under the following operations:

- (a) *Composition.* If f and g are monomorphisms, then so is $g \circ f$.¹
- (b) *Pullbacks.* Let

$$\begin{array}{ccc} A \times_C B & \longrightarrow & B \\ m' \downarrow & \lrcorner & \downarrow m \\ A & \longrightarrow & C \end{array}$$

be a diagram in C . If m is a monomorphism in C , then so is m' .

5. *Morphisms From the Terminal Object Are Monomorphisms.* If C has a terminal object $\mathbb{1}_C$, then every morphism of C from $\mathbb{1}_C$ is a monomorphism.

Proof. **Item 1, Characterisations:** The equivalence between **Items 1a** and **1b** is clear. We claim that **Items 1a** and **1c** are equivalent:

1. **Item 1a \implies Item 1c:** Suppose that f is a monomorphism. Then A satisfies the universal property of the pullback:

$$\begin{array}{ccccc} P & \xrightarrow{\phi} & A & \xrightarrow{id_A} & A \\ \exists! \quad \phi \quad \dashv & \searrow & \downarrow id_A & \searrow & \downarrow f \\ & \phi & A & \xrightarrow{id_A} & A \\ & & \downarrow id_A & & \downarrow f \\ & & A & \xrightarrow{f} & B. \end{array}$$

¹Conversely, if $g \circ f$ is a monomorphism, then so is f .

2. *Item 1c \implies Item 1a:* Suppose that $A \cong A \times_B A$ and let $g, h: C \rightrightarrows A$ be a pair of morphisms. Consider the diagram

$$\begin{array}{ccccc} & & C & & \\ & \searrow & g & & \\ & & h \searrow & & \\ & & A & \xrightarrow{\text{id}_A} & A \\ & & \downarrow & & \downarrow f \\ & & A & \xrightarrow{f} & B. \end{array}$$

The universal property of the pullback says that there exists a unique morphism $C \rightarrow A$ making the diagram

$$\begin{array}{ccccc} & & C & & \\ & \swarrow & \exists! & \searrow & \\ & & g & & \\ & \searrow & h \searrow & & \\ & & A & \xrightarrow{\text{id}_A} & A \\ & & \downarrow & & \downarrow f \\ & & A & \xrightarrow{f} & B \end{array}$$

commute, which implies $g = h$. Therefore, f is a monomorphism.

Item 3, Monomorphisms vs. Injective Maps: Assume that f is injective. As the forgetful functor from C to Sets is faithful, we see that [Proposition 12.1.2.1.2](#) together with ?? imply that f is a monomorphism.

Conversely, assume that f is a monomorphism. As F preserves pullbacks, it also preserves kernel pairs. By ??, we see that F preserves monomorphisms. Thus F_f is a monomorphism, and hence is injective by ??.

Item 4, Stability Properties: Let $f, g: X \rightrightarrows A \times_C B$ be two morphisms such that the diagram

$$X \xrightleftharpoons[g]{f} A \times_C B \xrightarrow{m'} A$$

commutes. It follows that the diagram

$$\begin{array}{ccccc}
 & X & & & \\
 & \swarrow f & \searrow \text{pr}_2 \circ f & & \\
 & A \times_C B & \xrightarrow{\quad \text{pr}_2 \rightarrow B} & & \\
 & \downarrow m' & \lrcorner & & \downarrow m \\
 & A & \xrightarrow{\quad \psi \quad} & C &
 \end{array}$$

$m' \circ g$ m'

also commutes. From the universal property of the pullback, it follows that there must be precisely one morphism from X to $A \times_C B$ making the above diagram commute. Thus $f = g$ and m' is a monomorphism.

Item 5, Morphisms From the Terminal Object Are Monomorphisms: Clear. \square

12.1.2 Monomorphism-Reflecting Functors

Definition 12.1.2.1.1. A functor $F: C \rightarrow \mathcal{D}$ **reflects monomorphisms** if, for each morphism f of C , whenever F_f is a monomorphism, so is f .

Proposition 12.1.2.1.2. Let $F: C \rightarrow \mathcal{D}$ be a functor. If F is faithful, then it reflects monomorphisms.

Proof. Let $f: A \rightarrow B$ be a morphism of C and suppose that $F_f: F_A \rightarrow F_B$ is a monomorphism. Let $g, h: B \rightrightarrows C$ be two morphisms of C such that $g \circ f = h \circ f$. As F is faithful, we must have

$$F_g \circ F_f = F_{g \circ f} = F_{h \circ f} = F_h \circ F_f,$$

but as F_f is a monomorphism, it must be that $F_g = F_h$. Using the faithfulness of F again, we see that $g = h$. Therefore f is a monomorphism. \square

12.1.3 Split Monomorphisms

Let C be a category.

Definition 12.1.3.1.1. A morphism $f: A \rightarrow B$ of C is a **split monomorphism**² if there exists a morphism $g: B \rightarrow A$ of C such that³

$$g \circ f = \text{id}_A.$$

²Further Terminology: Also called a **section**, or a **split monic** morphism.

³Warning: There exist monomorphisms which are not split monomorphisms, e.g. $\mathbb{Z}/2 \hookrightarrow \mathbb{Z}/4$ in

Proposition 12.1.3.1.2. Let C be a category.

1. *Split Monomorphisms are Monomorphisms.* If m is a split monomorphism, then m is a monomorphism.

Proof. **Item 1, Split Monomorphisms are Monomorphisms:** Let $m: A \rightarrow B$ be a split monomorphism of C , let $e: B \rightarrow A$ be a morphism of C with

$$e \circ m = \text{id}_A,$$

and let $f, g: C \rightrightarrows A$ be two morphisms of C such that the diagram

$$\begin{array}{ccccc} C & \xrightarrow{\quad f \quad} & A & \xrightarrow{\quad m \quad} & B \\ & \xrightarrow{\quad g \quad} & & & \end{array}$$

commutes. Then we have

$$\begin{aligned} f &= \text{id}_A \circ f \\ &= (e \circ m) \circ f \\ &= e \circ (m \circ f) \\ &= e \circ (m \circ g) \\ &= (e \circ m) \circ g \\ &= \text{id}_A \circ g \\ &= g, \end{aligned}$$

showing m to be a monomorphism. □

12.2 Epimorphisms

12.2.1 Foundations

Let C be a category.

Definition 12.2.1.1.1. A morphism $f: A \rightarrow B$ of C is an **epimorphism** if for every commutative⁴ diagram of the form

$$A \xrightarrow{\quad f \quad} B \xrightarrow{\quad g \quad} C, \quad h$$

we have $g = h$.

Ring.

⁴That is, with $g \circ f = h \circ f$.

Example 12.2.1.1.2. Let $f: A \rightarrow B$ be a function. The following conditions are equivalent:

1. The function f is injective.
2. The function f is an epimorphism in Sets.

Proof. Suppose that f is surjective and let $g, h: B \rightrightarrows C$ be morphisms such that $g \circ f = h \circ f$. Then for each $a \in A$, we have

$$g(f(a)) = h(f(a)),$$

but this implies that

$$g(b) = h(b)$$

for each $b \in B$, as f is surjective. Thus $g = h$ and f is an epimorphism.

To prove the converse, we proceed by contrapositive. So suppose that f is not surjective and consider the diagram

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

where h is the map defined by $h(b) = 0$ for each $b \in B$ and g is the map defined by

$$g(b) = \begin{cases} 1 & \text{if } b \in \text{Im}(f), \\ 0 & \text{otherwise.} \end{cases}$$

Then $h \circ f = g \circ f$, as $h(f(a)) = 1 = g(f(a))$ for each $a \in A$. However, for any $b \in B \setminus \text{Im}(f)$, we have

$$g(b) = 0 \neq 1 = h(b).$$

Therefore $g \neq h$ and f is not an epimorphism. \square

Proposition 12.2.1.1.3. Let C be a category.

1. *Characterisations.* Let C be a category with pullbacks and $f: A \rightarrow B$ be a morphism of C . The following conditions are equivalent:

- (a) The morphism f is an epimorphism.
- (b) For each $X \in \text{Obj}(C)$, the map of sets

$$f^*: \text{Hom}_{\text{Sets}}(B, X) \rightarrow \text{Hom}_{\text{Sets}}(A, X)$$

is injective.

- (c) The cokernel pair of f is trivial, i.e. we have

$$\begin{array}{ccc} B & \xleftarrow{\quad} & B \\ \uparrow \lrcorner & & \uparrow f \\ B & \xleftarrow{f} & A \end{array}$$

2. *Epimorphisms vs. Surjective Maps.* Let

- \mathcal{C} be a concrete category;
- $\text{忘} : \mathcal{C} \rightarrow \text{Sets}$ be the forgetful functor from \mathcal{C} to Sets;
- $f : A \rightarrow B$ be a morphism of \mathcal{C} .

If 忘 preserves pushouts, then the following conditions are equivalent:

- (a) The morphism f is a epimorphism.
- (b) The morphism f is surjective.

3. *Stability Properties.* The class of all epimorphisms of \mathcal{C} is stable under the following operations:

- (a) *Composition.* If f and g are epimorphisms, then so is $g \circ f$.⁵
- (b) *Pushouts.* Let

$$\begin{array}{ccc} A \coprod_C B & \xleftarrow{\quad} & B \\ \uparrow e' \quad \lrcorner & & \uparrow e \\ A & \longrightarrow & C \end{array}$$

be a diagram in \mathcal{C} . If e is an epimorphism in \mathcal{C} , then so is e' .

4. *Morphisms to the Initial Object Are Monomorphisms.* If \mathcal{C} has an initial object $\emptyset_{\mathcal{C}}$, then every morphism of \mathcal{C} to $\emptyset_{\mathcal{C}}$ is a epimorphism.

Proof. This is dual to [Proposition 12.1.1.1.3](#). □

12.2.2 Regular Epimorphisms

Proposition 12.2.2.1.1. Let \mathcal{C} be a category.

1. *Stability Under Pullbacks.* Consider the diagram

$$\begin{array}{ccc} A \times_C B & \longrightarrow & B \\ \downarrow e' \quad \lrcorner & & \downarrow e \\ A & \longrightarrow & C \end{array}$$

in \mathcal{C} . If e is a regular epimorphism, then so is e' .

Proof. Epimorphisms Need Not Be Stable Under Pullback. : Regular Epimorphisms Are Stable Under Pullback. : □

⁵Conversely, if $g \circ f$ is a epimorphism, then so is g .

12.2.3 Effective Epimorphisms

Let C be a category.

Definition 12.2.3.1.1. An epimorphism $f: A \rightarrow B$ of C is **effective** if we have an isomorphism

$$B \cong \text{CoEq}(A \times_B A \rightrightarrows A).$$

12.2.4 Split Epimorphisms

Let C be a category.

Definition 12.2.4.1.1. A morphism $f: A \rightarrow B$ of C is a **retraction**⁶ if there is an arrow $g: B \rightarrow A$ such that $f \circ g = \text{id}_B$.

Proposition 12.2.4.1.2. Let $f: A \rightarrow B$ be a morphism of C .

1. Every split epimorphism is an epimorphism.⁷

Proof. This is dual to ??.

□

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5. Relations
6. Spans
7. Posets

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⁶Further Terminology: Also called a **split epimorphism**.

⁷⚠️ Warning: There are epimorphisms which are not split epimorphisms, however, e.g. $\mathbb{Z} \hookrightarrow \mathbb{Z}/2$.

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Adjunctions and the Yoneda Lemma

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Chapter 15

Profunctors

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15.1 Profunctors

15.1.1 Foundations

Let \mathcal{C} and \mathcal{D} be categories.

Definition 15.1.1.1. A **profunctor**¹ $p: \mathcal{C} \nrightarrow \mathcal{D}$ from \mathcal{C} to \mathcal{D} is a functor $p: \mathcal{D}^{\text{op}} \times \mathcal{C} \rightarrow \text{Sets}$.

Remark 15.1.1.2. Equivalently, we may define a profunctor from \mathcal{C} to \mathcal{D} as:

1. A functor $p: \mathcal{D}^{\text{op}} \times \mathcal{C} \rightarrow \text{Sets}$;

¹*Further Terminology:* Also called a **distributor**, a **bimodule**, a **correspondence**, or a **relator**.

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 cocontinuous functor $\mathbf{p}: \mathbf{PSh}(\mathcal{C}) \rightarrow \mathbf{PSh}(\mathcal{D})$;

That is, we have isomorphisms of categories

$$\begin{aligned}\mathbf{Prof}(\mathcal{C}, \mathcal{D}) &\cong \mathbf{Fun}(\mathcal{C}, \mathbf{PSh}(\mathcal{D})), \\ &\cong \mathbf{Fun}(\mathcal{D}^{\text{op}}, \mathbf{CoPSh}(\mathcal{C})), \\ &\cong \mathbf{CoContFun}(\mathbf{PSh}(\mathcal{C}), \mathbf{PSh}(\mathcal{D})),\end{aligned}$$

natural in $\mathcal{C}, \mathcal{D} \in \mathbf{Obj}(\mathbf{Cats})$.

Proof. We claim that **Items 1 to 4** are indeed equivalent:

- The equivalence between **Items 1 and 2** is an instance of currying, following from the isomorphisms of categories

$$\mathbf{Fun}(\mathcal{D}^{\text{op}} \times \mathcal{C}, \mathbf{Sets}) \cong \mathbf{Fun}(\mathcal{C}, \mathbf{Fun}(\mathcal{D}^{\text{op}}, \mathbf{Sets})) \stackrel{\text{def}}{=} \mathbf{Fun}(\mathcal{C}, \mathbf{PSh}(\mathcal{D})).$$

- The equivalence between **Items 1 and 3** is also an instance of currying, following from the isomorphisms of categories

$$\mathbf{Fun}(\mathcal{D}^{\text{op}} \times \mathcal{C}, \mathbf{Sets}) \cong \mathbf{Fun}(\mathcal{D}^{\text{op}}, \mathbf{Fun}(\mathcal{C}, \mathbf{Sets})) \stackrel{\text{def}}{=} \mathbf{Fun}(\mathcal{D}^{\text{op}}, \mathbf{Fun}(\mathcal{C}, \mathbf{Sets})).$$

- The equivalence between **Items 1 and 4** follows from the universal property of the category $\mathbf{PSh}(\mathcal{C})$ of presheaves on \mathcal{C} as the free cocompletion of \mathcal{C} via the Yoneda embedding

$$\mathfrak{J}: \mathcal{C}^{\text{op}} \hookrightarrow \mathbf{PSh}(\mathcal{C})$$

of \mathcal{C} into $\mathbf{PSh}(\mathcal{C})$ (?? of ??).

This finishes the proof. □

15.2 Operations With Profunctors

15.2.1 The Domain and Range of a Profunctor

Definition 15.2.1.1.1. Let $\mathbf{p}: \mathcal{C} \nrightarrow \mathcal{D}$ be a profunctor.²

²In other words, the domain and range of \mathbf{p} are the functors

$$\begin{aligned}\text{dom}(\mathbf{p}) &: \mathcal{D}^{\text{op}} \rightarrow \mathbf{Sets}, \\ \text{range}(\mathbf{p}) &: \mathcal{C} \rightarrow \mathbf{Sets}\end{aligned}$$

1. The **domain of \mathbf{p}** is the presheaf $\text{dom}(\mathbf{p}): \mathcal{D}^{\text{op}} \rightarrow \text{Sets}$ on \mathcal{D} defined by

$$\text{dom}(\mathbf{p})^- \stackrel{\text{def}}{=} \underset{B \in \mathcal{D}}{\text{colim}} (\mathbf{p}_B^-).$$

2. The **range of \mathbf{p}** is the copresheaf $\text{range}(\mathbf{p}): \mathcal{C} \rightarrow \text{Sets}$ on \mathcal{C} defined by

$$\text{range}(\mathbf{p})_- \stackrel{\text{def}}{=} \underset{A \in \mathcal{D}}{\text{colim}} (\mathbf{p}_-^A).$$

15.2.2 Composition of Profunctors

Let \mathcal{C} , \mathcal{D} , and \mathcal{E} be categories and let $\mathbf{p}: \mathcal{C} \nrightarrow \mathcal{D}$ and $\mathbf{q}: \mathcal{D} \nrightarrow \mathcal{E}$ be profunctors.

Definition 15.2.2.1.1. The **composition of \mathbf{p} and \mathbf{q}** is the profunctor $\mathbf{q} \diamond \mathbf{p}: \mathcal{C} \nrightarrow \mathcal{E}$ defined by³

$$(\mathbf{q} \diamond \mathbf{p})_{-2}^{-1} \stackrel{\text{def}}{=} \int^{B \in \mathcal{D}} \mathbf{q}_B^{-1} \times \mathbf{p}_{-2}^B.$$

15.2.3 Representable Profunctors

Definition 15.2.3.1.1. The **representable profunctor associated to a functor** $F: \mathcal{C} \rightarrow \mathcal{D}$ is the profunctor $\widehat{F}^*: \mathcal{C} \nrightarrow \mathcal{D}$ defined as the adjunct of the composition

$$\mathcal{C} \xrightarrow{F} \mathcal{D} \xrightarrow{\mathbb{J}} \text{PSh}(\mathcal{D})$$

under the adjunction

$$\text{Fun}(\mathcal{D}^{\text{op}} \times \mathcal{C}, \text{Sets}) \cong \text{Fun}(\mathcal{C}, \text{PSh}(\mathcal{D}))$$

defined by

$$\begin{array}{ccc} \mathcal{D}^{\text{op}} & \xrightarrow{\mathbf{p}^\dagger} & \text{PSh}(\mathcal{D}) \\ \text{dom}(\mathbf{p}) \searrow & \downarrow \text{colim} & \\ & \text{Sets}, & \end{array} \quad \begin{array}{c} \text{dom}(\mathbf{p}) \stackrel{\text{def}}{=} \text{colim} \circ \mathbf{p}^\dagger, \\ \text{range}(\mathbf{p}) \stackrel{\text{def}}{=} \text{colim} \circ \mathbf{p}^\ddagger, \end{array} \quad \begin{array}{ccc} \mathcal{C} & \xrightarrow{\mathbf{p}^\ddagger} & \text{Fun}(\mathcal{C}, \text{Sets}) \\ \text{range}(\mathbf{p}) \searrow & \downarrow \text{colim} & \\ & \text{Sets}. & \end{array}$$

³Alternatively, we may define $\mathbf{q} \diamond \mathbf{p}$ (using the equivalent definition of Item 2 of Remark 15.1.1.1.2) by

$$\begin{array}{ccc} \mathcal{D} & \xrightarrow{\mathbf{p}^\dagger} & \text{PSh}(\mathcal{C}), \\ \downarrow \mathbb{J} & & \nearrow \text{Lan}_{\mathcal{E}}(\mathbf{p}^\dagger), \\ \mathcal{E} & \xrightarrow[\mathbf{q}^\dagger]{} & \text{PSh}(\mathcal{D}) \end{array}$$

of ?? of ??.⁴

Definition 15.2.3.1.2. A profunctor is **representable** if it is isomorphic to a representable profunctor.

Definition 15.2.3.1.3. The **corepresentable**⁵ **profunctor associated to a functor** $F: C \rightarrow \mathcal{D}$ is the profunctor $\widehat{F}_*: \mathcal{D} \nrightarrow C$ defined as the adjunct of the composition

$$C^{\text{op}} \xrightarrow{F^{\text{op}}} \mathcal{D}^{\text{op}} \xrightarrow{\text{?}} \text{CoPSh}(\mathcal{D})$$

under the adjunction

$$\text{Fun}(C^{\text{op}} \times \mathcal{D}, \text{Sets}) \cong \text{Fun}(C^{\text{op}}, \text{CoPSh}(\mathcal{D}))$$

of ?? of ??.⁶

Definition 15.2.3.1.4. A profunctor is **corepresentable** if it is isomorphic to a corepresentable profunctor.

15.2.4 Collages

Let C and \mathcal{D} be categories.

Definition 15.2.4.1.1. The **collage** of a profunctor $\mathbf{p}: C \nrightarrow \mathcal{D}$ is the category $\text{Coll}(\mathbf{p})$ ⁷

⁴That is, we have

$$\widehat{F}^* \stackrel{\text{def}}{=} \text{Hom}_{\mathcal{D}}(-_1, F_{-2}).$$

⁵Some authors call both \widehat{F}^* and \widehat{F}_* the **representable profunctors associated to F** .

⁶That is:

$$\widehat{F}_* \stackrel{\text{def}}{=} \text{Hom}_{\mathcal{D}}(F_{-1}, -_2).$$

⁷Further Notation: Also written $C \star^{\mathbf{p}} \mathcal{D}$, notably in [HigherToposTheory].

where⁸

- *Objects.* We have

$$\text{Obj}(\text{Coll}(\mathbf{p})) \stackrel{\text{def}}{=} \text{Obj}(C) \sqcup \text{Obj}(\mathcal{D});$$

- *Morphisms.* For each $A, B \in \text{Obj}(\text{Coll}(\mathbf{p}))$, we have

$$\text{Hom}_{\text{Coll}(\mathbf{p})}(A, B) \stackrel{\text{def}}{=} \begin{cases} \text{Hom}_C(A, B) & \text{if } A, B \in \text{Obj}(C), \\ \text{Hom}_{\mathcal{D}}(A, B) & \text{if } A, B \in \text{Obj}(\mathcal{D}), \\ \mathbf{p}(A, B) & \text{if } A \in \text{Obj}(C) \text{ and } B \in \text{Obj}(\mathcal{D}), \\ \emptyset & \text{if } A \in \text{Obj}(\mathcal{D}) \text{ and } B \in \text{Obj}(C); \end{cases}$$

- *Identities.* For each $A \in \text{Obj}(\text{Coll}(\mathbf{p}))$, the unit map

$$\mathbb{1}_A^{\text{Coll}(\mathbf{p})} : \text{pt} \rightarrow \text{Hom}_{\text{Coll}(\mathbf{p})}(A, A)$$

of $\text{Coll}(\mathbf{p})$ at A is defined by

$$\text{id}_A \stackrel{\text{def}}{=} \begin{cases} \text{id}_A^C & \text{if } A \in \text{Obj}(C), \\ \text{id}_A^{\mathcal{D}} & \text{if } A \in \text{Obj}(\mathcal{D}); \end{cases}$$

- *Composition.* For each $A, B, C \in \text{Obj}(\text{Coll}(\mathbf{p}))$, the composition map

$$\circ_{A, B, C}^{\text{Coll}(\mathbf{p})} : \text{Hom}_{\text{Coll}(\mathbf{p})}(B, C) \times \text{Hom}_{\text{Coll}(\mathbf{p})}(A, B) \rightarrow \text{Hom}_{\text{Coll}(\mathbf{p})}(A, C)$$

⁸We also have a functor $\phi : \text{Coll}(\mathbf{p}) \rightarrow \mathbb{1}$ where

- *Actions on Objects.* For each $A \in \text{Obj}(\text{Coll}(\mathbf{p}))$, we have

$$\phi_A \stackrel{\text{def}}{=} \begin{cases} [0] & \text{if } A \in \text{Obj}(C), \\ [1] & \text{if } A \in \text{Obj}(\mathcal{D}). \end{cases}$$

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

$$\phi_{A, B} : \text{Hom}_{\text{Coll}(\mathbf{p})}(A, B) \rightarrow \text{Hom}_{\text{Coll}(\mathbf{p})}(\phi_A, \phi_B)$$

of ϕ at (A, B) is given by

$$\phi_{A, B}(f) \stackrel{\text{def}}{=} \begin{cases} \text{id}_{[0]} & \text{if } A, B \in \text{Obj}(C), \\ \text{id}_{[1]} & \text{if } A, B \in \text{Obj}(\mathcal{D}), \\ [0] \rightarrow [1] & \text{if } A \in \text{Obj}(C) \text{ and } B \in \text{Obj}(\mathcal{D}). \end{cases}$$

If $A \in \text{Obj}(\mathcal{D})$ and $B \in \text{Obj}(C)$, we have $\phi_{A, B} \stackrel{\text{def}}{=} \text{id}_{\emptyset}$.

of $\text{Coll}(\mathbf{p})$ at (A, B, C) is defined by⁹

$$\circ_{A,B,C}^{\text{Coll}(\mathbf{p})} \stackrel{\text{def}}{=} \begin{cases} \circ_{A,B,C}^C & \text{if } A, B, C \in \text{Obj}(C), \\ \mathbf{p}_C^{A,B} & \text{if } A, B \in \text{Obj}(C) \text{ and } C \in \text{Obj}(\mathcal{D}), \\ \iota & \text{if } A, C \in \text{Obj}(C) \text{ and } B \in \text{Obj}(\mathcal{D}), \\ \iota & \text{if } B, C \in \text{Obj}(C) \text{ and } A \in \text{Obj}(\mathcal{D}), \\ \mathbf{p}_{B,C}^A & \text{if } A \in \text{Obj}(C) \text{ and } B, C \in \text{Obj}(\mathcal{D}), \\ \iota & \text{if } B \in \text{Obj}(C) \text{ and } A, C \in \text{Obj}(\mathcal{D}), \\ \iota & \text{if } C \in \text{Obj}(C) \text{ and } A, B \in \text{Obj}(\mathcal{D}), \\ \circ_{A,B,C}^{\mathcal{D}} & \text{if } A, B, C \in \text{Obj}(\mathcal{D}). \end{cases}$$

Example 15.2.4.1.2. If \mathbf{p} is the constant functor $\Delta_{\text{pt}}: \mathcal{D}^{\text{op}} \times \mathcal{C} \rightarrow \text{Sets}$ with value pt , then $\text{Coll}(\mathbf{p})$ is the join $\mathcal{C} \star \mathcal{D}$ of \mathcal{C} and \mathcal{D} of ?? .

Proposition 15.2.4.1.3. Let $\mathbf{p}: \mathcal{C} \dashv \mathcal{D}$ be a profunctor.

1. *Functoriality.* The assignment $\mathbf{p} \mapsto \text{Coll}(\mathbf{p})$ defines a functor¹⁰

$$\text{Coll}_{\mathcal{C}, \mathcal{D}}: \text{Prof}(\mathcal{C}, \mathcal{D}) \rightarrow \text{Cats}_{/\mathbb{K}}(\mathcal{C}, \mathcal{D}),$$

where

⁹Here the maps $\mathbf{p}_C^{A,B}$ and $\mathbf{p}_{B,C}^A$ are the maps

$$\begin{aligned} \mathbf{p}_C^{A,B}: \mathbf{p}_C^B \times \text{Hom}_{\mathcal{C}}(A, B) &\rightarrow \mathbf{p}_C^A, \\ \mathbf{p}_{B,C}^A: \text{Hom}_{\mathcal{D}}(B, C) \times \mathbf{p}_B^A &\rightarrow \mathbf{p}_C^A \end{aligned}$$

coming from the profunctor structure of \mathbf{p} and the ι 's are inclusions of the empty set into the appropriate Hom sets.

¹⁰Here $\text{Cats}_{/\mathbb{K}}(\mathcal{C}, \mathcal{D})$ is the category defined as the pullback

$$\text{Cats}_{/\mathbb{K}}(\mathcal{C}, \mathcal{D}) \stackrel{\text{def}}{=} \text{pt} \underset{[\mathcal{C}], \text{Cats}, \text{fib}_0}{\times} \text{Cats}_{/\mathbb{K}} \underset{\text{fib}_1, \text{Cats}, [\mathcal{D}]}{\times} \text{pt},$$

as in the diagram

$$\begin{array}{ccccc} & & \text{Cats}_{/\mathbb{K}}(\mathcal{C}, \mathcal{D}) & & \\ & \swarrow & & \searrow & \\ \text{Cats}_{/\mathbb{K}} \times \text{pt} & & & & \text{pt} \times \text{Cats}_{/\mathbb{K}} \\ \downarrow & & & & \downarrow \\ \text{pt} & & \text{Cats}_{/\mathbb{K}} & & \text{pt} \\ \downarrow & \swarrow & \searrow & \swarrow & \searrow \\ [C] & & \text{Cats} & & [\mathcal{D}] \\ \downarrow & \text{fib}_{[0]} & \downarrow & \text{fib}_{[1]} & \downarrow \\ & & \text{Cats} & & \end{array}$$

- *Action on Objects.* For each $\mathbf{p} \in \text{Obj}(\text{Prof}(C, \mathcal{D}))$, we have

$$[\text{Coll}](\mathbf{p}) \stackrel{\text{def}}{=} \text{Coll}(\mathbf{p});$$

- *Action on Morphisms.* For each $\mathbf{p}, \mathbf{q} \in \text{Obj}(\text{Prof}(C, \mathcal{D}))$, the action on Hom-sets

$$\text{Coll}_{\mathbf{p}, \mathbf{q}} : \text{Nat}(\mathbf{p}, \mathbf{q}) \rightarrow \text{Fun}_{/\mathbb{K}}(\text{Coll}(\mathbf{p}), \text{Coll}(\mathbf{q}))$$

of Coll at (\mathbf{p}, \mathbf{q}) is the function sending a natural transformation $\alpha : \mathbf{p} \Rightarrow \mathbf{q}$ to the functor

$$\text{Coll}(\alpha) : \text{Coll}(\mathbf{p}) \rightarrow \text{Coll}(\mathbf{q})$$

over \mathbb{K} where

- *Action on Objects.* For each $X \in \text{Obj}(\text{Coll}(\mathbf{p}))$, we have

$$[\text{Coll}(\alpha)](X) \stackrel{\text{def}}{=} X;$$

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

$$\text{Coll}(\alpha)_{X, Y} : \text{Hom}_{\text{Coll}(\mathbf{p})}(X, Y) \rightarrow \underbrace{\text{Hom}_{\text{Coll}(\mathbf{q})}([\text{Coll}(\alpha)](X), [\text{Coll}(\alpha)](Y))}_{\stackrel{\text{def}}{=} \text{Hom}_{\text{Coll}(\mathbf{q})}(X, Y)}$$

of $\text{Coll}(\alpha)$ at (X, Y) is defined as follows:

- * If $X, Y \in \text{Obj}(C)$ or $X, Y \in \text{Obj}(\mathcal{D})$, then we have

$$\text{Coll}(\alpha)_{X, Y}(f) \stackrel{\text{def}}{=} f$$

for each $f \in \text{Hom}_{\text{Coll}(\mathbf{p})}(X, Y)$.

- * If $X \in \text{Obj}(C)$ and $Y \in \text{Obj}(\mathcal{D})$, then

$$\text{Coll}(\alpha)_{X, Y} : \underbrace{\text{Hom}_{\text{Coll}(\mathbf{p})}(X, Y)}_{\stackrel{\text{def}}{=} \mathbf{p}_Y^X} \rightarrow \underbrace{\text{Hom}_{\text{Coll}(\mathbf{q})}(X, Y)}_{\stackrel{\text{def}}{=} \mathbf{q}_Y^X}$$

is defined by

$$\text{Coll}(\alpha)_{X, Y}(f) \stackrel{\text{def}}{=} \alpha_Y^X;$$

- * If $Y \in \text{Obj}(C)$ and $X \in \text{Obj}(\mathcal{D})$, then we have

$$\text{Coll}(\alpha)_{X, Y}(f) \stackrel{\text{def}}{=} \text{id}_\emptyset.$$

2. *Collages as Lax Colimits.* We have an isomorphism of categories

$$\text{Coll}(\mathbf{p}) \cong \text{colim}^{\text{lax}}(\mathbf{p}),$$

functorial in \mathbf{p} , where the above lax colimit is taken in the bicategory Prof .

3. *Profunctors vs.Collages.* We have an equivalence of categories

$$(Coll \dashv \Gamma): \text{Prof}(C, \mathcal{D}) \begin{array}{c} \xrightarrow{\text{Coll}} \\ \perp_{\text{eq}} \\ \xleftarrow{\Gamma} \end{array} \text{Cats}_{/\mathbb{K}},$$

where $\Gamma: \text{Cats}_{/\mathbb{K}} \rightarrow \text{Prof}(C, \mathcal{D})$ is the functor sending a functor $\mathcal{E} \rightarrow \mathbb{K}$ to the profunctor

$$\Gamma(\mathbf{p}): C \nrightarrow \mathcal{D}$$

given on objects by

$$\Gamma(\mathbf{p})_B^A \stackrel{\text{def}}{=} \text{Hom}_{\mathcal{E}}(A, B)$$

for each $A, B \in \text{Obj}(\mathcal{E})$.

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

[Item 2](#), *Collages as Lax Colimits*: See [[collages-as-lax-colimits](#)].

[Item 3](#), *Profunctors vs.Collages*: See [[joyal:distributors-and-barrels](#)]. □

15.3 Categories of Profunctors

15.3.1 The Bicategory of Profunctors

Definition 15.3.1.1. The **bicategory of profunctors** is the bicategory Prof where¹¹

1. *Objects.* The objects of Prof are categories;
2. *1-Morphisms.* The 1-morphisms of Prof are profunctors;
3. *2-Morphisms.* The 2-morphisms of Prof are natural transformations between profunctors;
4. *Identities.* For each $C \in \text{Obj}(\text{Prof})$, we have

$$\text{id}_C^{\text{Prof}} \stackrel{\text{def}}{=} \text{Hom}_C(-, -);$$

5. *Composition.* For each $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Prof})$, the composition bifunctor

$$\diamond: \text{Prof}(\mathcal{D}, \mathcal{E}) \times \text{Prof}(C, \mathcal{D}) \rightarrow \text{Prof}(C, \mathcal{E})$$

is defined on objects by sending profunctors $\mathbf{p}: C \nrightarrow \mathcal{D}$ and $\mathbf{q}: \mathcal{D} \nrightarrow \mathcal{E}$ to the profunctor $\mathbf{q} \diamond \mathbf{p}$ of [Definition 15.2.2.1.1](#).

Proof. See [Definition 15.3.1.1](#). □

¹¹The bicategory Prof admits a nice strictification to a 2-category: it is biequivalent to the sub-bicategory

15.3.2 Properties of Prof

Proposition 15.3.2.1.1. Let C and \mathcal{D} be categories.

1. *Self-Duality.* The bicategory Prof is self-dual: we have a biequivalence of bicategories

$$(-)^{\text{op}} : \text{Prof} \xrightarrow{\cong} \text{Prof}^{\text{op}}$$

where

- *Action on Objects.* The functor $(-)^{\text{op}}$ sends categories to their opposites;
- *Action on 1-Morphisms.* The functor $(-)^{\text{op}}$ sends profunctors to itself under the identification

$$\begin{aligned} \text{Prof}(C, \mathcal{D}) &\stackrel{\text{def}}{=} \text{Fun}(\mathcal{D}^{\text{op}} \times C, \text{Sets}), \\ &\cong \text{Fun}(C \times \mathcal{D}^{\text{op}}, \text{Sets}), \\ &\stackrel{\text{def}}{=} \text{Prof}(\mathcal{D}^{\text{op}}, C^{\text{op}}); \end{aligned}$$

- *Action on 2-Morphisms.* The functor $(-)^{\text{op}}$ sends natural transformations between profunctors to themselves.

2. *Relation to Cats.* The co/representable profunctor constructions of Definitions 15.2.3.1.1 and 15.2.3.1.3 define embeddings of bicategories

$$\begin{aligned} \text{Cats}^{\text{op}} &\hookrightarrow \text{Prof}, \\ \text{Cats}^{\text{co}} &\hookrightarrow \text{Prof}. \end{aligned}$$

3. *Equivalences in Prof and Cauchy Completions.* Every category is equivalent to its Cauchy completion in Prof.

4. *Equivalences in Prof.* The following conditions are equivalent:

- (a) The categories C and \mathcal{D} are equivalent in Prof.
- (b) The categories $\text{PSh}(C)$ and $\text{PSh}(\mathcal{D})$ are equivalent in Cats_2 .
- (c) The Cauchy completions of C and \mathcal{D} are equivalent in Cats_2 .

5. *Adjunctions in Prof.* Let C and \mathcal{D} be categories. The following data are equivalent:

- (a) An adjunction in Prof from C to \mathcal{D} .
- (b) A functor from C to the Cauchy completion $\overline{\mathcal{D}}$ of \mathcal{D} .
- (c) A **semifunctor** from C to \mathcal{D} .

of Cats spanned by the presheaf categories, cocontinuous functors between them, and natural transformation between these.

6. *As a Kleisli Bicategory.* We have a biequivalence of bicategories

$$\text{Prof} \cong \text{FreePsAlg}_{\text{PSh}},$$

where PSh is the presheaf category relative pseudomonad of [relative-pseudomonads-kleisli-bicategories-and-substitution-monoidal-structures]

7. *Closedness.* The bicategory Prof is a closed bicategory, where given a profunctor $\mathbf{p}: \mathcal{C} \nrightarrow \mathcal{D}$ and a category \mathcal{X} :

- *Right Kan Extensions.* The right adjoint

$$\text{Ran}_{\mathbf{p}}: \text{Rel}(\mathcal{C}, \mathcal{X}) \rightarrow \text{Rel}(\mathcal{D}, \mathcal{X})$$

to the precomposition functor $\mathbf{p}^*: \text{Rel}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Rel}(\mathcal{C}, \mathcal{X})$ is given by

$$\text{Ran}_{\mathbf{p}}(\mathbf{q}) \stackrel{\text{def}}{=} \int_{A \in \mathcal{C}} \text{Sets}\left(\mathbf{p}_A^{-2}, \mathbf{q}_A^{-1}\right)$$

for each $\mathbf{q} \in \text{Rel}(\mathcal{C}, \mathcal{X})$.

- *Right Kan Lifts.* The right adjoint to the postcomposition functor

$$\text{Rift}_{\mathbf{p}}: \text{Rel}(\mathcal{X}, \mathcal{D}) \rightarrow \text{Rel}(\mathcal{X}, \mathcal{C})$$

to the postcomposition functor $\mathbf{p}_*: \text{Rel}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Rel}(\mathcal{X}, \mathcal{D})$ is given by

$$\text{Rift}_{\mathbf{p}}(\mathbf{q}) \stackrel{\text{def}}{=} \int_{B \in \mathcal{D}} \text{Sets}\left(\mathbf{p}_{-1}^B, \mathbf{q}_{-2}^B\right)$$

for each $\mathbf{q} \in \text{Rel}(\mathcal{X}, \mathcal{D})$.

8. *Un/Straightening for Profunctors: Two-Sided Discrete Fibrations.* We have an equivalence of categories

$$\text{Prof}(\mathcal{C}, \mathcal{D}) \cong \text{DFib}(\mathcal{C}, \mathcal{D}).$$

Proof. Item 1, Self-Duality: See [loregian2020coend].

Item 2, Relation to Cats: See [loregian2020coend].

Item 3, Equivalences in Prof and Cauchy Completions: See [borceux-2].

Item 4, Equivalences in Prof: See [borceux-2].

Item 5, Adjunctions in Prof: Omitted.

Item 6, As a Kleisli Bicategory: See [relative-pseudomonads-kleisli-bicategories-and-substitution-monoidal-structures]

Item 7, Closedness: Omitted.

Item 8, Un/Straightening for Profunctors: Two-Sided Discrete Fibrations: See [riehl:two-sided-discrete-fibrations]

□

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Chapter 16

Cartesian Closed Categories

Create tags (see [MSE 350788] for some of these):

1. define bicategory $\text{Adj}(C)$
2. <https://www.google.com/search?q=category+of+categories+is+not+locally+cartesian+closed>
3. <https://math.stackexchange.com/questions/2864916/are-there-important-locally-cartesian-closed-categories-that-actually-are-not-ca>
4. Cats is not locally Cartesian closed: f^* does have a left adjoint (the proof for fibred sets seems to apply for any category with pullbacks), but does not have a right adjoint, as proved in example 1.7 of https://sinhp.github.io/files/CT/notes_on_lcccs.pdf
5. internal **Hom** in categories of co/Cartesian fibrations
6. <https://mathoverflow.net/questions/460146/universal-property-of-isbell-duality>
7. <http://www.tac.mta.ca/tac/volumes/36/12/36-12abs.html>
8. Cartesian closed categories and locally Cartesian closed categories
 - (a) <https://ncatlab.org/nlab/show/locally+cartesian+closed+functor>
 - (b) <https://ncatlab.org/nlab/show/cartesian+closed+functor>
 - (c) <https://ncatlab.org/nlab/show/locally+cartesian+closed+category>
 - (d) <https://ncatlab.org/nlab/show/Frobenius+reciprocity>
9. <https://math.stackexchange.com/questions/3657046/the-inverse-of-the-functor-from-locally-cartesian-closed-categories-to>

se-of-a-natural-isomorphism-is-a-natural-isomorphism to justify adjunctions via homs

10. <https://ncatlab.org/nlab/show/enrichment+versus+internalisation>
11. <https://mathoverflow.net/questions/382239/proof-that-a-cartesian-category-is-monoidal>
12. <https://arxiv.org/pdf/2004.08964.pdf>

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 - (c) <https://ncatlab.org/nlab/show/locally+cartesian+closed+category>
 - (d) <https://ncatlab.org/nlab/show/Frobenius+reciprocity>
5. <https://mathoverflow.net/questions/382239/proof-that-a-cartesian-category-is-monoidal>

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Part IV

Bicategories

Chapter 18

Bicategories

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Create tags and TODO:

1. spans in bicategories: add Proposition 7 here: <https://arxiv.org/abs/1903.03890>
2. add fact: internal adjunctions in $\text{PseudoFun}(\mathcal{C}, \mathcal{D})$ are precisely the invertible strong transformations as in [JY21, Example 6.2.7]. What are the internal adjunctions?

18.1 Monomorphisms in Bicategories

18.1.1 Faithful Monomorphisms

Let \mathcal{C} be a bicategory.

Definition 18.1.1.1. A 1-morphism $f: A \rightarrow B$ is a **faithful monomorphism in C** if the following equivalent conditions are satisfied:

1. 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.

2. Given a diagram in C of the form

$$\begin{array}{ccc} X & \xrightarrow{\alpha \parallel \beta} & A \xrightarrow{f} B, \\ & \psi \downarrow & \end{array}$$

if we have $\text{id}_f \star \alpha = \text{id}_f \star \beta$, then $\alpha = \beta$.

Example 18.1.1.2. Here are some examples of faithful monomorphisms.

1. Full Monomorphisms in Cats_2 .
2. Full Monomorphisms in Rel .
3. Full Monomorphisms in Span .

18.1.2 Full Monomorphisms

Let C be a bicategory.

Definition 18.1.2.1.1. A 1-morphism $f: A \rightarrow B$ is a **full monomorphism in C** if the following equivalent conditions are satisfied:

1. For each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is full.

2. For each $X \in \text{Obj}(C)$ and each 2-morphism

$$\gamma: f \circ \phi \Rightarrow f \circ \psi, \quad X \xrightarrow[\psi]{\gamma \Downarrow} B$$

of C , there exists a 2-morphism $\alpha: \phi \Rightarrow \psi$ of C such that we have an equality

$$X \xrightarrow[\psi]{\alpha \Downarrow} A \xrightarrow{f} B = X \xrightarrow[\psi]{\gamma \Downarrow} B$$

of pasting diagrams in C , i.e. such that we have

$$\gamma = \text{id}_f \star \alpha.$$

Example 18.1.2.1.2. Here are some examples of full monomorphisms.

1. *Full Monomorphisms in Cats_2 .*
2. *Full Monomorphisms in Rel .*
3. *Full Monomorphisms in Span .*

18.1.3 Fully Faithful Monomorphisms

Let C be a bicategory.

Definition 18.1.3.1.1. A 1-morphism $f: A \rightarrow B$ is a **fully faithful monomorphism in C** if the following equivalent conditions are satisfied:

1. The 1-morphism f is fully and faithful.
2. For each $X \in \text{Obj}(C)$, the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is fully faithful.

3. The conditions in Item 1 of Definition 18.1.1.1 and Item 1 of Definition 18.1.2.1.1 hold.

Example 18.1.3.1.2. Here are some examples of fully faithful monomorphisms.

1. *Fully Faithful Monomorphisms in Cats_2 .*
2. *Fully Faithful Monomorphisms in Rel .*
3. *Fully Faithful Monomorphisms in Span .*

18.1.4 Strict Monomorphisms

Let C be a bicategory.

Definition 18.1.4.1.1. A 1-morphism $f: A \rightarrow B$ is a **strict monomorphism in C** if the following equivalent conditions are satisfied:

1. For each $X \in \text{Obj}(C)$, the action on objects

$$f_*: \text{Obj}(\text{Hom}_C(X, A)) \rightarrow \text{Obj}(\text{Hom}_C(X, B))$$

of the functor

$$f_*: \text{Hom}_C(X, A) \rightarrow \text{Hom}_C(X, B)$$

given by postcomposition by f is injective.

2. For each diagram in C of the form

$$X \xrightarrow[\psi]{\phi} A \xrightarrow{f} B,$$

if $f \circ \phi = f \circ \psi$, then $\phi = \psi$.

Example 18.1.4.1.2. Here are some examples of strict monomorphisms.

1. Strict Monomorphisms in Cats_2 .
2. Strict Monomorphisms in Rel .
3. Strict Monomorphisms in Span .

18.2 Epimorphisms in Bicategories

18.2.1 Faithful Epimorphisms

Let C be a bicategory.

Definition 18.2.1.1.1. A 1-morphism $f: A \rightarrow B$ is a **faithful epimorphism in C** if the following equivalent conditions are satisfied:

1. 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.

2. Given a diagram in C of the form

$$A \xrightarrow{f} B \xrightarrow[\psi]{\alpha \parallel \beta} X,$$

if we have $\alpha \star \text{id}_f = \beta \star \text{id}_f$, then $\alpha = \beta$.

Example 18.2.1.1.2. Here are some examples of faithful epimorphisms.

1. Full Epimorphisms in Cats_2 .
2. Full Epimorphisms in Rel .
3. Full Epimorphisms in Span .

18.2.2 Full Epimorphisms

Let C be a bicategory.

Definition 18.2.2.1.1. A 1-morphism $f: A \rightarrow B$ is a **full epimorphism in C** if the following equivalent conditions are satisfied:

1. 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.

2. For each $X \in \text{Obj}(C)$ and each 2-morphism

$$\gamma: \phi \circ f \Rightarrow \psi \circ f, \quad X \xrightarrow[\psi \circ f]{\gamma \Downarrow} B$$

of C , there exists a 2-morphism $\alpha: \phi \Rightarrow \psi$ of C such that we have an equality

$$A \xrightarrow{f} B \xrightarrow[\psi]{\alpha \Downarrow} X = A \xrightarrow[\psi \circ f]{\phi \Downarrow} X$$

of pasting diagrams in C , i.e. such that we have

$$\gamma = \alpha \star \text{id}_f.$$

Example 18.2.2.1.2. Here are some examples of full epimorphisms.

1. Full Epimorphisms in Cats_2 .
2. Full Epimorphisms in Rel .
3. Full Epimorphisms in Span .

18.2.3 Fully Faithful Epimorphisms

Let C be a bicategory.

Definition 18.2.3.1.1. A 1-morphism $f: A \rightarrow B$ is a **fully faithful epimorphism in C** if the following equivalent conditions are satisfied:

1. The 1-morphism f is fully and faithful.
2. For each $X \in \text{Obj}(C)$, the functor

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

given by precomposition by f is fully faithful.

3. The conditions in [Item 1](#) of [Definition 18.2.1.1.1](#) and [Item 1](#) of [Definition 18.2.2.1.1](#) hold.

Example 18.2.3.1.2. Here are some examples of fully faithful epimorphisms.

1. *Fully Faithful Epimorphisms in Cats₂.*
2. *Fully Faithful Epimorphisms in Rel.*
3. *Fully Faithful Epimorphisms in Span.*

18.2.4 Strict Epimorphisms

Let \mathcal{C} be a bicategory.

Definition 18.2.4.1.1. A 1-morphism $f: A \rightarrow B$ is a **strict epimorphism in \mathcal{C}** if the following equivalent conditions are satisfied:

1. For each $X \in \text{Obj}(\mathcal{C})$, the action on objects

$$f^*: \text{Obj}(\text{Hom}_{\mathcal{C}}(B, X)) \rightarrow \text{Obj}(\text{Hom}_{\mathcal{C}}(A, X))$$

of the functor

$$f^*: \text{Hom}_{\mathcal{C}}(B, X) \rightarrow \text{Hom}_{\mathcal{C}}(A, X)$$

given by precomposition by f is injective.

2. For each diagram in \mathcal{C} of the form

$$A \xrightarrow{f} B \rightrightarrows X,$$

if $\phi \circ f = \psi \circ f$, then $\phi = \psi$.

Example 18.2.4.1.2. Here are some examples of strict epimorphisms.

1. *Strict Epimorphisms in Cats₂.*
2. *Strict Epimorphisms in Rel.*
3. *Strict Epimorphisms in Span.*

18.3 bicategories of spans

Proposition 18.3.0.1.1. Let A and B be objects of \mathcal{C} .

1. As a Pullback. We have an isomorphism of categories

$$\begin{array}{ccc} \text{Span}(A, B) & \rightarrow & C_{/B} \\ \downarrow & \lrcorner & \downarrow \text{忘} \\ \text{Span}_C(A, B) \cong C_{/A} \times_C C_{/B}, & & \\ \downarrow & & \downarrow \\ C_{/A} & \xrightarrow{\text{忘}} & C. \end{array}$$

Proof. Item 1, As a Pullback: In detail, the pullback $C_{/A} \times_C C_{/B}$ is the category where

- *Objects.* The objects of $C_{/A} \times_C C_{/B}$ consist of pairs $((S, f), (S', g))$ of objects of C consisting of
 - A pair (S, f) in $\text{Obj}(C_{/A})$ consisting of an object S of C and a morphism $f: S \rightarrow A$ of C ;
 - A pair (S', g) in $\text{Obj}(C_{/B})$ consisting of an object S' of C and a morphism $g: S' \rightarrow B$ of C ;

such that

$$\overbrace{(S, f)}^{\text{def } S} = \overbrace{(S', g)}^{\text{def } S'}.$$

Thus the objects of $C_{/A} \times_C C_{/B}$ are the same as spans in C from A to B .

- *Morphisms.* A morphism of $C_{/A} \times_C C_{/B}$ from $((S, f), (S', g))$ to $((S'', f''), (S''', g''))$ consists of a pair of morphisms

$$\begin{aligned} \phi: S &\rightarrow S' \\ \psi: S &\rightarrow S' \end{aligned}$$

such that the diagrams

$$\begin{array}{ccc} S & \xrightarrow{\phi} & S' \\ f \searrow & & \swarrow f' \\ A & & \end{array} \quad \begin{array}{ccc} S & \xrightarrow{\psi} & S' \\ g \searrow & & \swarrow g' \\ B & & \end{array}$$

such that

$$\overbrace{\phi}^{\text{def } \phi} = \overbrace{\psi}^{\text{def } \psi}.$$

Thus the morphisms of $C_{/A} \times_C C_{/B}$ are also the same as morphisms of spans in C from (S, f, g) to (S'', f'', g'') .

- *Identities and Composition.* The identities and composition of $C_{/A} \times_C C_{/B}$ are also the same as those in $\text{Span}_C(A, B)$.

This finishes the proof. □

Appendices

18.A Other Chapters

Sets	Internal Category Theory
1. Sets	20. Internal Categories
2. Constructions With Sets	Cyclic Stuff
3. Pointed Sets	21. The Cycle Category
4. Tensor Products of Pointed Sets	Cubical Stuff
5. Relations	22. The Cube Category
6. Spans	Globular Stuff
7. Posets	23. The Globe Category
Indexed and Fibred Sets	Cellular Stuff
7. Indexed Sets	24. The Cell Category
8. Fibred Sets	Monoids
9. Un/Straightening for Indexed and Fibred Sets	25. Monoids
Category Theory	26. Constructions With Monoids
11. Categories	Monoids With Zero
12. Types of Morphisms in Categories	27. Monoids With Zero
13. Adjunctions and the Yoneda Lemma	28. Constructions With Monoids With Zero
14. Constructions With Categories	Groups
15. Profunctors	29. Groups
16. Cartesian Closed Categories	30. Constructions With Groups
17. Kan Extensions	Hyper Algebra
Bicategories	31. Hypermonoids
18. Bicategories	32. Hypergroups
19. Internal Adjunctions	33. Hypersemirings and Hyperrings
	34. Quantales
	Near-Rings

35. Near-Semirings

36. Near-Rings

Real Analysis

37. Real Analysis in One Variable

38. Real Analysis in Several Variables

Measure Theory

39. Measurable Spaces

40. Measures and Integration

Probability Theory

40. Probability Theory

Stochastic Analysis

41. Stochastic Processes, Martingales, and Brownian Motion

42. Itô Calculus

43. Stochastic Differential Equations

Differential Geometry

44. Topological and Smooth Manifolds

Schemes

45. Schemes

18.2 Other Chapters

Sets

1. Sets

2. Constructions With Sets

3. Pointed Sets

4. Tensor Products of Pointed Sets

5. Relations

6. Spans

7. Posets

Indexed and Fibred Sets

7. Indexed Sets

8. Fibred Sets

9. Un/Straightening for Indexed and Fibred Sets

Category Theory

11. Categories

12. Types of Morphisms in Categories

13. Adjunctions and the Yoneda Lemma

14. Constructions With Categories

15. Profunctors

16. Cartesian Closed Categories

17. Kan Extensions

Bicategories

18. Bicategories

19. Internal Adjunctions

Internal Category Theory

20. Internal Categories

Cyclic Stuff

21. The Cycle Category

Cubical Stuff

22. The Cube Category

Globular Stuff

23. The Globe Category

Cellular Stuff

24. The Cell Category	36. Near-Rings
Monoids	Real Analysis
25. Monoids	37. Real Analysis in One Variable
26. Constructions With Monoids	38. Real Analysis in Several Variables
Monoids With Zero	Measure Theory
27. Monoids With Zero	39. Measurable Spaces
28. Constructions With Monoids With Zero	40. Measures and Integration
Groups	Probability Theory
29. Groups	40. Probability Theory
30. Constructions With Groups	Stochastic Analysis
Hyper Algebra	41. Stochastic Processes, Martingales, and Brownian Motion
31. Hypermonoids	42. Itô Calculus
32. Hypergroups	43. Stochastic Differential Equations
33. Hypersemirings and Hyperrings	Differential Geometry
34. Quantales	44. Topological and Smooth Manifolds
Near-Rings	Schemes
35. Near-Semirings	45. Schemes

Chapter 19

Internal Adjunctions

Create tags:

1. <https://www.google.com/search?q=mate+of+an+adjunction>
2. Moreover, by uniqueness of adjoints ([Item 2 of Proposition 19.1.2.1.4](#)), this implies also that $S = f^{-1}$.
3. define bicategory $\text{Adj}(C)$
4. walking monad
5. proposition: 2-functors preserve unitors and associators
6. <https://ncatlab.org/nlab/show/2-category+of+adjunctions. Is there a 3-category too?>
7. <https://ncatlab.org/nlab/show/free+monad>
8. <https://ncatlab.org/nlab/show/CatAdj>
9. <https://ncatlab.org/nlab/show/Adj>
10. $\text{Adj}(\text{Adj}(C))$

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19.1 Internal Adjunctions

19.1.1 The Walking Adjunction

Definition 19.1.1.1. The **walking adjunction** is the bicategory Adj freely generated by¹

- *Objects.* A pair of objects A and B ;
- *Morphisms.* A pair of morphisms

$$L: A \rightarrow B,$$

$$R: B \rightarrow A;$$

- *2-Morphisms.* A pair of 2-morphisms

$$\eta: \text{id}_A \rightarrow R \circ L,$$

$$\epsilon: L \circ R \rightarrow \text{id}_B;$$

¹See [SS86] for an explicit description of the 2-category (as opposed to a bicategory) version of Adj in terms of finite ordinals, similar to the description of the 2-category version of the walking monad (??) as a subcategory of Δ .

subject to the equalities

$$\begin{array}{ccc}
 \begin{array}{c} B \\ \swarrow L \quad \uparrow \eta \quad \searrow R \\ A \xrightarrow{\text{id}_A} A \end{array} & = & \begin{array}{c} B \\ \swarrow L \quad \uparrow \text{id}_B \quad \searrow R \\ A \xrightarrow{\text{id}_A} A \end{array} \\
 \begin{array}{c} A \\ \swarrow R \quad \uparrow \epsilon \quad \searrow L \\ B \xrightarrow{\text{id}_B} B \end{array} & = & \begin{array}{c} A \\ \swarrow R \quad \uparrow \text{id}_A \quad \searrow L \\ B \xrightarrow{\text{id}_B} B \end{array}
 \end{array}$$

of pasting diagrams, which are equivalent to the following conditions:

1. *The Left Triangle Identity.* The diagram

$$\begin{array}{ccccc}
 L \circ \text{id}_A & \xrightarrow{\text{id}_L \star \eta} & L \circ (R \circ L) & \xrightarrow{(\alpha_{L,R,L}^{\text{Adj}})^{-1}} & (L \circ R) \circ L \\
 & \searrow & & \downarrow \rho_L^{\text{Adj}} & \downarrow \epsilon \star \text{id}_L \\
 & & & & \text{id}_B \circ L \\
 & & & \searrow & \downarrow \lambda_L^{\text{Adj}} \\
 & & & & L
 \end{array}$$

commutes.

2. *The Right Triangle Identity.* The diagram

$$\begin{array}{ccccc}
 \text{id}_A \circ R & \xrightarrow{\eta \star \text{id}_R} & (R \circ L) \circ R & \xrightarrow{\alpha_{R,L,R}^{\text{Adj}}} & R \circ (L \circ R) \\
 & \searrow & & \downarrow \lambda_R^{\text{Adj}} & \downarrow \text{id}_R \star \epsilon \\
 & & & & R \circ \text{id}_B \\
 & & & \searrow & \downarrow \rho_R^{\text{Adj}} \\
 & & & & R
 \end{array}$$

19.1.2 Internal Adjunctions

Let C be a bicategory.

Definition 19.1.2.1.1. An **internal adjunction** in $C^{2,3}$ is a 2-functor $\text{Adj} \rightarrow C$.

Remark 19.1.2.1.2. In detail, an **internal adjunction** in C consists of

- *Objects.* A pair of objects A and B of C ;
- *Morphisms.* A pair of morphisms

$$L: A \rightarrow B,$$

$$R: B \rightarrow A$$

of C ;

- *2-Morphisms.* A pair of 2-morphisms

$$\eta: \text{id}_A \rightarrow R \circ L,$$

$$\epsilon: L \circ R \rightarrow \text{id}_B$$

of C ;

subject to the equalities

$$\begin{array}{ccc}
 \begin{array}{c}
 \begin{array}{ccccc}
 & B & \xrightarrow{\quad \text{id}_B \quad} & B & \\
 & \swarrow L & \uparrow \eta & \searrow R & \\
 A & \xrightarrow{\quad \text{id}_A \quad} & A & &
 \end{array} \\
 = \\
 \begin{array}{ccccc}
 & B & \xrightarrow{\quad \text{id}_B \quad} & B & \\
 & \swarrow L & \Downarrow \text{id}_L & \searrow R & \\
 A & \xrightarrow{\quad \text{id}_A \quad} & A & &
 \end{array}
 \end{array}
 & = &
 \begin{array}{ccc}
 \begin{array}{c}
 \begin{array}{ccccc}
 & A & \xrightarrow{\quad \text{id}_A \quad} & A & \\
 & \swarrow R & \uparrow \eta & \searrow L & \\
 B & \xrightarrow{\quad \text{id}_B \quad} & B & &
 \end{array} \\
 = \\
 \begin{array}{ccccc}
 & A & \xrightarrow{\quad \text{id}_A \quad} & A & \\
 & \swarrow R & \Downarrow \text{id}_R & \searrow L & \\
 B & \xrightarrow{\quad \text{id}_B \quad} & B & &
 \end{array}
 \end{array}
 \end{array}$$

of pasting diagrams in C , which are equivalent to the following conditions:⁴

²Further Terminology: Also called an **adjunction internal to C** .

³Further Terminology: In this situation, we also call (g, f) an **adjoint pair**, f the **left adjoint** of the pair, g the **right adjoint** of the pair, η the **unit** of the adjunction, and ϵ the **counit** of the adjunction.

⁴When C is a 2-category, these diagrams take the following form:

$$\begin{array}{ccc}
 \begin{array}{c}
 \begin{array}{ccc}
 L & \xrightarrow{\quad \text{id}_L \star \eta \quad} & L \circ R \circ L \\
 \Downarrow \text{id}_L & & \Downarrow \epsilon \star \text{id}_L \\
 & & L
 \end{array} \\
 = \\
 \begin{array}{ccc}
 R & \xrightarrow{\quad \text{id}_R \star \eta \quad} & R \circ L \circ R \\
 \Downarrow \text{id}_R & & \Downarrow \epsilon \star \text{id}_R \\
 & & R
 \end{array}
 \end{array}
 \end{array}$$

1. *The Left Triangle Identity.* The diagram

$$\begin{array}{ccccc}
 L \circ \text{id}_A & \xrightarrow{\text{id}_L \star \eta} & L \circ (R \circ L) & \xrightarrow{(\alpha_{L,R,L}^C)^{-1}} & (L \circ R) \circ L \\
 & \searrow \rho_L^C & & & \downarrow \epsilon \star \text{id}_L \\
 & & & & \text{id}_B \circ L \\
 & & & & \downarrow \lambda_L^C \\
 & & & & L
 \end{array}$$

commutes.

2. *The Right Triangle Identity.* The diagram

$$\begin{array}{ccccc}
 \text{id}_A \circ R & \xrightarrow{\eta \star \text{id}_R} & (R \circ L) \circ R & \xrightarrow{\alpha_{R,L,R}^C} & R \circ (L \circ R) \\
 & \searrow \lambda_R^C & & & \downarrow \text{id}_R \star \epsilon \\
 & & & & R \circ \text{id}_B \\
 & & & & \downarrow \rho_R^C \\
 & & & & R.
 \end{array}$$

Example 19.1.2.1.3. Here are some examples of internal adjunctions.

1. *Internal Adjunctions in Cats₂.* The internal adjunctions in the 2-category Cats₂ of categories, functors, and natural transformations are precisely the adjunctions of ??.
2. *Internal Adjunctions in Rel.* The internal adjunctions in **Rel** are precisely the relations of the form $\text{Gr}(f) \dashv f^{-1}$ with f a function; see ?? of ??.
3. *Internal Adjunctions in Span.* The internal adjunctions in **Span** are precisely the spans of the form

$$\begin{array}{ccc}
 & S & \\
 \phi \swarrow & & \searrow g \\
 A & & B
 \end{array}$$

with ϕ an isomorphism; see ?? of ??.

Proposition 19.1.2.1.4. Let \mathcal{C} be a bicategory.

1. *Duality.* Let (f, g, η, ϵ) be an internal adjunction in \mathcal{C} .
 - (a) The quadruple (g, f, η, ϵ) is an internal adjunction in \mathcal{C}^{op} .
 - (b) The quadruple (g, f, ϵ, η) is an internal adjunction in \mathcal{C}^{co} .
 - (c) The quadruple (f, g, η, ϵ) is an internal adjunction in $\mathcal{C}^{\text{coop}}$.
2. *Uniqueness of Adjoints.* Let (f, g, η, ϵ) and $(f, g', \eta', \epsilon')$ be internal adjunctions in \mathcal{C} . We have a canonical isomorphism⁵

$$g \xrightarrow{(\lambda_g^C)^{-1}} \text{id}_A \circ g \xrightarrow{\eta' \star \text{id}_g} (g' \circ f) \circ g \xrightarrow{\alpha_{g', f, g}^C} g' \circ (f \circ g) \xrightarrow{\text{id}_{g'} \star \epsilon} g' \circ \text{id}_B \xrightarrow{(\rho_{g'}^C)^{-1}} g'$$

with inverse

$$g' \xrightarrow{(\lambda_{g'}^C)^{-1}} \text{id}_B \circ g' \xrightarrow{\eta \star \text{id}_{g'}} (g \circ f) \circ g' \xrightarrow{\alpha_{g', f, g}^C} g \circ (f \circ g') \xrightarrow{\text{id}_g \star \epsilon'} g \circ \text{id}_B \xrightarrow{(\lambda_g^C)^{-1}} g.$$

3. *Carrying Internal Adjunctions Through Pseudofunctors.* Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a pseudofunctor and (f, g, η, ϵ) be an internal adjunction in \mathcal{C} . There is an induced internal adjunction⁶

$$(F(f), F(g), \bar{\eta}, \bar{\epsilon})$$

in \mathcal{D} , where:

- (a) The unit

$$\bar{\eta}: \text{id}_{F(A)} \Rightarrow F(g) \circ F(f)$$

is the composition

$$\text{id}_{F(A)} \xrightarrow{F_A} F(\text{id}_A) \xrightarrow{F(\eta)} F(g \circ f) \xrightarrow{F_{g, f}^{-1}} F(g) \circ F(f).$$

- (b) The counit

$$\bar{\epsilon}: F(f) \circ F(g) \Rightarrow \text{id}_{F(B)}$$

is the composition

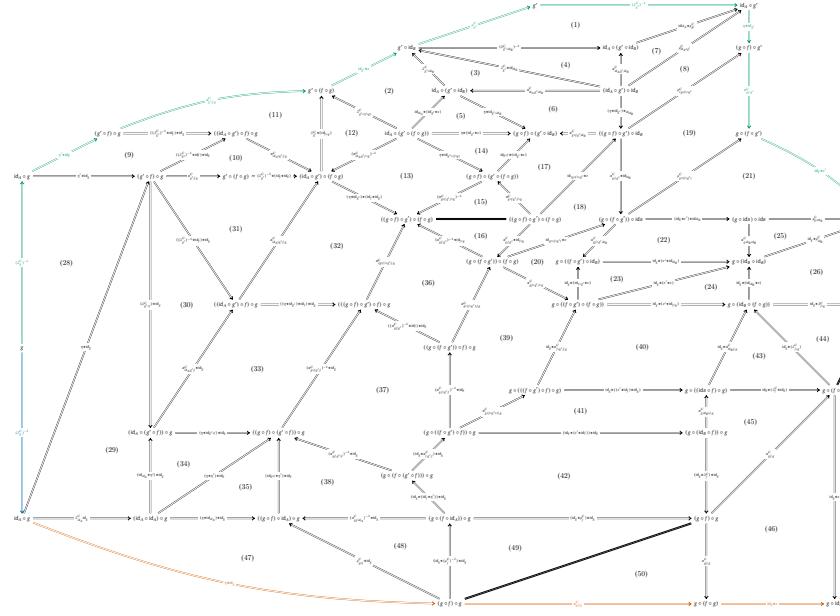
$$F(f) \circ F(g) \xrightarrow{F_{f, g}} F(f \circ g) \xrightarrow{F(\epsilon)} F(\text{id}_B) \xrightarrow{F_B} \text{id}_{F(B)}.$$

⁵*Slogan:* Left adjoints are unique up to canonical isomorphism. Dually, so are right adjoints.

⁶ *Warning:* Lax or oplax functors which are not pseudofunctors need not preserve internal adjunctions.

Proof. **Item 1, Duality:** Omitted.⁷

Item 2, Uniqueness of Adjoints: ⁸ Consider the diagram (if you *really* want to consider it I fear you will need to zoom in)



In this diagram:

1. The morphisms in green are the composition $g \xrightarrow{\cong} g' \xrightarrow{\cong} g$;
2. The morphisms in red are equal to λ_g^C by the right triangle identity for (f, g, η, ϵ) . Hence the composition of the morphism in blue with the morphisms in red is the identity;
3. Subdiagrams (1), (2), (10), (11), (29), (31), and (43) commute by the naturality of the left unit of C and its inverse;
4. Subdiagrams (8), (19), and (21) commute by the naturality of the right unit of C and its inverse;
5. Subdiagrams (6), (13), (17), (18), (20), (22), (32), (33), (36), (38), (40), (41), and (45) commute by the naturality of the associator of C and its inverse;
6. Subdiagrams (37), (39), and (42) commute by the pentagon identity for C ;
7. Subdiagrams (3), (4), (7), (12), (25), (30), and (48) commute by ?? of ??;

⁷Reference: [JY21, Exercise 6.6.2].

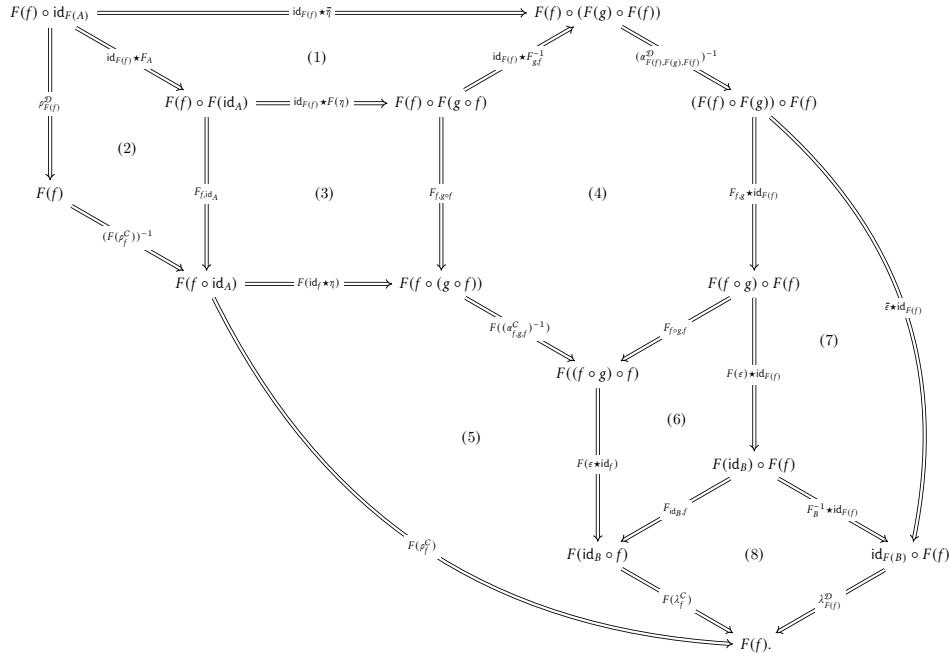
⁸Reference: [JY21, Lemma 6.1.6].

8. Subdiagrams (5), (14), (23), (24), (34), and (35) commute by middle-four exchange;
9. Subdiagrams (9), (15), (16), (27), (28), (44), (46), (49), and (50) commute trivially;
10. Subdiagram (26) commutes by ???? of ?? ;
11. Subdiagram (47) commutes by ?? of ?? and the naturality of the left unit of right unit of C .

Hence $g \cong g'$.

Item 3, Carrying Internal Adjunctions Through Pseudofunctors: ⁹We claim that the left and right triangle identities for $(F(f), F(g), \bar{\eta}, \bar{\epsilon})$ hold:

1. The left triangle identity for $(F(f), F(g), \bar{\eta}, \bar{\epsilon})$ is the condition that the boundary diagram of the diagram (you may need to zoom in)

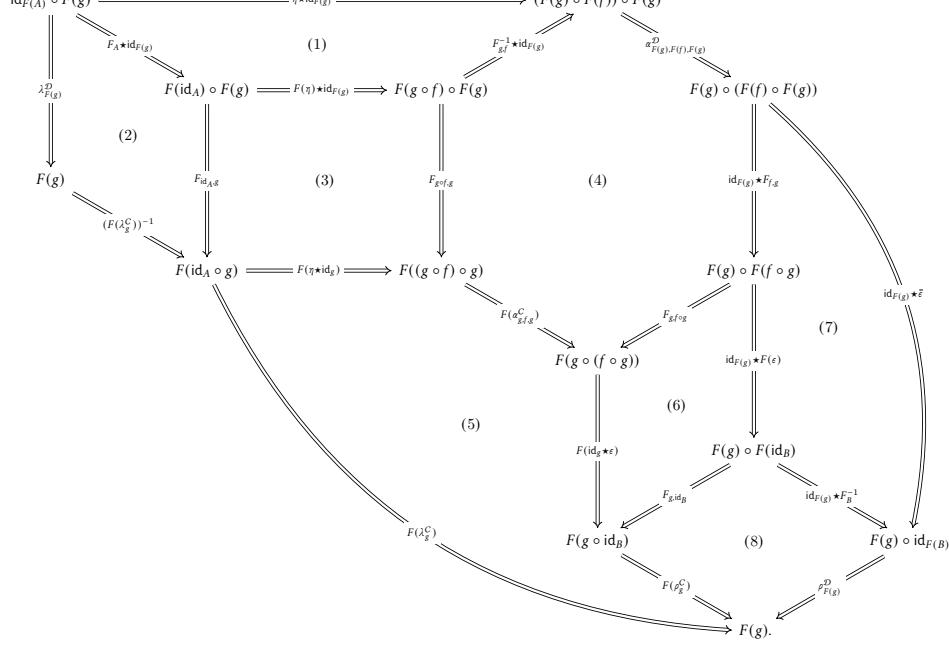


commutes. Since

- (a) Subdiagrams (1) and (7) commute by applying middle-four exchange twice,
- (b) Subdiagrams (2) and (8) commute by the left and right lax unity conditions for F ,
- (c) Subdiagrams (3) and (6) commute by the naturality of the lax functoriality constraints of F ,

⁹Reference: [JY21, Proposition 6.1.7].

- (d) Subdiagram (4) commutes by the lax associativity condition for F , and
(e) Subdiagram (5) commutes by the left triangle identity for (f, g, η, ϵ) ,
- so does the boundary diagram.
2. The right triangle identity for $(F(f), F(g), \bar{\eta}, \bar{\epsilon})$ is the condition that the boundary diagram of the diagram (you may need to zoom in)



commutes. Since

- (a) Subdiagrams (1) and (7) commute by applying middle-four exchange twice,
- (b) Subdiagrams (2) and (8) commute by the left and right lax unity conditions for F ,
- (c) Subdiagrams (3) and (6) commute by the naturality of the lax functoriality constraints of F ,
- (d) Subdiagram (4) commutes by the lax associativity condition for F , and
- (e) Subdiagram (5) commutes by the right triangle identity for (f, g, η, ϵ) ,

so does the boundary diagram.

This finishes the proof. □

19.1.3 Internal Adjoint Equivalences

Let C be a bicategory.

Definition 19.1.3.1.1. An internal adjunction (f, g, η, ϵ) in \mathcal{C} is an **internal adjoint equivalence** if η and ϵ are isomorphisms in \mathcal{C} .

Example 19.1.3.1.2. Here are some examples of internal adjoint equivalences.

1. *Internal Adjoint Equivalences in Cats_2 .* The internal adjoint equivalences in the 2-category Cats_2 of categories, functors, and natural transformations are precisely the adjoint equivalences of ?? .¹⁰
2. *Internal Adjoint Equivalences in Mod .* The internal adjoint equivalences in Mod are precisely the invertible R -modules; see ?? .¹¹
3. *Internal Adjoint Equivalences in $\text{PseudoFun}(\mathcal{C}, \mathcal{D})$.* The internal adjoint equivalences in $\text{PseudoFun}(\mathcal{C}, \mathcal{D})$ are precisely the invertible strong transformations; see ?? .¹²
4. *Internal Adjoint Equivalences in Rel .* The internal adjoint equivalences in Rel are precisely the relations of the form $\text{Gr}(f) \dashv f^{-1}$ with f an isomorphism; see ?? .
5. *Internal Adjoint Equivalences in Span .* The internal adjoint equivalences in Span are precisely the spans of the form $A \xleftarrow{\phi} S \xrightarrow{\psi} B$ with ϕ and ψ isomorphisms; see ?? .

Proposition 19.1.3.1.3. Let \mathcal{C} be a bicategory.

1. *Carrying Internal Adjoint Equivalences Through Pseudofunctors.* Let $F : \mathcal{C} \longrightarrow \mathcal{D}$ be a pseudofunctor and (f, g, η, ϵ) be an internal adjunction in \mathcal{C} . If (f, g, η, ϵ) is an internal adjoint equivalence in \mathcal{C} , then the induced internal adjunction

$$(F(f), F(g), \bar{\eta}, \bar{\epsilon})$$

in \mathcal{D} of Item 3 of Proposition 19.1.2.1.4 is an internal adjoint equivalence as well.

2. *Internal Adjunctions Always Refine to Internal Adjoint Equivalences.* Let (f, g, η, ϵ) be an internal adjunction in \mathcal{C} . If f is an equivalence, then there exist 2-morphisms

$$\begin{aligned}\bar{\eta} &: \text{id}_A \Longrightarrow g \circ f \\ \bar{\epsilon} &: f \circ g \Longrightarrow \text{id}_B\end{aligned}$$

of \mathcal{C} such that $(f, g, \bar{\eta}, \bar{\epsilon})$ is an internal adjoint equivalence.

Proof. Item 1, Carrying Internal Adjoint Equivalences Through Pseudofunctors: See [JY21, Proposition 6.2.3].

Item 2, Internal Adjunctions Always Refine to Internal Adjoint Equivalences: See [JY21, Proposition 6.2.4]. \square

¹⁰Reference: [JY21, Examples 6.2.5].

¹¹Reference: [JY21, Examples 6.2.6].

¹²Reference: [JY21, Examples 6.2.7].

19.1.4 Mates

Let C be a bicategory, let (f, g, η, ϵ) and $(f', g', \eta', \epsilon')$ be adjunctions, and let h and k be morphisms of C as in the diagram

$$\begin{array}{ccc} A & \begin{array}{c} \xrightarrow{f} \\ \perp \\ \xleftarrow{g} \end{array} & B \\ h \downarrow & & \downarrow k \\ C & \begin{array}{c} \xrightarrow{f'} \\ \perp \\ \xleftarrow{g'} \end{array} & D. \end{array}$$

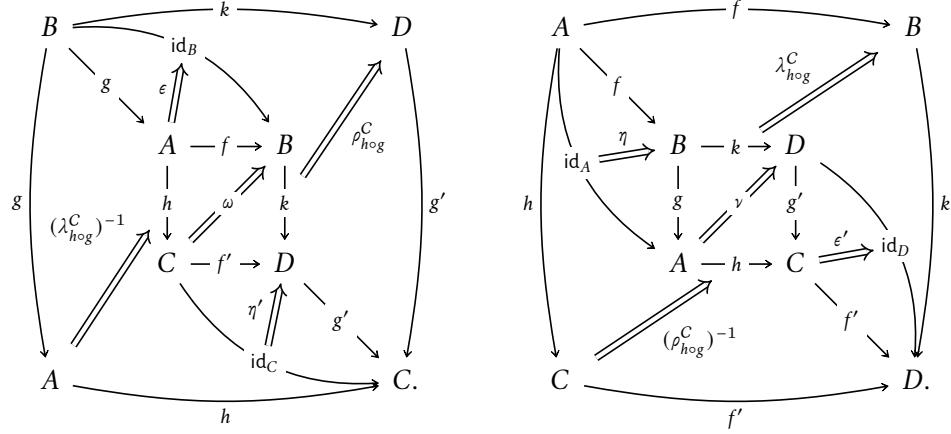
Definition 19.1.4.1.1. The **mates** of a pair of 2-morphisms

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ h \downarrow & \nearrow \omega & \downarrow k \\ C & \xrightarrow{f'} & D \end{array} \quad \begin{array}{l} \omega: f' \circ h \Rightarrow k \circ f, \\ \nu: h \circ g \Rightarrow g' \circ k \end{array} \quad \begin{array}{ccc} A & \xleftarrow{g} & B \\ h \downarrow & \nearrow \gamma & \downarrow k \\ C & \xleftarrow{g'} & D \end{array}$$

are the 2-morphisms

$$\begin{array}{ccc} A & \xleftarrow{g} & B \\ h \downarrow & \nearrow \omega^\dagger & \downarrow k \\ C & \xleftarrow{g'} & D \end{array} \quad \begin{array}{l} \omega^\dagger: h \circ g \Rightarrow g' \circ k, \\ \nu^\dagger: f' \circ h \Rightarrow k \circ f \end{array} \quad \begin{array}{ccc} A & \xrightarrow{f} & B \\ h \downarrow & \nearrow \nu^\dagger & \downarrow k \\ C & \xrightarrow{f'} & D \end{array}$$

defined as the pastings of the diagrams¹³



Proposition 19.1.4.1.2. Let $\omega: f' \circ h \Rightarrow k \circ f$ and $\nu: h \circ g \Rightarrow g' \circ k$ be 2-morphisms.

1. *The Mate Correspondence.* The map

$$(-)^\dagger: \text{Hom}_{\text{Hom}_C(A,C)}(f' \circ h, k \circ f) \longrightarrow \text{Hom}_{\text{Hom}_C(B,D)}(h \circ g, g' \circ k)$$

$$\omega \longmapsto \omega^\dagger$$

is a bijection.

Proof. **Item 1, The Mate Correspondence:** Here we give a proof for 2-categories (which indirectly proves also the general case by ??). A proof for general bicategories can be found in [JY21, Lemma 6.1.13].

¹³If C is a 2-category, these pasting diagrams become the following:

$$\begin{array}{ccc}
 \begin{array}{c} B \xrightarrow{g} A \\ \downarrow k \\ D \xrightarrow{g'} C \end{array} & = & \begin{array}{c} B \xrightarrow{g} A \xrightarrow{h} C \\ \downarrow \text{id}_B \quad \downarrow f \\ B \xrightarrow{k} D \xrightarrow{g'} C \end{array} \\
 \begin{array}{c} C \xrightarrow{f'} D \\ \uparrow h \\ A \xrightarrow{f} B \end{array} & = & \begin{array}{c} A \xrightarrow{h} C \xrightarrow{f'} D \\ \uparrow \text{id}_A \quad \uparrow g \\ A \xrightarrow{k} D \end{array}
 \end{array}$$

Let

$$\nu: h \circ g \Rightarrow g' \circ k$$

$$\begin{array}{ccc} A & \xleftarrow{g} & B \\ h \downarrow & \swarrow \eta & \searrow \\ C & \xleftarrow{g'} & D \end{array}$$

be a 2-morphism of C . The mate ν^\dagger of ν is then given by

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ h \downarrow & \swarrow \nu^\dagger & \searrow \\ C & \xrightarrow{f'} & D \end{array} = \begin{array}{ccc} A & \xleftarrow{g} & B \\ h \downarrow & \swarrow \eta & \searrow \\ C & \xleftarrow{g'} & D \\ f' \downarrow & \swarrow \epsilon' & \searrow id_D \\ D, \end{array}$$

and the mate of ν^\dagger is the 2-morphism $(\nu^\dagger)^\dagger: f' \circ h \Rightarrow k \circ f$ given by

$$\begin{array}{cccc} A & \xleftarrow{g} & B & A \xleftarrow{g} B \\ h \downarrow & \swarrow (\nu^\dagger)^\dagger & \searrow & id_A \downarrow \\ C & \xleftarrow{g'} & D & \end{array} = \begin{array}{ccc} A & \xleftarrow{g} & B \\ h \downarrow & \swarrow \eta & \searrow \\ C & \xleftarrow{g'} & D \\ id_C \downarrow & \swarrow \eta' & \searrow \\ C & \xleftarrow{g'} & D \end{array} = \begin{array}{ccc} A & \xleftarrow{g} & B \\ id_A \downarrow & \swarrow \epsilon & \searrow id_B \\ A & \xleftarrow{g} & B \\ h \downarrow & \swarrow \eta & \searrow \\ C & \xleftarrow{g'} & D \\ id_C \downarrow & \swarrow \epsilon' & \searrow id_D \\ C & \xleftarrow{g'} & D \end{array} = \begin{array}{ccc} A & \xleftarrow{g} & B \\ id_g \downarrow & \swarrow id_B & \searrow id_B \\ A & \xleftarrow{g} & B \\ h \downarrow & \swarrow \eta & \searrow \\ C & \xleftarrow{g'} & D \\ id_{g'} \downarrow & \swarrow id_D & \searrow id_D \\ C & \xleftarrow{g'} & D \end{array} = \begin{array}{ccc} A & \xleftarrow{g} & B \\ h \downarrow & \swarrow \eta & \searrow \\ C & \xleftarrow{g'} & D \end{array}$$

Similarly, $(\omega)^\dagger = \omega$. □

19.2 Morphisms of Internal Adjunctions

19.2.1 Lax Morphisms of Internal Adjunctions

Let C be a bicategory and let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in C .

Definition 19.2.1.1.1. A **lax morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ is a lax transformation between these viewed as 2-functors from the walking adjunction.

Remark 19.2.1.1.2. In detail, a **lax morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ consists of

- **1-Morphisms.** A pair of 1-morphisms

$$\begin{aligned}\phi: A &\rightarrow A', \\ \psi: B &\rightarrow B'\end{aligned}$$

of \mathcal{C} ;

- **2-Morphisms.** A pair of 2-morphisms

$$\begin{array}{ccc} \begin{array}{c} A \xrightarrow{F} B \\ \phi \downarrow \quad \lrcorner \alpha \lrcorner \\ A' \xrightarrow{F'} B' \end{array} & \begin{array}{c} \alpha: F' \circ \phi \Rightarrow \psi \circ F, \\ \beta: G' \circ \phi \Rightarrow \psi \circ G \end{array} & \begin{array}{c} A \xleftarrow{G} B \\ \phi \downarrow \quad \lrcorner \beta \lrcorner \\ A' \xleftarrow{G'} B' \end{array} \end{array}$$

of \mathcal{C} ;

satisfying the following conditions:

1. **Compatibility With Units.** We have an equality

$$\begin{array}{ccc} \begin{array}{c} F \curvearrowright B \\ \eta \uparrow \\ A \xrightarrow{\text{id}_A} A \\ \phi \downarrow \quad \lrcorner \lambda_\phi^C \lrcorner \\ A' \xrightarrow{\text{id}_{A'}} \end{array} & = & \begin{array}{c} F \curvearrowright B \\ \eta \uparrow \\ A \xrightarrow{\psi} B' \\ \phi \downarrow \quad \lrcorner \alpha \lrcorner \\ A' \xrightarrow{\text{id}_{A'}} \end{array} \end{array}$$

of pasting diagrams in \mathcal{C} ;

2. **Compatibility With Counits.** We have an equality

$$\begin{array}{ccc} \begin{array}{c} \text{id}_B \curvearrowright B \\ \epsilon \uparrow \\ B \xrightarrow{G} A \\ \psi \downarrow \quad \lrcorner \beta \lrcorner \\ B' \xrightarrow{\text{id}_{B'}} \end{array} & = & \begin{array}{c} \text{id}_B \curvearrowright B \\ \epsilon \uparrow \\ B \xrightarrow{\psi} B' \\ \lambda_\psi^C \lrcorner \lrcorner \quad \lrcorner \rho_{\psi}^{C,-1} \lrcorner \\ B' \xrightarrow{\text{id}_{B'}} \end{array} \end{array}$$

of pasting diagrams in \mathcal{C} .

19.2.2 Oplax Morphisms of Internal Adjunctions

Let \mathcal{C} be a bicategory and let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in \mathcal{C} .

Definition 19.2.2.1.1. An **oplax morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ is an oplax transformation between these viewed as 2-functors from the walking adjunction.

Remark 19.2.2.1.2. In detail, an **oplax morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ consists of

- **1-Morphisms.** A pair of 1-morphisms

$$\begin{aligned}\phi: A &\rightarrow A', \\ \psi: B &\rightarrow B'\end{aligned}$$

of \mathcal{C} ;

- **2-Morphisms.** A pair of 2-morphisms

$$\begin{array}{ccc} \begin{array}{ccc} A & \xrightarrow{F} & B \\ \phi \downarrow & \swarrow \alpha & \downarrow \psi \\ A' & \xrightarrow{F'} & B' \end{array} & \alpha: \psi \circ F \Rightarrow F' \circ \phi, & \begin{array}{ccc} A & \xleftarrow{G} & B \\ \phi \downarrow & \swarrow \beta & \downarrow \psi \\ A' & \xleftarrow{G'} & B' \end{array} \\ \beta: \psi \circ G \Rightarrow G' \circ \phi & & \end{array}$$

of \mathcal{C} ;

satisfying the following conditions:

1. **Compatibility With Units.** We have an equality

$$\begin{array}{ccc} \begin{array}{ccccc} & G & \nearrow & A & \searrow F \\ B & \xrightarrow{\quad id_B \quad} & & B & \\ \psi \downarrow & \swarrow \lambda_{\phi}^{C,-1} & \nearrow \psi & \searrow \rho_{\phi}^C & \downarrow \psi \\ B' & \xrightarrow{id_{B'}} & & B' & \end{array} & = & \begin{array}{ccccc} & G & \nearrow & A & \searrow F \\ B & \xrightarrow{\quad id_B \quad} & \swarrow \beta & \downarrow \phi & \searrow \alpha \\ \psi \downarrow & & & \downarrow \epsilon' & \\ B' & \xrightarrow{id_{B'}} & G' & \parallel & F' \\ & & & \downarrow & \\ & & & & B' \end{array} \end{array}$$

of pasting diagrams in \mathcal{C} ;

2. *Compatibility With Counits.* We have an equality

of pasting diagrams in \mathcal{C} .

19.2.3 Strong Morphisms of Internal Adjunctions

Let \mathcal{C} be a bicategory and let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in \mathcal{C} .

Definition 19.2.3.1.1. A **strong morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ is a strong transformation between these viewed as 2-functors from the walking adjunction.

Remark 19.2.3.1.2. In detail, a **strong morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ is equivalently:

1. A lax morphism of internal adjunctions as in [Remark 19.2.1.1.2](#) whose 2-morphisms are invertible.
2. An oplax morphism of internal adjunctions as in [Remark 19.2.2.1.2](#) whose 2-morphisms are invertible.

19.2.4 Strict Morphisms of Internal Adjunctions

Let \mathcal{C} be a bicategory and let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in \mathcal{C} .

Definition 19.2.4.1.1. A **strict morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ is a strict transformation between these viewed as 2-functors from the walking adjunction.

Remark 19.2.4.1.2. In detail, a **strict morphism of internal adjunctions** from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$ is equivalently:

1. A lax morphism of internal adjunctions as in [Remark 19.2.1.1.2](#) whose 2-morphisms are identities.
2. An oplax morphism of internal adjunctions as in [Remark 19.2.2.1.2](#) whose 2-morphisms are identities.

19.3 2-Morphisms Between Morphisms of Internal Adjunctions

19.3.1 2-Morphisms Between Lax Morphisms of Internal Adjunctions

Let C be a bicategory, let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in C , and let $(\phi_1, \psi_1, \alpha_1, \beta_1)$ and $(\phi_2, \psi_2, \alpha_2, \beta_2)$ be lax morphisms of internal adjunctions from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$.

Definition 19.3.1.1.1. A **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ is a modification between these viewed as lax transformations.

Remark 19.3.1.1.2. In detail, a **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ consist of 2-morphisms

$$\begin{aligned}\Gamma: \phi_1 &\Rightarrow \phi_2 \\ \Sigma: \psi_1 &\Rightarrow \psi_2\end{aligned}$$

of C such that we have equalities

$$\begin{array}{ccc} \begin{array}{c} A \xrightarrow{F} B \\ \phi_1 \left(\begin{array}{c} \xrightarrow{\Gamma} \\ \Rightarrow \end{array} \right) \phi_2 \quad \begin{array}{c} \nearrow \alpha_2 \\ \equiv \end{array} \quad \psi_2 \end{array} & = & \begin{array}{c} A \xrightarrow{F} B \\ \phi_1 \left(\begin{array}{c} \nearrow \alpha_1 \\ \equiv \end{array} \right) \psi_1 \left(\begin{array}{c} \xrightarrow{\Sigma} \\ \Rightarrow \end{array} \right) \psi_2 \end{array} \\ \begin{array}{c} A' \xrightarrow{F'} B' \\ \downarrow \end{array} & & \begin{array}{c} A' \xrightarrow{F'} B' \\ \downarrow \end{array} \\ \begin{array}{c} B \xrightarrow{G} A \\ \psi_1 \left(\begin{array}{c} \xrightarrow{\Sigma} \\ \Rightarrow \end{array} \right) \psi_2 \quad \begin{array}{c} \nearrow \beta_2 \\ \equiv \end{array} \quad \phi_2 \end{array} & = & \begin{array}{c} B \xrightarrow{G} A \\ \psi_1 \left(\begin{array}{c} \nearrow \beta_1 \\ \equiv \end{array} \right) \phi_1 \left(\begin{array}{c} \xrightarrow{\Gamma} \\ \Rightarrow \end{array} \right) \phi_2 \end{array} \\ \begin{array}{c} B' \xrightarrow{G'} A' \\ \downarrow \end{array} & & \begin{array}{c} B' \xrightarrow{G'} A' \\ \downarrow \end{array} \end{array}$$

of pasting diagrams in C .

19.3.2 2-Morphisms Between Oplax Morphisms of Internal Adjunctions

Let C be a bicategory, let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in C , and let $(\phi_1, \psi_1, \alpha_1, \beta_1)$ and $(\phi_2, \psi_2, \alpha_2, \beta_2)$ be oplax morphisms of internal adjunctions from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$.

Definition 19.3.2.1.1. A **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ is a modification between these viewed as oplax transformations.

Remark 19.3.2.1.2. In detail, a **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ consist of 2-morphisms

$$\begin{aligned}\Gamma: \phi_1 &\Rightarrow \phi_2 \\ \Sigma: \psi_1 &\Rightarrow \psi_2\end{aligned}$$

of C such that we have equalities

$$\begin{array}{ccc}
 \begin{array}{c} A \xrightarrow{F} B \\ \phi_2 \left(\begin{array}{c} \Gamma \\ \Downarrow \end{array} \right) \phi_1 \quad \alpha_1 \quad \Downarrow \\ \Downarrow \quad \Downarrow \quad \Downarrow \\ A' \xrightarrow{F'} B' \end{array} & = & \begin{array}{c} A \xrightarrow{F} B \\ \phi_2 \left(\begin{array}{c} \alpha_2 \quad \Downarrow \\ \Downarrow \quad \Sigma \end{array} \right) \psi_2 \left(\begin{array}{c} \Sigma \\ \Downarrow \end{array} \right) \psi_1 \\ \Downarrow \quad \Downarrow \\ A' \xrightarrow{F'} B' \end{array} \\
 \begin{array}{c} B \xrightarrow{G} A \\ \psi_2 \left(\begin{array}{c} \Sigma \\ \Downarrow \end{array} \right) \psi_1 \quad \beta_1 \quad \Downarrow \\ \Downarrow \quad \Downarrow \quad \Downarrow \\ B' \xrightarrow{G'} A' \end{array} & = & \begin{array}{c} B \xrightarrow{G} A \\ \psi_2 \left(\begin{array}{c} \beta_2 \quad \Downarrow \\ \Downarrow \quad \Gamma \end{array} \right) \phi_2 \left(\begin{array}{c} \Gamma \\ \Downarrow \end{array} \right) \phi_1 \\ \Downarrow \quad \Downarrow \\ B' \xrightarrow{G'} A' \end{array}
 \end{array}$$

of pasting diagrams in C .

19.3.3 2-Morphisms Between Strong Morphisms of Internal Adjunctions

Let C be a bicategory, let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in C , and let $(\phi_1, \psi_1, \alpha_1, \beta_1)$ and $(\phi_2, \psi_2, \alpha_2, \beta_2)$ be strong morphisms of internal adjunctions from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$.

Definition 19.3.3.1.1. A **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ is a modification between these viewed as strong transformations.

Remark 19.3.3.1.2. In detail, a **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ is equivalently:

- A 2-morphism (Γ, Σ) from $(\phi_1, \psi_1, \alpha_1, \beta_1)$ to $(\phi_2, \psi_2, \alpha_2, \beta_2)$ viewed as lax transformations as in [Remark 19.3.1.1.2](#).
- A 2-morphism (Γ, Σ) from $(\phi_1, \psi_1, \alpha_1, \beta_1)$ to $(\phi_2, \psi_2, \alpha_2, \beta_2)$ viewed as oplax transformations as in [Remark 19.3.2.1.2](#).

19.3.4 2-Morphisms Between Strict Morphisms of Internal Adjunctions

Let C be a bicategory, let $(A, B, F, G, \eta, \epsilon)$ and $(A', B', F', G', \eta', \epsilon')$ be internal adjunctions in C , and let $(\phi_1, \psi_1, \alpha_1, \beta_1)$ and $(\phi_2, \psi_2, \alpha_2, \beta_2)$ be lax morphisms of internal adjunctions from $(A, B, F, G, \eta, \epsilon)$ to $(A', B', F', G', \eta', \epsilon')$.

Definition 19.3.4.1.1. A **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ is a modification between these viewed as strict transformations.

Remark 19.3.4.1.2. In detail, a **2-morphism from** $(\phi_1, \psi_1, \alpha_1, \beta_1)$ **to** $(\phi_2, \psi_2, \alpha_2, \beta_2)$ is equivalently:

- A 2-morphism (Γ, Σ) from $(\phi_1, \psi_1, \alpha_1, \beta_1)$ to $(\phi_2, \psi_2, \alpha_2, \beta_2)$ viewed as lax transformations as in Remark 19.3.1.1.2.
- A 2-morphism (Γ, Σ) from $(\phi_1, \psi_1, \alpha_1, \beta_1)$ to $(\phi_2, \psi_2, \alpha_2, \beta_2)$ viewed as oplax transformations as in Remark 19.3.2.1.2.
- A 2-morphism (Γ, Σ) from $(\phi_1, \psi_1, \alpha_1, \beta_1)$ to $(\phi_2, \psi_2, \alpha_2, \beta_2)$ viewed as strong transformations as in Remark 19.3.3.1.2.

19.4 Bicategories of Internal Adjunctions in a Bicategory

Appendices

19.A Other Chapters

Sets	15. Profunctors
1. Sets	16. Cartesian Closed Categories
2. Constructions With Sets	17. Kan Extensions
3. Pointed Sets	Bicategories
4. Tensor Products of Pointed Sets	18. Bicategories
5. Relations	19. Internal Adjunctions
6. Spans	Internal Category Theory
7. Posets	20. Internal Categories
Indexed and Fibred Sets	Cyclic Stuff
7. Indexed Sets	21. The Cycle Category
8. Fibred Sets	Cubical Stuff
9. Un/Straightening for Indexed and Fibred Sets	22. The Cube Category
Category Theory	Globular Stuff
11. Categories	23. The Globe Category
12. Types of Morphisms in Categories	Cellular Stuff
13. Adjunctions and the Yoneda Lemma	24. The Cell Category
14. Constructions With Categories	Monoids
	25. Monoids

26. Constructions With Monoids

37. Real Analysis in One Variable

Monoids With Zero

38. Real Analysis in Several Variables

27. Monoids With Zero

Measure Theory

28. Constructions With Monoids With Zero

39. Measurable Spaces

Groups

40. Measures and Integration

29. Groups

Probability Theory

30. Constructions With Groups

40. Probability Theory

Hyper Algebra

Stochastic Analysis

31. Hypermonoids

41. Stochastic Processes, Martingales, and Brownian Motion

32. Hypergroups

42. Itô Calculus

33. Hypersemirings and Hyperrings

43. Stochastic Differential Equations

34. Quantales

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18. Bicategories	34. Quantales
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Part XIX

Differential Geometry

Chapter 45

Topological and Smooth Manifolds

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Part XX

Schemes

Chapter 46

Schemes

46.1 Introduction

In this document we define schemes. A basic reference is [ECA].

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Part XXI

Secret Part

Chapter 47

To Do List

This chapter contains some material about relations and constructions with them. Notably, we discuss and explore:

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47.1 Notes to Self

47.1.1 Things To Ask On MO/Zulip

Remark 47.1.1.1. Here is a list of things to be asked on MO/Zulip.

1. What are
 - (a) Cartesian bicategories
 - (b) Double categories of relations (<https://arxiv.org/abs/2107.07621>)
 - (c) Categories of relations
 - (d) Allegories
 - (e) 1-Category equipped with relations (<https://ncatlab.org/nlab/show/1-category+equipped+with+relations>)

good for? What have these notions been developed for, why are they important, and what have they lead to?

47.1.2 Things To Explore/Add

Remark 47.1.2.1.1. Here is a list of things to be explored.

1. <https://mathoverflow.net/a/461814>
2. there's some cool stuff in <https://arxiv.org/abs/2312.00990>, e.g. on cofunctors.
3. internal adjunctions in Mod as in [JY21, Section 6.3]; see [JY21, Example 6.2.6].
4. write the “profunctors” equivalent of the relations chapter
5. change χ_B notation throughout the notes
6. maybe note that skew monoidal structures on $\mathbf{Rel}(A, B)$ satisfy coherence trivially since the 2-morphisms are inclusions
7. reconsider notation $\text{FreeAlg}_{\mathcal{P}}$ in [Relations](#)
8. Constructions With Sets: Isbell duality for powersets
9. Categories: comma category notation as in <https://mathoverflow.net/questions/455630>
10. Universal property of the bicategory of spans, <https://ncatlab.org/nlab/show/span>
11. Codensity monad $\text{Ran}_J(J)$ of a relation (What about $\text{Rift}_J(J)$?)
12. Relative comonads in \mathbf{Rel} .
13. Write proper sections on straightening for lax functors from sets to \mathbf{Rel} or \mathbf{Span} (displayed sets) when I study the corresponding notions for categories
14. Write about cospans.
15. CoCartesian fibration classifying $\text{Fun}(F, G)$, <https://mathoverflow.net/questions/457533/cocartesian-fibration-classifying-\mathrm{fun}\ f-g>
16. Constructions With Sets: functoriality of limits/colimits, like functoriality of pullbacks
17. <https://ncatlab.org/nlab/show/adjoint+lifting+theorem>
18. <https://ncatlab.org/nlab/show/Gabriel%20%93Ulmer+duality>

47.1.3 Random Cool Papers

Remark 47.1.3.1.1. Here are some random cool papers that appeared on arXiv and that I want to check eventually.

1. A Derived Geometric Approach to Propagation of Solution Singularities for Non-linear PDEs I: Foundations
2. The Fundamental Theorem of Calculus point-free, with applications to exponentials and logarithms

47.1.4 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 some of the ones that I really want to add to the notes at some point.

Remark 47.1.4.1.1. Here is a list of omitted proofs that I really want to eventually write up or add a reference to.

- ?? of ??

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