Constructions With Sets

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This chapter develops some material relating to constructions with sets with an eye towards its categorical and higher-categorical counterparts to be introduced later in this work. Of particular interest are perhaps the following:

1. Explicit descriptions of the major types of co/limits in Sets, including in particular explicit descriptions of pushouts and coequalisers (see Definitions 4.2.4.1.1 and 4.2.5.1.1 and Remarks 4.2.4.1.4 and 4.2.5.1.4).

2. A discussion of powersets as decategorifications of categories of presheaves, including in particular results such as:

   (a) A discussion of the internal Hom of a powerset (Section 4.4.7).

   (b) A 0-categorical version of the Yoneda lemma (Presheaves and the Yoneda Lemma, Theorem 12.1.5.1.1), which we term the *Yoneda lemma for sets* (Proposition 4.5.5.1.1).

   (c) A characterisation of powersets as free cocompletions (Section 4.4.5), mimicking the corresponding statement for categories of presheaves (**??**).

   (d) A characterisation of powersets as free completions (Section 4.4.6), mimicking the corresponding statement for categories of copresheaves (**??**).

   (e) A (-1)-categorical version of un/straightening (Item 2 of Proposition 4.5.1.1.4 and Remark 4.5.1.1.6).

   (f) A 0-categorical form of Isbell duality internal to powersets (Section 4.4.8).

3. A lengthy discussion of the adjoint triple

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

of functors (i.e. morphisms of posets) between $\mathcal{P}(A)$ and $\mathcal{P}(B)$ induced by a map of sets $f\colon A \to B$, including in particular:

   (a) How f^{-1} can be described as a precomposition while $f_!$ and f_* can be described as Kan extensions (Remarks 4.6.1.1.4, 4.6.2.1.2 and 4.6.3.1.4).

   (b) An extensive list of the properties of $f_!$, f^{-1}, and f_* (Propositions 4.6.1.1.5, 4.6.1.1.7, 4.6.2.1.3, 4.6.2.1.5, 4.6.3.1.7 and 4.6.3.1.9).

   (c) How the functors $f_!$, f^{-1}, f_*, along with the functors

$$-_1 \cap -_2 \colon \mathcal{P}(X) \times \mathcal{P}(X) \to \mathcal{P}(X),$$
$$[-_1, -_2]_X \colon \mathcal{P}(X)^{\mathrm{op}} \times \mathcal{P}(X) \to \mathcal{P}(X)$$

   may be viewed as a six-functor formalism with the empty set $\emptyset$ as the dualising object (Section 4.6.4).

Contents

4.1 Limits of Sets

4.1.1 The Terminal Set

Definition 4.1.1.1.1 ▶ The Terminal Set

The **terminal set** is the terminal object of Sets as in Limits and Colimits, **??**.

Construction 4.1.1.1.2 ▶ Construction of the Terminal Set

Concretely, the terminal set is the pair $(\mathrm{pt}, \{!_A\}_{A\in\mathrm{Obj}(\mathsf{Sets})})$ consisting of:

1. *The Limit.* The punctual set $\mathrm{pt} \overset{\mathrm{def}}{=} \{\star\}$.
2. *The Cone.* The collection of maps

$$\{!_A \colon A \longrightarrow \mathrm{pt}\}_{A\in\mathrm{Obj}(\mathsf{Sets})}$$

   defined by

$$!_A(a) \overset{\mathrm{def}}{=} \star$$

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

Proof 4.1.1.1.3 ▶ Proof of Construction 4.1.1.1.2

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

$$A \qquad \mathrm{pt}$$

in Sets. Then there exists a unique map $\phi \colon A \longrightarrow \mathrm{pt}$ making the diagram

$$A \overset{\phi}{\underset{\exists!}{\dashrightarrow}} \mathrm{pt}$$

commute, namely $!_A$.

4.1.2 Products of Families of Sets

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

Definition 4.1.2.1.1 ▶ The Product of a Family of Sets

The **product**[1] **of** $\{A_i\}_{i\in I}$ is the product of $\{A_i\}_{i\in I}$ in Sets as in Limits and Colimits, **??**.

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

Construction 4.1.2.1.2 ▶ Construction of the Product of a Family of Sets

Concretely, the product of $\{A_i\}_{i\in I}$ is the pair $(\prod_{i\in I} A_i, \{\mathrm{pr}_i\}_{i\in I})$ consisting of:

1. *The Limit.* The set $\prod_{i\in I} A_i$ defined by
$$\prod_{i\in I} A_i \overset{\text{def}}{=} \left\{ f \in \mathsf{Sets}\left(I, \bigcup_{i\in I} A_i\right) \,\middle|\, \begin{array}{l}\text{for each } i \in I \text{, we}\\ \text{have } f(i) \in A_i\end{array} \right\}.$$

2. *The Cone.* The collection
$$\left\{ \mathrm{pr}_i \colon \prod_{i\in I} A_i \to A_i \right\}_{i\in I}$$
of maps given by
$$\mathrm{pr}_i(f) \overset{\text{def}}{=} f(i)$$
for each $f \in \prod_{i\in I} A_i$ and each $i \in I$.

Proof 4.1.2.1.3 ▶ Proof of Construction 4.1.2.1.2

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

$$\begin{tikzcd} P \arrow[dr, "p_i"] & \\ \prod\limits_{i\in I} A_i \arrow[r, "\mathrm{pr}_i"'] & A_i \end{tikzcd}$$

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

$$\begin{tikzcd} P \arrow[d, dashed, "\phi"', "\exists!"] \arrow[dr, "p_i"] & \\ \prod\limits_{i\in I} A_i \arrow[r, "\mathrm{pr}_i"'] & A_i \end{tikzcd}$$

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

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

for each $x \in P$. ∎

Remark 4.1.2.1.4 ▶ Unwinding Construction 4.1.2.1.2

Less formally, we may think of Cartesian products and projection maps as follows:

1. We think of $\prod_{i\in I} A_i$ as the set whose elements are I-indexed collections $(a_i)_{i\in I}$ with $a_i \in A_i$ for each $i \in I$.

2. We view the projection maps

$$\left\{\mathrm{pr}_i\colon \prod_{i\in I} A_i \to A_i\right\}_{i\in I}$$

as being given by

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

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

Proposition 4.1.2.1.5 ► Properties of Products of Families of Sets

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

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

$$\prod_{i\in I} \colon \mathsf{Fun}(I_{\mathsf{disc}}, \mathsf{Sets}) \longrightarrow \mathsf{Sets}$$

where

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

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

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

$$\left(\prod_{i\in I}\right)_{(A_i)_{i\in I},(B_i)_{i\in I}} \colon \mathrm{Nat}((A_i)_{i\in I}, (B_i)_{i\in I}) \to \mathsf{Sets}\left(\prod_{i\in I} A_i, \prod_{i\in I} B_i\right)$$

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

$$\{f_i \colon A_i \longrightarrow B_i\}_{i\in I}$$

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

$$\prod_{i\in I} f_i \colon \prod_{i\in I} A_i \to \prod_{i\in I} B_i$$

defined by

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

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

Item 1: Functoriality

This follows from Limits and Colimits, **??** of **??**.

4.1.3 Binary Products of Sets

Let A and B be sets.

Definition 4.1.3.1.1 ▶ Binary Products of Sets

The **product of** A **and** B[1] is the product of A and B in Sets as in Limits and Colimits, **??**.

[1] *Further Terminology:* Also called the **Cartesian product of** A **and** B.

Construction 4.1.3.1.2 ▶ Construction of Binary Products of Sets

Concretely, the product of A and B is the pair $(A \times B, \{\mathrm{pr}_1, \mathrm{pr}_2\})$ consisting of:

1. *The Limit.* The set $A \times B$ defined by
$$\begin{aligned} A \times B &\overset{\text{def}}{=} \prod_{z \in \{A,B\}} z \\ &\overset{\text{def}}{=} \{f \in \mathsf{Sets}(\{0,1\}, A \cup B) \mid \text{we have } f(0) \in A \text{ and } f(1) \in B\} \\ &\cong \{\{\{a\},\{a,b\}\} \in \mathcal{P}(\mathcal{P}(A \cup B)) \mid \text{we have } a \in A \text{ and } b \in B\} \\ &\cong \left\{ \begin{matrix} \text{ordered pairs } (a,b) \text{ with} \\ a \in A \text{ and } b \in B \end{matrix} \right\}. \end{aligned}$$

2. *The Cone.* The maps
$$\begin{aligned} \mathrm{pr}_1 &\colon A \times B \to A, \\ \mathrm{pr}_2 &\colon A \times B \to B \end{aligned}$$
defined by
$$\begin{aligned} \mathrm{pr}_1(a,b) &\overset{\text{def}}{=} a, \\ \mathrm{pr}_2(a,b) &\overset{\text{def}}{=} b \end{aligned}$$
for each $(a,b) \in A \times B$.

Proof 4.1.3.1.3 ▶ Proof of Construction 4.1.3.1.2

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

$$\begin{tikzcd}
 & P \arrow[dl, bend right, "p_1"'] \arrow[dr, bend left, "p_2"] & \\
A & A \times B \arrow[l, two heads, "\mathrm{pr}_1"] \arrow[r, two heads, "\mathrm{pr}_2"'] & B
\end{tikzcd}$$

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

$$\begin{tikzcd}
 & P \arrow[dl, bend right, "p_1"'] \arrow[dr, bend left, "p_2"] \arrow[d, dashed, "\phi"', "\exists!"] & \\
A & A \times B \arrow[l, two heads, "\mathrm{pr}_1"] \arrow[r, two heads, "\mathrm{pr}_2"'] & B
\end{tikzcd}$$

commute, being uniquely determined by the conditions

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

via

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

for each $x \in P$. □

Proposition 4.1.3.1.4 ▶ Properties of Products of Sets

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

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

$$\begin{aligned}
A \times -\colon &\quad \mathsf{Sets} &&\longrightarrow \mathsf{Sets},\\
- \times B\colon &\quad \mathsf{Sets} &&\longrightarrow \mathsf{Sets},\\
-_1 \times -_2\colon &\quad \mathsf{Sets} \times \mathsf{Sets} &&\longrightarrow \mathsf{Sets},
\end{aligned}$$

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

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

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

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

$$\times_{(A,B),(X,Y)} : \mathsf{Sets}(A, X) \times \mathsf{Sets}(B, Y) \longrightarrow \mathsf{Sets}(A \times B, X \times Y)$$

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

$$f \times g \colon A \times B \longrightarrow X \times Y$$

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 $A, B \in \mathrm{Obj}(\mathsf{Sets})$.

2. *Adjointness I.* We have adjunctions

$$\left(A \times - \dashv \mathsf{Sets}(A, -)\right)\colon \quad \begin{tikzcd} \mathsf{Sets} \arrow[r, bend left, "A\times-"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}, \arrow[l, bend left, "\mathsf{Sets}(A,-)"] \end{tikzcd}$$

$$\left(- \times B \dashv \mathsf{Sets}(B, -)\right)\colon \quad \begin{tikzcd} \mathsf{Sets} \arrow[r, bend left, "-\times B"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}, \arrow[l, bend left, "\mathsf{Sets}(B,-)"] \end{tikzcd}$$

witnessed by bijections

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

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

3. *Adjointness II.* We have an adjunction

$$(\Delta_{\mathsf{Sets}} \dashv -_1 \times -_2)\colon \quad \begin{tikzcd} \mathsf{Sets} \arrow[r, bend left, "\Delta_{\mathsf{Sets}}"] \arrow[r, phantom, "\perp"] & \mathsf{Sets} \times \mathsf{Sets}, \arrow[l, bend left, "-_1\times-_2"] \end{tikzcd}$$

witnessed by a bijection

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

natural in $A \in \mathrm{Obj}(\mathsf{Sets})$ and in $(B,C) \in \mathrm{Obj}(\mathsf{Sets}\times\mathsf{Sets})$.

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

$$\alpha^{\mathsf{Sets}}_{A,B,C}\colon (A\times B)\times C \overset{\sim}{\dashrightarrow} A\times(B\times C),$$

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

5. *Unitality.* We have isomorphisms of sets

$$\lambda^{\mathsf{Sets}}_{A}\colon \mathrm{pt}\times A \overset{\sim}{\dashrightarrow} A,$$
$$\rho^{\mathsf{Sets}}_{A}\colon A\times \mathrm{pt} \overset{\sim}{\dashrightarrow} A,$$

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

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

$$\sigma^{\mathsf{Sets}}_{A,B}\colon A\times B \overset{\sim}{\dashrightarrow} B\times A,$$

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

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

$$\delta^{\mathsf{Sets}}_{\ell}\colon A\times(B\textstyle\coprod C) \overset{\sim}{\dashrightarrow} (A\times B)\textstyle\coprod(A\times C),$$
$$\delta^{\mathsf{Sets}}_{r}\colon (A\textstyle\coprod B)\times C \overset{\sim}{\dashrightarrow} (A\times C)\textstyle\coprod(B\times C),$$

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

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

$$\zeta_\ell^{\mathsf{Sets}} \colon \emptyset \times A \overset{\sim}{\dashrightarrow} \emptyset,$$
$$\zeta_r^{\mathsf{Sets}} \colon A \times \emptyset \overset{\sim}{\dashrightarrow} \emptyset,$$

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

9. *Distributivity Over Unions.* Let X be a set. For each $U, V, W \in \mathcal{P}(X)$, we have equalities

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

of subsets of $\mathcal{P}(X \times X)$.

10. *Distributivity Over Intersections.* Let X be a set. For each $U, V, W \in \mathcal{P}(X)$, we have equalities

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

of subsets of $\mathcal{P}(X \times X)$.

11. *Distributivity Over Differences.* Let X be a set. For each $U, V, W \in \mathcal{P}(X)$, we have equalities

$$U \times (V \setminus W) = (U \times V) \setminus (U \times W),$$
$$(U \setminus V) \times W = (U \times W) \setminus (V \times W)$$

of subsets of $\mathcal{P}(X \times X)$.

12. *Distributivity Over Symmetric Differences.* Let X be a set. For each $U, V, W \in \mathcal{P}(X)$, we have equalities

$$U \times (V \bigtriangleup W) = (U \times V) \bigtriangleup (U \times W),$$
$$(U \bigtriangleup V) \times W = (U \times W) \bigtriangleup (V \times W)$$

of subsets of $\mathcal{P}(X \times X)$.

13. *Middle-Four Exchange with Respect to Intersections.* The diagram

$$\begin{tikzcd}
(\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[r, "\cap \times \cap"] \arrow[d, "\mathcal{P}^{\times}_{X,X} \times \mathcal{P}^{\times}_{X,X}"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X \times X) \times \mathcal{P}(X \times X) \arrow[r, "\cap"'] & \mathcal{P}(X \times X)
\end{tikzcd}$$

commutes, i.e. we have

$$(U \times V) \cap (W \times T) = (U \cap V) \times (W \cap T).$$

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

14. *Symmetric Monoidality.* The 8-tuple $\left(\mathsf{Sets}, \times, \mathrm{pt}, \mathsf{Sets}(-_1, -_2), \alpha^{\mathsf{Sets}}, \lambda^{\mathsf{Sets}}, \rho^{\mathsf{Sets}}, \sigma^{\mathsf{Sets}}\right)$ is a closed symmetric monoidal category.

15. *Symmetric Bimonoidality.* The 18-tuple

$$\begin{gathered}\Big(\mathsf{Sets}, \coprod, \times, \emptyset, \mathrm{pt}, \mathsf{Sets}(-_1, -_2), \alpha^{\mathsf{Sets}}, \lambda^{\mathsf{Sets}}, \rho^{\mathsf{Sets}}, \sigma^{\mathsf{Sets}}, \\ \alpha^{\mathsf{Sets}, \coprod}, \lambda^{\mathsf{Sets}, \coprod}, \rho^{\mathsf{Sets}, \coprod}, \sigma^{\mathsf{Sets}, \coprod}, \delta^{\mathsf{Sets}}_{\ell}, \delta^{\mathsf{Sets}}_{r}, \zeta^{\mathsf{Sets}}_{\ell}, \zeta^{\mathsf{Sets}}_{r}\Big),\end{gathered}$$

is a symmetric closed bimonoidal category, where $\alpha^{\mathsf{Sets}, \coprod}$, $\lambda^{\mathsf{Sets}, \coprod}$, $\rho^{\mathsf{Sets}, \coprod}$, and $\sigma^{\mathsf{Sets}, \coprod}$ are the natural transformations from Items 3 to 5 of Proposition 4.2.3.1.4.

PROOF 4.1.3.1.5 ▶ PROOF OF PROPOSITION 4.1.3.1.4

Item 1: Functoriality

This follows from Limits and Colimits, **??** of **??**.

Item 2: Adjointness

We prove only that there's an adjunction $- \times B \dashv \mathsf{Sets}(B, -)$, witnessed by a bijection

$$\mathsf{Sets}(A \times B, C) \cong \mathsf{Sets}(A, \mathsf{Sets}(B, C)),$$

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

- *Map I.* We define a map

  $$\Phi_{B,C} \colon \mathsf{Sets}(A \times B, C) \to \mathsf{Sets}(A, \mathsf{Sets}(B, C)),$$

  by sending a function

  $$\xi \colon A \times B \to C$$

  to the function

  $$\begin{aligned} \xi^{\dagger} \colon A &\longrightarrow \mathsf{Sets}(B, C), \\ a &\longmapsto (\xi^{\dagger}_a \colon B \to C), \end{aligned}$$

  where we define

  $$\xi^{\dagger}_a(b) \overset{\text{def}}{=} \xi(a, b)$$

  for each $b \in B$. In terms of the $[\![a \mapsto f(a)]\!]$ notation of Sets, Notation 3.1.1.1.2, we have

  $$\xi^{\dagger} \overset{\text{def}}{=} [\![a \mapsto [\![b \mapsto \xi(a, b)]\!]]\!].$$

- *Map II.* We define a map

  $$\Psi_{B,C} \colon \mathsf{Sets}(A, \mathsf{Sets}(B, C)), \to \mathsf{Sets}(A \times B, C)$$

  given by sending a function

  $$\begin{aligned} \xi \colon A &\longrightarrow \mathsf{Sets}(B, C), \\ a &\longmapsto (\xi_a \colon B \to C), \end{aligned}$$

  to the function

  $$\xi^{\dagger} \colon A \times B \to C$$

defined by

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

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

- *Invertibility I.* We claim that

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

  Indeed, given a function $\xi\colon A \times B \to C$, we have

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

- *Invertibility II.* We claim that

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

  Indeed, given a function

  $$\begin{aligned}\xi\colon A &\longrightarrow \mathsf{Sets}(B,C),\\ a &\longmapsto (\xi_a\colon B \to C),\end{aligned}$$

  we have

$$[\Phi_{A,B} \circ \Psi_{A,B}](\xi) \overset{\text{def}}{=} \Phi_{A,B}(\Psi_{A,B}(\xi))$$

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

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

$$\begin{tikzcd}
\mathsf{Sets}(A \times B', C) \arrow[r, "\Phi_{B',C}"] \arrow[d, "\mathrm{id}_A \times g^*"'] & \mathsf{Sets}(A, \mathsf{Sets}(B', C)), \arrow[d, "(g^*)_!"] \\
\mathsf{Sets}(A \times B, C) \arrow[r, "\Phi_{B,C}"'] & \mathsf{Sets}(A, \mathsf{Sets}(B, C))
\end{tikzcd}$$

commutes. Indeed, given a function

$$\xi\colon A \times B' \to C,$$

we have

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

Alternatively, using the $\llbracket a \mapsto f(a) \rrbracket$ notation of Sets, Notation 3.1.1.1.2, we have

$$[\Phi_{B,C} \circ (\mathrm{id}_A \times g^*)](\xi) = \Phi_{B,C}([\mathrm{id}_A \times g^*](\xi))$$

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

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

$$
\begin{tikzcd}
\mathsf{Sets}(A \times B, C) \arrow[r, "\Phi_{B,C}"] \arrow[d, "h_!"'] & \mathsf{Sets}(A, \mathsf{Sets}(B, C)), \arrow[d, "(h_!)_!"] \\
\mathsf{Sets}(A \times B, C') \arrow[r, "\Phi_{B,C'}"'] & \mathsf{Sets}(A, \mathsf{Sets}(B, C'))
\end{tikzcd}
$$

commutes. Indeed, given a function

$$\xi\colon A \times B \to C,$$

we have

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

- *Naturality for* Ψ. Since Φ is natural in each argument and Φ is a componentwise inverse to Ψ in each argument, it follows from Categories, Item 2 of Proposition 11.9.7.1.2 that Ψ is also natural in each argument.

This finishes the proof.

Item 3: Adjointness II

This follows from the universal property of the product.

Item 4: Associativity

This is proved in the proof of Monoidal Structures on the Category of Sets, Definition 5.1.4.1.1.

Item 5: Unitality

This is proved in the proof of Monoidal Structures on the Category of Sets, Definitions 5.1.5.1.1 and 5.1.6.1.1.

Item 6: Commutativity

This is proved in the proof of Monoidal Structures on the Category of Sets, Definition 5.1.7.1.1.

Item 7: Distributivity Over Coproducts

This is proved in the proof of Monoidal Structures on the Category of Sets, Definitions 5.3.1.1.1 and 5.3.2.1.1.

Item 8: Annihilation With the Empty Set

This is proved in the proof of Monoidal Structures on the Category of Sets, Definitions 5.3.3.1.1 and 5.3.4.1.1.

Item 9: Distributivity Over Unions

See [Pro25c].

Item 10: Distributivity Over Intersections

See [Pro25d, Corollary 1].

Item 11: Distributivity Over Differences

See [Pro25a].

Item 12: Distributivity Over Symmetric Differences

See [Pro25b].

Item 13: Middle-Four Exchange With Respect to Intersections

See [Pro25d, Corollary 1].

Item 14: Symmetric Monoidality

This is a repetition of Monoidal Structures on the Category of Sets, Proposition 5.1.9.1.1, and is proved there.

Item 15: Symmetric Bimonoidality

This is a repetition of Monoidal Structures on the Category of Sets, Proposition 5.3.5.1.1, and is proved there.

Remark 4.1.3.1.6 ▶ The Cartesian Product of Sets as an $(\mathbb{E}_k, \mathbb{E}_\ell)$-Tensor Product

As shown in Item 1 of Proposition 4.1.3.1.4, the Cartesian product of sets defines a functor

$$-_1 \times -_2 \colon \mathsf{Sets} \times \mathsf{Sets} \longrightarrow \mathsf{Sets}.$$

This functor is the $(k, \ell) = (-1, -1)$ case of a family of functors

$$\otimes_{k,\ell} \colon \mathsf{Mon}_{\mathbb{E}_k}(\mathsf{Sets}) \times \mathsf{Mon}_{\mathbb{E}_\ell}(\mathsf{Sets}) \longrightarrow \mathsf{Mon}_{\mathbb{E}_{k+\ell}}(\mathsf{Sets})$$

of tensor products of $\mathbb{E}_k$-monoid objects on Sets with $\mathbb{E}_\ell$-monoid objects on Sets; see **??**.

Remark 4.1.3.1.7 ▶ Diagrams for Items 9 to 12 of Proposition 4.1.3.1.4

We may state the equalities in Items 9 to 12 of Proposition 4.1.3.1.4 as the commutativity of the following diagrams:

$$\begin{tikzcd}
& (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[dr, "\mu_4^{\mathsf{Sets}}"] & \\
\mathcal{P}(X) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)} \times \mathrm{id}_{\mathcal{P}(X)} \times \mathrm{id}_{\mathcal{P}(X)}"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \times \cup"'] & & (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X} \times \mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X \times X) \times \mathcal{P}(X \times X) \arrow[dl, "\cup"] \\
& \mathcal{P}(X \times X) &
\end{tikzcd}
\qquad
\begin{tikzcd}
& (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[dr, "\mu_4^{\mathsf{Sets}}"] & \\
(\mathcal{P}(X) \times \mathcal{P}(X)) \times \mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)} \times \mathrm{id}_{\mathcal{P}(X)} \times \Delta_{\mathcal{P}(X)}"] \arrow[d, "\cup \times \mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X} \times \mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X \times X) \times \mathcal{P}(X \times X) \arrow[dl, "\cup"] \\
& \mathcal{P}(X \times X) &
\end{tikzcd}$$

$$\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4}"] & \\
\mathcal{P}(X)\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\times\cap"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X}\times\mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X\times X)\times\mathcal{P}(X\times X) \arrow[dl, "\cap"] \\
 & \mathcal{P}(X\times X) &
\end{tikzcd}$$

$$\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4}"] & \\
(\mathcal{P}(X)\times\mathcal{P}(X))\times\mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}\times\Delta_{\mathcal{P}(X)}"] \arrow[d, "\cap\times\mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X}\times\mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X\times X)\times\mathcal{P}(X\times X) \arrow[dl, "\cap"] \\
 & \mathcal{P}(X\times X) &
\end{tikzcd}$$

$$\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4}"] & \\
\mathcal{P}(X)\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\times\setminus"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X}\times\mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X\times X)\times\mathcal{P}(X\times X) \arrow[dl, "\setminus"] \\
 & \mathcal{P}(X\times X) &
\end{tikzcd}$$

$$\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4}"] & \\
(\mathcal{P}(X)\times\mathcal{P}(X))\times\mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}\times\Delta_{\mathcal{P}(X)}"] \arrow[d, "\setminus\times\mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X}\times\mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X\times X)\times\mathcal{P}(X\times X) \arrow[dl, "\setminus"] \\
 & \mathcal{P}(X\times X) &
\end{tikzcd}$$

$$\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4}"] & \\
\mathcal{P}(X)\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\times\triangle"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X}\times\mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X\times X)\times\mathcal{P}(X\times X) \arrow[dl, "\triangle"] \\
 & \mathcal{P}(X\times X) &
\end{tikzcd}$$

$$\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4}"] & \\
(\mathcal{P}(X)\times\mathcal{P}(X))\times\mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)}\times\Delta_{\mathcal{P}(X)}"] \arrow[d, "\triangle\times\mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\mathcal{P}^{\times}_{X,X}\times\mathcal{P}^{\times}_{X,X}"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\mathcal{P}^{\times}_{X,X}"'] & & \mathcal{P}(X\times X)\times\mathcal{P}(X\times X) \arrow[dl, "\triangle"] \\
 & \mathcal{P}(X\times X) &
\end{tikzcd}$$

4.1.4 Pullbacks

Let A, B, and C be sets and let $f\colon A \to C$ and $g\colon B \to C$ be functions.

Definition 4.1.4.1.1 ▶ Pullbacks of Sets

The **pullback of** A **and** B **over** C **along** f **and** g[1] is the pullback of A and B over C along f and g in Sets as in Limits and Colimits, **??**.

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

CONSTRUCTION 4.1.4.1.2 ▶ CONSTRUCTION OF PULLBACKS OF SETS

Concretely, the pullback of A and B over C along f and g is the pair $(A \times_C B, \{\mathrm{pr}_1, \mathrm{pr}_2\})$ consisting of:

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

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

2. *The Cone.* The maps[1]

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

defined by

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

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

[1]*Further Notation:* Also written $\mathrm{pr}_1^{A \times_C B}$ and $\mathrm{pr}_2^{A \times_C B}$.

PROOF 4.1.4.1.3 ▶ PROOF OF CONSTRUCTION 4.1.4.1.2

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

$$f \circ \mathrm{pr}_1 = g \circ \mathrm{pr}_2, \qquad \begin{tikzcd} A \times_C B \arrow[r, two heads, "\mathrm{pr}_2"] \arrow[d, "\mathrm{pr}_1"'] & B \arrow[d, "g"] \\ A \arrow[r, "f"'] & C. \end{tikzcd}$$

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

$$[f \circ \mathrm{pr}_1](a, b) = f(\mathrm{pr}_1(a, b))$$

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

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

$$
\begin{tikzcd}
P \arrow[drr, bend left, "p_2"] \arrow[ddr, bend right, "p_1"'] & & \\
& A \times_C B \arrow[r, two heads, "\mathrm{pr}_2"] \arrow[d, two heads, "\mathrm{pr}_1"] \arrow[dr, phantom, very near start, "\lrcorner"] & B \arrow[d, "g"] \\
& A \arrow[r, "f"'] & C
\end{tikzcd}
$$

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

$$
\begin{tikzcd}
P \arrow[drr, bend left, "p_2"] \arrow[ddr, bend right, "p_1"'] \arrow[dr, dashed, "\phi", "\exists!"'] & & \\
& A \times_C B \arrow[r, two heads, "\mathrm{pr}_2"] \arrow[d, two heads, "\mathrm{pr}_1"] \arrow[dr, phantom, very near start, "\lrcorner"] & B \arrow[d, "g"] \\
& A \arrow[r, "f"'] & C
\end{tikzcd}
$$

commute, being uniquely determined by the conditions

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

via

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

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

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

which gives

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

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

Remark 4.1.4.1.4 ▶ Pullbacks of Sets Depend on the Maps

It is common practice to write $A \times_C B$ for the pullback of A and B over C along f and g, omitting the maps f and g from the notation and instead leaving them implicit, to be understood from the context.
However, the set $A \times_C B$ depends very much on the maps f and g, and sometimes it is necessary or useful to note this dependence explicitly. In such situations, we will write $A \times_{f,C,g} B$ or $A \times_C^{f,g} B$ for $A \times_C B$.

Example 4.1.4.1.5 ▶ Examples of Pullbacks of Sets

Here are some examples of pullbacks of sets.

1. *Unions via Intersections.* Let X be a set. We have

$$A \cap B \cong A \times_{A \cup B} B, \qquad \begin{tikzcd} A \cap B \arrow[r, two heads] \arrow[d, two heads] \arrow[dr, phantom, very near start, "\lrcorner"] & B \arrow[d, hook, "\iota_B"] \\ A \arrow[r, hook, "\iota_A"'] & A \cup B \end{tikzcd}$$

for each $A, B \in \mathcal{P}(X)$.

Proof 4.1.4.1.6 ▶ Proof of Example 4.1.4.1.5

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. ∎

Proposition 4.1.4.1.7 ▶ Properties of Pullbacks of Sets

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

   $$-_1 \times_{-_3} -_1 \colon \mathsf{Fun}(\mathcal{P}, \mathsf{Sets}) \longrightarrow \mathsf{Sets},$$

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

   $$\begin{tikzcd} & \bullet \arrow[d] \\ \bullet \arrow[r] & \bullet. \end{tikzcd}$$

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

   $$\begin{tikzcd} A \times_C B \arrow[rr] \arrow[dd] \arrow[dr, phantom, very near start, "\lrcorner"] & & B \arrow[dd, "g" near start] \arrow[dr, "\psi"] & \\ & A' \times_{C'} B' \arrow[rr] \arrow[dd] \arrow[dr, phantom, very near start, "\lrcorner"] & & B' \arrow[dd, "g'"] \\ A \arrow[rr, "f" near start] \arrow[dr, "\phi"'] & & C \arrow[dr, "\chi"] & \\ & A' \arrow[rr, "f'"'] & & C' \end{tikzcd}$$

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

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

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

$$\begin{tikzcd}
A \times_C B \arrow[rr] \arrow[dd] \arrow[dr, dashed] \arrow[dr, phantom, very near start, "\lrcorner"] & & B \arrow[dd, "g"] \arrow[dr, "\psi"] & \\
& A' \times_{C'} B' \arrow[rr] \arrow[dd] \arrow[d, phantom, very near start, "\lrcorner"] & & B' \arrow[dd, "g'"] \\
A \arrow[rr, "f"] \arrow[dr, "\phi"'] & & C \arrow[dr, "\chi"] & \\
& A' \arrow[rr, "f'"'] & & C'
\end{tikzcd}$$

commute.

2. *Adjointness I.* We have adjunctions

$$\left(A \times_X - \dashv \mathbf{Sets}_{/X}(A, -)\right) : \quad \begin{tikzcd} \mathsf{Sets}_{/X} \arrow[r, bend left, "A\times_X -"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}_{/X}, \arrow[l, bend left, "\mathbf{Sets}_{/X}(A,-)"] \end{tikzcd}$$

$$\left(- \times_X B \dashv \mathbf{Sets}_{/X}(B, -)\right) : \quad \begin{tikzcd} \mathsf{Sets}_{/X} \arrow[r, bend left, "-\times_X B"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}_{/X}, \arrow[l, bend left, "\mathbf{Sets}_{/X}(B,-)"] \end{tikzcd}$$

witnessed by bijections

$$\begin{aligned}
\mathsf{Sets}_{/X}(A \times_X B, C) &\cong \mathsf{Sets}_{/X}(A, \mathbf{Sets}_{/X}(B, C)), \\
\mathsf{Sets}_{/X}(A \times_X B, C) &\cong \mathsf{Sets}_{/X}(B, \mathbf{Sets}_{/X}(A, C)),
\end{aligned}$$

natural in $(A, \phi_A), (B, \phi_B), (C, \phi_C) \in \mathrm{Obj}(\mathsf{Sets}_{/X})$, where $\mathbf{Sets}_{/X}(A, B)$ is the object of $\mathsf{Sets}_{/X}$ consisting of (see Fibred Sets, **??**):

- *The Set.* The set $\mathbf{Sets}_{/X}(A, B)$ defined by

$$\mathbf{Sets}_{/X}(A, B) \stackrel{\text{def}}{=} \coprod_{x \in X} \mathsf{Sets}(\phi_A^{-1}(x), \phi_Y^{-1}(x))$$

- *The Map to X.* The map

$$\phi_{\mathbf{Sets}_{/X}(A,B)}\colon \mathbf{Sets}_{/X}(A,B) \to X$$

defined by

$$\phi_{\mathbf{Sets}_{/X}(A,B)}(x,f) \overset{\text{def}}{=} x$$

for each $(x,f) \in \mathbf{Sets}_{/X}(A,B)$.

3. *Adjointness II.* We have an adjunction

$$\left(\Delta_{\mathsf{Sets}_{/X}} \dashv -_1 \times -_2\right)\colon \quad \begin{tikzcd} \mathsf{Sets}_{/X} \arrow[r, bend left, "\Delta_{\mathsf{Sets}_{/X}}"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}_{/X} \times \mathsf{Sets}_{/X}, \arrow[l, bend left, "-_1\times-_2"] \end{tikzcd}$$

witnessed by a bijection

$$\mathrm{Hom}_{\mathsf{Sets}_{/X}\times\mathsf{Sets}_{/X}}((A,A),(B,C)) \cong \mathsf{Sets}_{/X}(A, B\times_X C),$$

natural in $A \in \mathrm{Obj}(\mathsf{Sets}_{/X})$ and in $(B,C) \in \mathrm{Obj}(\mathsf{Sets}_{/X} \times \mathsf{Sets}_{/X})$.

4. *Associativity.* Given a diagram

$$\begin{tikzcd} A \arrow[dr, "f"'] & & B \arrow[dl, "g"] \arrow[dr, "h"'] & & C \arrow[dl, "k"] \\ & X & & Y & \end{tikzcd}$$

in Sets, we have isomorphisms of sets

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

where these pullbacks are built as in the diagrams

$$\begin{tikzcd} & & (A \times_X B) \times_Y C \arrow[dl] \arrow[ddrr] \arrow[d, phantom, "\lrcorner" rotate=-45] & & \\ & A \times_X B \arrow[dl] \arrow[dr] \arrow[d, phantom, "\lrcorner" rotate=-45] & {} & & \\ A \arrow[dr, "f"'] & {} & B \arrow[dl, "g"] \arrow[dr, "h"'] & & C, \arrow[dl, "k"] \\ & X & & Y & \end{tikzcd}$$

$$\begin{tikzcd} & & (A \times_X B) \times_B (B \times_Y C) \arrow[dl] \arrow[dr] \arrow[d, phantom, "\lrcorner" rotate=-45] & & \\ & A \times_X B \arrow[dl] \arrow[dr] \arrow[d, phantom, "\lrcorner" rotate=-45] & {} & B \times_Y C \arrow[dl] \arrow[dr] \arrow[d, phantom, "\lrcorner" rotate=-45] & \\ A \arrow[dr, "f"'] & {} & B \arrow[dl, "g"] \arrow[dr, "h"'] & {} & C, \arrow[dl, "k"] \\ & X & & Y & \end{tikzcd}$$

$$\begin{tikzcd} & & & A \times_X (B \times_Y C) \arrow[ddll] \arrow[dr] \arrow[d, phantom, "\lrcorner" rotate=-45] & \\ & & & {} & B \times_Y C \arrow[dl] \arrow[dr] \arrow[d, phantom, "\lrcorner" rotate=-45] \\ & A \arrow[dr, "f"'] & & B \arrow[dl, "g"] \arrow[dr, "h"'] & {} & C. \arrow[dl, "k"] \\ & & X & & Y & \end{tikzcd}$$

5. *Interaction With Composition.* Given a diagram

$$\begin{tikzcd}
X \arrow[dr, "\phi"'] & & & & Y \arrow[dl, "\psi"] \\
& A \arrow[dr, "f"'] & & B \arrow[dl, "g"] & \\
& & K & &
\end{tikzcd}$$

in Sets, we have isomorphisms of sets

$$\begin{aligned}
X \times_K^{f\circ\phi, g\circ\psi} Y &\cong (X \times_A^{\phi,q_1} (A \times_K^{f,g} B)) \times_{A\times_K^{f,g} B}^{p_2,p_1} ((A \times_K^{f,g} B) \times_B^{q_2,\psi} Y) \\
&\cong X \times_A^{\phi,p} ((A \times_K^{f,g} B) \times_B^{q_2,\psi} Y) \\
&\cong (X \times_A^{\phi,q_1} (A \times_K^{f,g} B)) \times_B^{q,\psi} Y
\end{aligned}$$

where

$$q_1 = \mathrm{pr}_1^{A\times_K^{f,g} B}, \qquad q_2 = \mathrm{pr}_2^{A\times_K^{f,g} B},$$

$$p_1 = \mathrm{pr}_1^{(A\times_K^{f,g} B)\times_Y^{q_2,\psi}}, \qquad p_2 = \mathrm{pr}_2^{X\times^{\phi,q_1}_{A\times_K^{f,g} B}(A\times_K^{f,g} B)},$$

$$p = q_1 \circ \mathrm{pr}_1^{(A\times_K^{f,g} B)\times_B^{q_2,\psi} Y}, \qquad q = q_2 \circ \mathrm{pr}_2^{X\times_A^{\phi,q_1}(A\times_K^{f,g} B)},$$

and where these pullbacks are built as in the following diagrams:

$$\begin{tikzcd}[column sep=tiny]
& & (X \times_A (A \times_K B)) \times_{A\times_K B} ((A \times_K B) \times_B Y) \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner", very near start] & & \\
& X \times_A (A \times_K B) \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner", very near start] & & (A \times_K B) \times_B Y \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner", very near start] & \\
X \arrow[dr, "\phi"'] & & A \times_K B \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner", very near start] & & Y, \arrow[dl, "\psi"] \\
& A \arrow[dr, "f"'] & & B \arrow[dl, "g"] & \\
& & K & &
\end{tikzcd}
\qquad
\begin{tikzcd}[column sep=tiny]
& & X \times_A ((A \times_K B) \times_B Y) \arrow[ddll] \arrow[dr] \arrow[dd, phantom, "\lrcorner", very near start] & & \\
& & & (A \times_K B) \times_B Y \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner", very near start] & \\
X \arrow[dr, "\phi"'] & & A \times_K B \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner", very near start] & & Y, \arrow[dl, "\psi"] \\
& A \arrow[dr, "f"'] & & B \arrow[dl, "g"] & \\
& & K & &
\end{tikzcd}$$

$$
\begin{tikzcd}[column sep=small]
 & & (X \times_A (A \times_K B)) \times_B Y \arrow[dl] \arrow[ddrr] \arrow[dd, phantom, "\lrcorner"{rotate=-45}, very near start] & & \\
 & X \times_A (A \times_K B) \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner"{rotate=-45}, very near start] & & & \\
X \arrow[dr, "\phi"'] & & A \times_K B \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner"{rotate=-45}, very near start] & & Y, \arrow[dl, "\psi"] \\
 & A \arrow[dr, "f"'] & & B \arrow[dl, "g"] & \\
 & & K & &
\end{tikzcd}
\qquad
\begin{tikzcd}[column sep=small]
 & & X \times_K Y \arrow[ddll] \arrow[ddrr] \arrow[dd, phantom, "\lrcorner"{rotate=-45}, very near start] & & \\
 & & & & \\
X \arrow[dr, "\phi"'] & & & & Y. \arrow[dl, "\psi"] \\
 & A \arrow[dr, "f"'] & & B \arrow[dl, "g"] & \\
 & & K & &
\end{tikzcd}
$$

6. *Unitality.* We have isomorphisms of sets

$$
\begin{tikzcd}
A \arrow[r, equal] \arrow[d, "f"'] \arrow[dr, phantom, "\lrcorner", very near start] & A \arrow[d, "f"] \\
X \arrow[r, equal] & X
\end{tikzcd}
\qquad
\begin{aligned}
\lambda^{\mathsf{Sets}/X}_A &\colon X \times_X A \overset{\sim}{\dashrightarrow} A, \\
\rho^{\mathsf{Sets}/X}_A &\colon A \times_X X \overset{\sim}{\dashrightarrow} A,
\end{aligned}
\qquad
\begin{tikzcd}
A \arrow[r, "f"] \arrow[d, equal] \arrow[dr, phantom, "\lrcorner", very near start] & X \arrow[d, equal] \\
X \arrow[r, "f"'] & X,
\end{tikzcd}
$$

natural in $(A, f) \in \mathrm{Obj}(\mathsf{Sets}_{/X})$.

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

$$
\begin{tikzcd}
A \times_X B \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & B \arrow[d, "g"] \\
A \arrow[r, "f"'] & X,
\end{tikzcd}
\qquad
\sigma^{\mathsf{Sets}/X}_{A,B} \colon A \times_X B \overset{\sim}{\dashrightarrow} B \times_X A
\qquad
\begin{tikzcd}
B \times_X A \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & A \arrow[d, "f"] \\
B \arrow[r, "g"'] & X,
\end{tikzcd}
$$

natural in $(A, f), (B, g) \in \mathrm{Obj}(\mathsf{Sets}_{/X})$.

8. *Distributivity Over Coproducts.* Let A, B, and C be sets and let $\phi_A \colon A \to X$, $\phi_B \colon B \to X$, and $\phi_C \colon C \to X$ be morphisms of sets. We have isomorphisms of sets

$$
\begin{aligned}
\delta^{\mathsf{Sets}/X}_\ell &\colon A \times_X (B \textstyle\coprod C) \overset{\sim}{\dashrightarrow} (A \times_X B) \textstyle\coprod (A \times_X C), \\
\delta^{\mathsf{Sets}/X}_r &\colon (A \textstyle\coprod B) \times_X C \overset{\sim}{\dashrightarrow} (A \times_X C) \textstyle\coprod (B \times_X C),
\end{aligned}
$$

as in the diagrams

$$
\begin{tikzcd}
(A \times_X B) \coprod (A \times_X C) \arrow[r, two heads] \arrow[d, two heads] \arrow[dr, phantom, "\lrcorner", very near start] & B \coprod C \arrow[d, "\phi_B \coprod \phi_C"] \\
A \arrow[r, "\phi_A"'] & X
\end{tikzcd}
\qquad
\begin{tikzcd}
(A \times_X C) \coprod (B \times_X C) \arrow[r, two heads] \arrow[d, two heads] \arrow[dr, phantom, "\lrcorner", very near start] & C \arrow[d, "\phi_C"] \\
A \coprod B \arrow[r, "\phi_A \coprod \phi_B"'] & X
\end{tikzcd}
$$

natural in $A, B, C \in \mathrm{Obj}(\mathsf{Sets}_{/X})$.

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

$$
\begin{tikzcd}
\emptyset \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & \emptyset \arrow[d] \\
A \arrow[r, "f"'] & X,
\end{tikzcd}
\qquad
\begin{aligned}
\zeta^{\mathsf{Sets}_{/X}}_{\ell} &\colon A \times_X \emptyset \overset{\sim}{\dashrightarrow} \emptyset, \\
\zeta^{\mathsf{Sets}_{/X}}_{r} &\colon \emptyset \times_X A \overset{\sim}{\dashrightarrow} \emptyset,
\end{aligned}
\qquad
\begin{tikzcd}
\emptyset \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & A \arrow[d, "f"] \\
\emptyset \arrow[r] & X,
\end{tikzcd}
$$

natural in $(A, f) \in \mathrm{Obj}(\mathsf{Sets}_{/X})$.

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

$$
A \times_{\mathrm{pt}} B \cong A \times B,
\qquad
\begin{tikzcd}
A \times B \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & B \arrow[d, "!_B"] \\
A \arrow[r, "!_A"'] & \mathrm{pt}.
\end{tikzcd}
$$

11. *Symmetric Monoidality.* The 8-tuple $\left(\mathsf{Sets}_{/X}, \times_X, X, \mathbf{Sets}_{/X}, \alpha^{\mathsf{Sets}_{/X}}, \lambda^{\mathsf{Sets}_{/X}}, \rho^{\mathsf{Sets}_{/X}}, \sigma^{\mathsf{Sets}_{/X}}\right)$ is a symmetric closed monoidal category.

PROOF 4.1.4.1.8 ► PROOF OF PROPOSITION 4.1.4.1.7

Item 1: Functoriality

This is a special case of functoriality of co/limits, Limits and Colimits, **??**

of **??**, with the explicit expression for ξ following from the commutativity of the cube pullback diagram.

Item 2: Adjointness I

This is a repetition of Fibred Sets, **??** of **??**, and is proved there.

Item 3: Adjointness II

This follows from the universal property of the product (pullbacks are products in $\mathsf{Sets}_{/X}$).

Item 4: Associativity

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

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

where we have used Item 6 for the isomorphism $B \times_B B \cong B$.

Item 5: Interaction With Composition

By Item 4, it suffices to construct only the isomorphism

$$X \times_K^{f \circ \phi, g \circ \psi} Y \cong (X \times_A^{\phi, q_1} (A \times_K^{f,g} B)) \times_{A \times_K^{f,g} B}^{p_2, p_1} ((A \times_K^{f,g} B) \times_B^{q_2, \psi} Y).$$

We have

$$\begin{aligned}(X \times^{\phi,q_1}_{A} (A \times^{f,g}_{K} B)) &\overset{\text{def}}{=} \left\{(x,(a,b)) \in X \times (A \times^{f,g}_{K} B) \,\middle|\, \phi(x) = q_1(a,b)\right\}\\ &\overset{\text{def}}{=} \left\{(x,(a,b)) \in X \times (A \times^{f,g}_{K} B) \,\middle|\, \phi(x) = a\right\}\\ &\cong \{(x,(a,b)) \in X \times (A \times B) \mid \phi(x) = a \text{ and } f(a) = g(b)\},\\ ((A \times^{f,g}_{K} B) \times^{q_2,\psi}_{B} Y) &\overset{\text{def}}{=} \left\{((a,b),y) \in (A \times^{f,g}_{K} B) \times Y \,\middle|\, q_2(a,b) = \psi(y)\right\}\\ &\overset{\text{def}}{=} \left\{((a,b),y) \in (A \times^{f,g}_{K} B) \times Y \,\middle|\, b = \psi(y)\right\}\\ &\cong \{((a,b),y) \in (A \times B) \times Y \mid b = \psi(y) \text{ and } f(a) = g(b)\},\end{aligned}$$

so writing

$$\begin{aligned}S &= (X \times^{\phi,q_1}_{A} (A \times^{f,g}_{K} B))\\ S' &= ((A \times^{f,g}_{K} B) \times^{q_2,\psi}_{B} Y),\end{aligned}$$

we have

$$\begin{aligned}S \times^{p_2,p_1}_{A \times^{f,g}_{K} B} S' &\overset{\text{def}}{=} \{((x,(a,b)),((a',b'),y)) \in S \times S' \mid p_1(x,(a,b)) = p_2((a',b'),y)\}\\ &\overset{\text{def}}{=} \{((x,(a,b)),((a',b'),y)) \in S \times S' \mid (a,b) = (a',b')\}\\ &\cong \{((x,a,b,y)) \in X \times A \times B \times Y \mid \phi(x) = a, \psi(y) = b, \text{ and } f(a) = g(b)\}\\ &\cong \{((x,a,b,y)) \in X \times A \times B \times Y \mid f(\phi(x)) = g(\psi(y))\}\\ &\overset{\text{def}}{=} X \times_K Y.\end{aligned}$$

This finishes the proof.

Item 6: Unitality

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 $(a,x) \mapsto a$. The proof of the naturality of $\lambda^{\mathsf{Sets}/X}$ and $\rho^{\mathsf{Sets}/X}$ is omitted.

Item 7: Commutativity

We have

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

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

The proof of the naturality of $\sigma^{\mathsf{Sets}/X}$ is omitted.

Item 8: Distributivity Over Coproducts

We have

$$
\begin{aligned}
A \times_X \left(B \textstyle\coprod C\right) &\stackrel{\text{def}}{=} \left\{(a,z) \in A \times \left(B \textstyle\coprod C\right) \,\middle|\, \phi_A(a) = \phi_{B\coprod C}(z)\right\} \\
&= \left\{(a,z) \in A \times \left(B \textstyle\coprod C\right) \,\middle|\, z = (0,b) \text{ and } \phi_A(a) = \phi_{B\coprod C}(z)\right\} \\
&\quad \cup \left\{(a,z) \in A \times \left(B \textstyle\coprod C\right) \,\middle|\, z = (1,c) \text{ and } \phi_A(a) = \phi_{B\coprod C}(z)\right\} \\
&= \{(a,z) \in A \times (B \textstyle\coprod C) \mid z = (0,b) \text{ and } \phi_A(a) = \phi_B(b)\} \\
&\quad \cup \{(a,z) \in A \times (B \textstyle\coprod C) \mid z = (1,c) \text{ and } \phi_A(a) = \phi_C(c)\} \\
&\cong \{(a,b) \in A \times B \mid \phi_A(a) = \phi_B(b)\} \\
&\quad \cup \{(a,c) \in A \times C \mid \phi_A(a) = \phi_C(c)\} \\
&\stackrel{\text{def}}{=} (A \times_X B) \cup (A \times_X C) \\
&\cong (A \times_X B) \textstyle\coprod (A \times_X C),
\end{aligned}
$$

with the construction of the isomorphism

$$
\delta_r^{\mathsf{Sets}/X} \colon \left(A \textstyle\coprod B\right) \times_X C \stackrel{\sim}{\dashrightarrow} (A \times_X C) \textstyle\coprod (B \times_X C)
$$

being similar. The proof of the naturality of $\delta_\ell^{\mathsf{Sets}/X}$ and $\delta_r^{\mathsf{Sets}/X}$ is omitted.

Item 9: Annihilation With the Empty Set

We have

$$
\begin{aligned}
A \times_X \emptyset &\stackrel{\text{def}}{=} \{(a,b) \in A \times \emptyset \mid f(a) = g(b)\} \\
&= \{k \in \emptyset \mid f(a) = g(b)\} \\
&= \emptyset,
\end{aligned}
$$

and similarly for $\emptyset \times_X A$, where we have used Item 8 of Proposition 4.1.3.1.4. The proof of the naturality of $\zeta_\ell^{\mathsf{Sets}/X}$ and $\zeta_r^{\mathsf{Sets}/X}$ is omitted.

Item 10: Interaction With Products

We have

$$\begin{aligned} A \times_{\mathrm{pt}} B &\overset{\mathrm{def}}{=} \{(a,b) \in A \times B \mid !_A(a) = !_B(b)\} \\ &\overset{\mathrm{def}}{=} \{(a,b) \in A \times B \mid \star = \star\} \\ &= \{(a,b) \in A \times B\} \\ &= A \times B. \end{aligned}$$

Item 11: Symmetric Monoidality

Omitted.

4.1.5 Equalisers

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

Definition 4.1.5.1.1 ▶ Equalisers of Sets

The **equaliser of f and g** is the equaliser of f and g in Sets as in Limits and Colimits, **??**.

Construction 4.1.5.1.2 ▶ Construction of Equalisers of Sets

Concretely, the equaliser of f and g is the pair $(\mathrm{Eq}(f,g), \mathrm{eq}(f,g))$ consisting of:

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

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

2. *The Cone.* The inclusion map

$$\mathrm{eq}(f,g) \colon \mathrm{Eq}(f,g) \hookrightarrow A.$$

Proof 4.1.5.1.3 ▶ Proof of Construction 4.1.5.1.2

We claim that $\mathrm{Eq}(f,g)$ 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

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

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

$$\begin{tikzcd} \mathrm{Eq}(f,g) \arrow[r, hook, "\mathrm{eq}(f,g)"] & A \arrow[r, shift left, "f"] \arrow[r, shift right, "g"'] & B \\ E \arrow[ur, "e"'] & & \end{tikzcd}$$

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

$$\begin{tikzcd} \mathrm{Eq}(f,g) \arrow[r, hook, "\mathrm{eq}(f,g)"] & A \arrow[r, shift left, "f"] \arrow[r, shift right, "g"'] & B \\ E \arrow[u, dashed, "\phi", "\exists!"'] \arrow[ur, "e"'] & & \end{tikzcd}$$

commute, being uniquely determined by the condition

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

via

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

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

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

which gives

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

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

Proposition 4.1.5.1.4 ► Properties of Equalisers of Sets

Let A, B, and C be sets.

1. *Associativity.* We have isomorphisms of sets[1]

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

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

$$A \overset{f}{\underset{h}{\overset{\xrightarrow{\quad g \quad}}{\rightrightarrows}}} B$$

in Sets, being explicitly given by

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

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

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

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

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

4. *Interaction With Composition.* Let

$$A \underset{g}{\overset{f}{\rightrightarrows}} B \underset{k}{\overset{h}{\rightrightarrows}} C$$

be functions. We have an inclusion of sets

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

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

$$\mathrm{Eq}(f,g) \overset{\mathrm{eq}(f,g)}{\hookrightarrow} A \underset{g}{\overset{f}{\rightrightarrows}} B \underset{k}{\overset{h}{\rightrightarrows}} C.$$

[1]That is, the following three ways of forming "the" equaliser of (f, g, h) agree:

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

$$A \underset{h}{\overset{f}{\underset{\xrightarrow{\;g\;}}{\rightrightarrows}}} B$$

in Sets.

(b) First take the equaliser of f and g, forming a diagram

$$\mathrm{Eq}(f, g) \overset{\mathrm{eq}(f,g)}{\hookrightarrow} A \underset{g}{\overset{f}{\rightrightarrows}} B$$

and then take the equaliser of the composition

$$\mathrm{Eq}(f, g) \overset{\mathrm{eq}(f,g)}{\hookrightarrow} A \underset{h}{\overset{f}{\rightrightarrows}} B,$$

obtaining a subset

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

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

(c) First take the equaliser of g and h, forming a diagram

$$\mathrm{Eq}(g, h) \overset{\mathrm{eq}(g,h)}{\hookrightarrow} A \underset{h}{\overset{g}{\rightrightarrows}} B$$

and then take the equaliser of the composition

$$\mathrm{Eq}(g, h) \overset{\mathrm{eq}(g,h)}{\hookrightarrow} A \underset{g}{\overset{f}{\rightrightarrows}} B,$$

obtaining a subset

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

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

Proof 4.1.5.1.5 ► **Proof of Proposition 4.1.5.1.4**

Item 1: Associativity

We first prove that $\mathrm{Eq}(f,g,h)$ is indeed given by

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

Indeed, suppose we have a diagram of the form

$$\begin{tikzcd} \mathrm{Eq}(f,g,h) \arrow[r, hook, "\mathrm{eq}(f,g,h)"] & A \arrow[r, shift left=2, "f"] \arrow[r, "g" description] \arrow[r, shift right=2, "h"'] & B \\ E \arrow[ur, "e"'] & & \end{tikzcd}$$

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

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

being necessarily given by

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

for each $x \in E$, where we note that $e(x) \in A$ indeed lies in $\mathrm{Eq}(f,g,h)$ 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 $e(x) \in \mathrm{Eq}(f,g,h)$.
We now check the equalities

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

Indeed, we have

$$\mathrm{Eq}(f \circ \mathrm{eq}(g,h), g \circ \mathrm{eq}(g,h)) \cong \{x \in \mathrm{Eq}(g,h) \mid [f \circ \mathrm{eq}(g,h)](a) = [g \circ \mathrm{eq}(g,h)](a)\}$$

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

Similarly, we have

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

Item 2: Unitality

Indeed, we have

$$\begin{aligned}
\mathrm{Eq}(f,f) &\overset{\text{def}}{=} \{a \in A \mid f(a) = f(a)\}\\
&= A.
\end{aligned}$$

Item 3: Commutativity

Indeed, we have

$$\begin{aligned}
\mathrm{Eq}(f,g) &\overset{\text{def}}{=} \{a \in A \mid f(a) = g(a)\}\\
&= \{a \in A \mid g(a) = f(a)\}\\
&\overset{\text{def}}{=} \mathrm{Eq}(g,f).
\end{aligned}$$

Item 4: Interaction With Composition

Indeed, we have

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

and

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

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

4.1.6 Inverse Limits

Let $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I} \colon (I, \preceq) \to \mathsf{Sets}$ be an inverse system of sets.

Definition 4.1.6.1.1 ► Inverse Limits of Sets

The **inverse limit of** $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$ is the inverse limit of $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$ in Sets as in Limits and Colimits, **??**.

Construction 4.1.6.1.2 ► Construction of Inverse Limits of Sets

Concretely, the inverse limit of $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$ is the pair $\left(\varprojlim_{\alpha\in I}(X_\alpha), \{\mathrm{pr}_\alpha\}_{\alpha\in I}\right)$ consisting of:

1. *The Limit.* The set $\varprojlim_{\alpha\in I}(X_\alpha)$ defined by
$$\varprojlim_{\alpha\in I}(X_\alpha) \stackrel{\text{def}}{=} \left\{ (x_\alpha)_{\alpha\in I} \in \prod_{\alpha\in I} X_\alpha \;\middle|\; \begin{array}{l}\text{for each } \alpha,\beta\in I, \text{ if } \alpha\preceq\beta,\\ \text{then we have } x_\alpha = f_{\alpha\beta}(x_\beta)\end{array} \right\}.$$

2. *The Cone.* The collection
$$\left\{ \mathrm{pr}_\gamma \colon \varprojlim_{\alpha\in I}(X_\alpha) \to X_\gamma \right\}_{\gamma\in I}$$
of maps of sets defined as the restriction of the maps
$$\left\{ \mathrm{pr}_\gamma \colon \prod_{\alpha\in I} X_\alpha \to X_\gamma \right\}_{\gamma\in I}$$
of Item 2 of Construction 4.1.2.1.2 to $\varprojlim_{\alpha\in I}(X_\alpha)$ and hence given by
$$\mathrm{pr}_\gamma((x_\alpha)_{\alpha\in I}) \stackrel{\text{def}}{=} x_\gamma$$
for each $\gamma\in I$ and each $(x_\alpha)_{\alpha\in I} \in \varprojlim_{\alpha\in I}(X_\alpha)$.

PROOF 4.1.6.1.3 ► PROOF OF CONSTRUCTION 4.1.6.1.2

We claim that $\lim_{\longleftarrow \alpha\in I}(X_\alpha)$ is the limit of the inverse system of sets $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$. First we need to check that the limit diagram defined by it commutes, i.e. that we have

$$f_{\alpha\beta}\circ \mathrm{pr}_\alpha = \mathrm{pr}_\beta, \qquad \begin{tikzcd} & \lim\limits_{\substack{\longleftarrow \\ \alpha\in I}}(X_\alpha) \arrow[dl, "\mathrm{pr}_\alpha"'] \arrow[dr, "\mathrm{pr}_\beta"] & \\ X_\alpha \arrow[rr, "f_{\alpha\beta}"'] & & X_\beta \end{tikzcd}$$

for each $\alpha, \beta \in I$ with $\alpha \preceq \beta$. Indeed, given $(x_\gamma)_{\gamma\in I} \in \lim_{\longleftarrow \gamma\in I}(X_\gamma)$, we have

$$\begin{aligned} [f_{\alpha\beta}\circ \mathrm{pr}_\alpha]((x_\gamma)_{\gamma\in I}) &\overset{\text{def}}{=} f_{\alpha\beta}(\mathrm{pr}_\alpha((x_\gamma)_{\gamma\in I})) \\ &\overset{\text{def}}{=} f_{\alpha\beta}(x_\alpha) \\ &= x_\beta \\ &\overset{\text{def}}{=} \mathrm{pr}_\beta((x_\gamma)_{\gamma\in I}), \end{aligned}$$

where the third equality comes from the definition of $\lim_{\longleftarrow \alpha\in I}(X_\alpha)$. Next, we prove that $\lim_{\longleftarrow \alpha\in I}(X_\alpha)$ satisfies the universal property of an inverse limit. Suppose that we have, for each $\alpha, \beta \in I$ with $\alpha \preceq \beta$, a diagram of the form

$$\begin{tikzcd} & L \arrow[ddl, bend right, "p_\alpha"'] \arrow[ddr, bend left, "p_\beta"] \arrow[d, dashed] & \\ & \lim\limits_{\substack{\longleftarrow \\ \alpha\in I}}(X_\alpha) \arrow[dl, "\mathrm{pr}_\alpha"'] \arrow[dr, "\mathrm{pr}_\beta"] & \\ X_\alpha \arrow[rr, "f_{\alpha\beta}"'] & & X_\beta \end{tikzcd}$$

in Sets. Then there indeed exists a unique map $\phi \colon L \xrightarrow{\exists!} \varprojlim_{\alpha\in I}(X_\alpha)$ making the diagram

$$\begin{tikzcd}
 & L \arrow[dl, bend right, "p_\alpha"'] \arrow[d, dashed, "\phi", "\exists!"'] \arrow[dr, bend left, "p_\beta"] & \\
 & \varprojlim_{\alpha\in I}(X_\alpha) \arrow[dl, "\mathrm{pr}_\alpha"] \arrow[dr, "\mathrm{pr}_\beta"'] & \\
X_\alpha \arrow[rr, "f_{\alpha\beta}"'] & & X_\beta
\end{tikzcd}$$

commute, being uniquely determined by the family of conditions

$$\left\{p_\alpha = \mathrm{pr}_\alpha \circ \phi\right\}_{\alpha\in I}$$

via

$$\phi(\ell) = (p_\alpha(\ell))_{\alpha\in I}$$

for each $\ell \in L$, where we note that $(p_\alpha(\ell))_{\alpha\in I} \in \prod_{\alpha\in I} X_\alpha$ indeed lies in $\varprojlim_{\alpha\in I}(X_\alpha)$, as we have

$$\begin{aligned} f_{\alpha\beta}(p_\alpha(\ell)) &\overset{\text{def}}{=} [f_{\alpha\beta} \circ p_\alpha](\ell) \\ &\overset{\text{def}}{=} p_\beta(\ell) \end{aligned}$$

for each $\beta \in I$ with $\alpha \preceq \beta$ by the commutativity of the diagram for $(L, \{p_\alpha\}_{\alpha\in I})$.

Example 4.1.6.1.4 ► Examples of Inverse Limits of Sets

Here are some examples of inverse limits of sets.

1. *The p-Adic Integers.* The ring of p-adic integers $\mathbb{Z}_p$ of **??** is the inverse limit

$$\mathbb{Z}_p \cong \varprojlim_{n\in\mathbb{N}}(\mathbb{Z}_{/p^n});$$

see **??**.

2. *Rings of Formal Power Series.* The ring $R[\![t]\!]$ of formal power series in a variable t is the inverse limit

$$R[\![t]\!] \cong \lim_{\substack{\longleftarrow \\ n\in\mathbb{N}}} (R[t]/t^n R[t]);$$

see **??**.

3. *Profinite Groups.* Profinite groups are inverse limits of finite groups; see **??**.

4.2 Colimits of Sets

4.2.1 The Initial Set

Definition 4.2.1.1.1 ▶ The Initial Set

The **initial set** is the initial object of Sets as in Limits and Colimits, **??**.

Construction 4.2.1.1.2 ▶ Construction of the Initial Set

Concretely, the initial set is the pair $(\emptyset, \{\iota_A\}_{A\in\mathrm{Obj}(\mathsf{Sets})})$ consisting of:

1. *The Colimit.* The empty set $\emptyset$ of Definition 4.3.1.1.1.
2. *The Cocone.* The collection of maps

$$\{\iota_A : \emptyset \to A\}_{A\in\mathrm{Obj}(\mathsf{Sets})}$$

given by the inclusion maps from $\emptyset$ to A.

Proof 4.2.1.1.3 ▶ Proof of Construction 4.2.1.1.2

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

$$\emptyset \qquad A$$

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

$$\emptyset \overset{\phi}{\underset{\exists!}{\dashrightarrow}} A$$

commute, namely the inclusion map ι_A.

4.2.2 Coproducts of Families of Sets

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

Definition 4.2.2.1.1 ► The Coproduct of a Family of Sets

The **coproduct of** $\{A_i\}_{i\in I}$[1] is the coproduct of $\{A_i\}_{i\in I}$ in Sets as in Limits and Colimits, **??**.

[1] *Further Terminology:* Also called the **disjoint union of the family** $\{A_i\}_{i\in I}$.

Construction 4.2.2.1.2 ► Construction of the Coproduct of a Family of Sets

Concretely, the disjoint union of $\{A_i\}_{i\in I}$ is the pair $(\coprod_{i\in I} A_i, \{\mathrm{inj}_i\}_{i\in I})$ consisting of:

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

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

2. *The Cocone.* The collection

$$\left\{ \mathrm{inj}_i \colon A_i \to \coprod_{i\in I} A_i \right\}_{i\in I}$$

of maps given by

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

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

Proof 4.2.2.1.3 ▶ Proof of Construction 4.2.2.1.2

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

$$\begin{tikzcd} & C \\ A_i \arrow[ur, "\iota_i"] \arrow[r, "\mathrm{inj}_i"'] & \coprod_{i\in I} A_i \end{tikzcd}$$

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

$$\begin{tikzcd} & C \\ A_i \arrow[ur, "\iota_i"] \arrow[r, "\mathrm{inj}_i"'] & \coprod_{i\in I} A_i \arrow[u, dashed, "\phi", "\exists!"'] \end{tikzcd}$$

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

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

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

Proposition 4.2.2.1.4 ▶ Properties of Coproducts of Families of Sets

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

$$\coprod_{i\in I}\colon \mathsf{Fun}(I_{\mathrm{disc}}, \mathsf{Sets}) \longrightarrow \mathsf{Sets}$$

where

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

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

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

$$\left(\coprod_{i\in I}\right)_{(A_i)_{i\in I},(B_i)_{i\in I}} : \mathrm{Nat}((A_i)_{i\in I}, (B_i)_{i\in I}) \to \mathsf{Sets}\left(\coprod_{i\in I} A_i, \coprod_{i\in I} B_i\right)$$

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

$$\{f_i \colon A_i \to B_i\}_{i\in I}$$

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

$$\coprod_{i\in I} f_i \colon \coprod_{i\in I} A_i \to \coprod_{i\in I} B_i$$

defined by

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

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

Proof 4.2.2.1.5 ► Proof of Proposition 4.2.2.1.4

Item 1: Functoriality

This follows from Limits and Colimits, **??** of **??**.

4.2.3 Binary Coproducts

Let A and B be sets.

Definition 4.2.3.1.1 ► Coproducts of Sets

The **coproduct of** A **and** B[1] is the coproduct of A and B in Sets as in Limits and Colimits, **??**.

[1] *Further Terminology:* Also called the **disjoint union of** A **and** B.

Construction 4.2.3.1.2 ► Construction of Coproducts of Sets

Concretely, the coproduct of A and B is the pair $(A \coprod B, \{\mathrm{inj}_1, \mathrm{inj}_2\})$ consisting of:

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

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

   where $S = \{0,1\} \times (A \cup B)$.

2. *The Cocone.* The maps

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

   given by

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

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

Proof 4.2.3.1.3 ▶ Proof of Construction 4.2.3.1.2

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

$$\begin{tikzcd} & C & \\ A \arrow[ur, bend left, "\iota_1"] \arrow[r, hook, "\mathrm{inj}_1"'] & A \coprod B & B \arrow[ul, bend right, "\iota_2"'] \arrow[l, hook', "\mathrm{inj}_2"] \end{tikzcd}$$

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

$$\begin{tikzcd} & C & \\ A \arrow[ur, bend left, "\iota_1"] \arrow[r, hook, "\mathrm{inj}_1"'] & A \coprod B \arrow[u, dashed, "\phi", "\exists!"'] & B \arrow[ul, bend right, "\iota_2"'] \arrow[l, hook', "\mathrm{inj}_2"] \end{tikzcd}$$

commute, being uniquely determined by the conditions

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

via

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

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

Proposition 4.2.3.1.4 ▶ Properties of Coproducts of Sets

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

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

$$\begin{aligned} A \coprod - \colon &\quad \mathsf{Sets} &\to \mathsf{Sets}, \\ - \coprod B \colon &\quad \mathsf{Sets} &\to \mathsf{Sets}, \\ -_1 \coprod -_2 \colon &\quad \mathsf{Sets} \times \mathsf{Sets} &\to \mathsf{Sets}, \end{aligned}$$

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

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

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

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

$$\coprod_{(A,B),(X,Y)} \colon \mathsf{Sets}(A, X) \times \mathsf{Sets}(B, Y) \longrightarrow \mathsf{Sets}(A \coprod B, X \coprod Y)$$

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

$$f \coprod g \colon A \coprod B \to X \coprod Y$$

defined by

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

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

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

2. *Adjointness.* We have an adjunction

$$(-_1 \coprod -_2 \dashv \Delta_{\mathsf{Sets}}) \colon \quad \begin{tikzcd} \mathsf{Sets} \times \mathsf{Sets} \arrow[r, bend left, "-_1 \coprod -_2"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}, \arrow[l, bend left, "\Delta_{\mathsf{Sets}}"] \end{tikzcd}$$

witnessed by a bijection

$$\mathsf{Sets}(A \coprod B, C), \cong \mathrm{Hom}_{\mathsf{Sets} \times \mathsf{Sets}}((A, B), (C, C))$$

natural in $(A, B) \in \mathrm{Obj}(\mathsf{Sets} \times \mathsf{Sets})$ and in $C \in \mathrm{Obj}(\mathsf{Sets})$.

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

$$\alpha^{\mathsf{Sets}, \coprod}_{X,Y,Z} \colon (X \coprod Y) \coprod Z \overset{\sim}{\dashrightarrow} X \coprod (Y \coprod Z),$$

natural in $X, Y, Z \in \mathrm{Obj}(\mathsf{Sets})$.

4. *Unitality.* We have isomorphisms of sets

$$\lambda_X^{\mathsf{Sets},\coprod} \colon \emptyset \coprod X \xrightarrow{\sim} X,$$
$$\rho_X^{\mathsf{Sets},\coprod} \colon X \coprod \emptyset \xrightarrow{\sim} X,$$

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

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

$$\sigma_{X,Y}^{\mathsf{Sets},\coprod} \colon X \coprod Y \xrightarrow{\sim} Y \coprod X,$$

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

6. *Symmetric Monoidality.* The 7-tuple $(\mathsf{Sets}, \coprod, \emptyset, \alpha^{\mathsf{Sets}}_{\coprod}, \lambda^{\mathsf{Sets}}_{\coprod}, \rho^{\mathsf{Sets}}_{\coprod}, \sigma^{\mathsf{Sets}})$ is a symmetric monoidal category.

PROOF 4.2.3.1.5 ▶ PROOF OF PROPOSITION 4.2.3.1.4

Item 1: Functoriality

This follows from Limits and Colimits, **??** of **??**.

Item 2: Adjointness

This follows from the universal property of the coproduct.

Item 3: Associativity

This is proved in the proof of Monoidal Structures on the Category of Sets, Definition 5.2.3.1.1.

Item 4: Unitality

This is proved in the proof of Monoidal Structures on the Category of Sets, Definitions 5.2.4.1.1 and 5.2.5.1.1.

Item 5: Commutativity

This is proved in the proof of Monoidal Structures on the Category of Sets, Definition 5.2.6.1.1.

Item 6: Symmetric Monoidality

This is a repetition of Monoidal Structures on the Category of Sets, Proposition 5.2.7.1.1, and is proved there.

4.2.4 Pushouts

Let A, B, and C be sets and let $f\colon C \to A$ and $g\colon C \to B$ be functions.

Definition 4.2.4.1.1 ▶ Pushouts of Sets

The **pushout of** A **and** B **over** C **along** f **and** g[1] is the pushout of A and B over C along f and g in Sets as in Limits and Colimits, **??**.

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

Construction 4.2.4.1.2 ▶ Construction of Pushouts of Sets

Concretely, the pushout of A and B over C along f and g is the pair $(A \coprod_C B, \{\mathrm{inj}_1, \mathrm{inj}_2\})$ consisting of:

1. *The Colimit.* The set $A \coprod_C B$ defined by
$$A \coprod_C B \overset{\text{def}}{=} A \coprod B/{\sim_C},$$
where $\sim_C$ is the equivalence relation on $A \coprod B$ generated by $(0, f(c)) \sim_C (1, g(c))$.

2. *The Cocone.* The maps
$$\mathrm{inj}_1\colon A \to A \coprod_C B,$$
$$\mathrm{inj}_2\colon B \to A \coprod_C B$$
given by
$$\mathrm{inj}_1(a) \overset{\text{def}}{=} [(0, a)]$$
$$\mathrm{inj}_2(b) \overset{\text{def}}{=} [(1, b)]$$
for each $a \in A$ and each $b \in B$.

Proof 4.2.4.1.3 ► **Proof of Construction 4.2.4.1.2**

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

$$\mathrm{inj}_1 \circ f = \mathrm{inj}_2 \circ g, \qquad \begin{tikzcd} A \coprod_C B & B \arrow[l, "\mathrm{inj}_2"'] \\ A \arrow[u, "\mathrm{inj}_1"] & C. \arrow[l, "f"] \arrow[u, "g"'] \end{tikzcd}$$

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

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

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

$$\begin{tikzcd} P & & \\ & A \coprod_C B \arrow[ul, phantom] & B \arrow[l, "\mathrm{inj}_2"'] \arrow[ull, bend right, "\iota_2"'] \\ & A \arrow[u, "\mathrm{inj}_1"] \arrow[uul, bend left, "\iota_1"] & C \arrow[l, "f"] \arrow[u, "g"'] \end{tikzcd}$$

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

$$\begin{tikzcd}
P & & \\
& A \coprod_C B \arrow[ul, dashed, "\exists!", "\phi"'] \arrow[dr, phantom, "\ulcorner", very near start] & B \arrow[l, "\mathrm{inj}_2"'] \arrow[ull, bend right, "\iota_2"'] \\
& A \arrow[u, "\mathrm{inj}_1"] \arrow[uul, bend left, "\iota_1"] & C \arrow[l, "f"] \arrow[u, "g"']
\end{tikzcd}$$

commute, being uniquely determined by the conditions

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

via

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

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

1. *Case 1:* Suppose we have $x = [(0,a)] = [(0,a')]$ for some $a, a' \in A$. Then, by Remark 4.2.4.1.4, 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 4.2.4.1.4, 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 4.2.4.1.4, we have a sequence

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

In all these cases, we declare $x \sim' y$ iff there exists some $c \in C$ such that $x = (0, f(c))$ and $y = (1, g(c))$ or $x = (1, g(c))$ and $y = (0, f(c))$. Then, the equality $\iota_1 \circ f = \iota_2 \circ g$ gives

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

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

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

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. □

Remark 4.2.4.1.4 ► Unwinding Definition 4.2.4.1.1

In detail, by Conditions on Relations, Construction 10.5.2.1.2, the relation $\sim$ of Definition 4.2.4.1.1 is given by declaring $a \sim b$ iff one of the following conditions is satisfied:

1. We have $a, b \in A$ and $a = b$.
2. We have $a, b \in B$ and $a = b$.
3. There exist $x_1, \ldots, x_n \in A \coprod B$ such that $a \sim' x_1 \sim' \cdots \sim' x_n \sim'$

b, where we declare $x \sim' y$ if one of the following conditions is satisfied:

(a) There exists $c \in C$ such that $x = (0, f(c))$ and $y = (1, g(c))$.

(b) There exists $c \in C$ such that $x = (1, g(c))$ and $y = (0, f(c))$.

In other words, there exist $x_1, \ldots, x_n \in A \coprod B$ satisfying the following conditions:

(c) There exists $c_0 \in C$ satisfying one of the following conditions:

   i. We have $a = f(c_0)$ and $x_1 = g(c_0)$.

   ii. We have $a = g(c_0)$ and $x_1 = f(c_0)$.

(d) For each $1 \leq i \leq n-1$, there exists $c_i \in C$ satisfying one of the following conditions:

   i. We have $x_i = f(c_i)$ and $x_{i+1} = g(c_i)$.

   ii. We have $x_i = g(c_i)$ and $x_{i+1} = f(c_i)$.

(e) There exists $c_n \in C$ satisfying one of the following conditions:

   i. We have $x_n = f(c_n)$ and $b = g(c_n)$.

   ii. We have $x_n = g(c_n)$ and $b = f(c_n)$.

Remark 4.2.4.1.5 ► Pushouts of Sets Depend on the Maps

It is common practice to write $A \coprod_C B$ for the pushout of A and B over C along f and g, omitting the maps f and g from the notation and instead leaving them implicit, to be understood from the context.
However, the set $A \coprod_C B$ depends very much on the maps f and g, and sometimes it is necessary or useful to note this dependence explicitly. In such situations, we will write $A \coprod_{f,C,g} B$ or $A \coprod_C^{f,g} B$ for $A \coprod_C B$.

Example 4.2.4.1.6 ► Examples of Pushouts of Sets

Here are some examples of pushouts of sets.

1. *Wedge Sums of Pointed Sets.* The wedge sum of two pointed sets of Pointed Sets, Definition 6.3.3.1.1 is an example of a pushout of sets.

2. *Intersections via Unions.* Let X be a set. We have

$$A \cup B \cong A \textstyle\coprod_{A\cap B} B,$$

$$\begin{tikzcd} A \cup B \arrow[dr, phantom, "\ulcorner", very near start] & B \arrow[l, hook'] \\ A \arrow[u, hook] & A \cap B \arrow[l, hook'] \arrow[u, hook] \end{tikzcd}$$

for each $A, B \in \mathcal{P}(X)$.

Proof 4.2.4.1.7 ▶ Proof of Example 4.2.4.1.6

Item 1: Wedge Sums of Pointed Sets

This follows by definition, as the wedge sum of two pointed sets is defined as a pushout.

Item 2: Intersections via Unions

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

Proposition 4.2.4.1.8 ▶ Properties of Pushouts of Sets

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

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

$$-_1 \textstyle\coprod_{-_3} -_1 \colon \mathsf{Fun}(\mathcal{P}, \mathsf{Sets}) \longrightarrow \mathsf{Sets},$$

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

$$\begin{tikzcd} & \bullet \\ \bullet & \bullet. \arrow[l] \arrow[u] \end{tikzcd}$$

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

$$
\begin{tikzcd}
A \coprod_C B \arrow[dr, phantom, very near start, "\ulcorner"] & & B \arrow[ll] \arrow[dr, "\psi"] & \\
& A' \coprod_{C'} B' \arrow[dr, phantom, very near start, "\ulcorner"] & & B' \arrow[ll] \\
A \arrow[uu] \arrow[dr, "\phi"'] & & C \arrow[ll, "f"'] \arrow[uu, "g"] \arrow[dr, "\chi"] & \\
& A' \arrow[uu] & & C' \arrow[ll, "f'"] \arrow[uu, "g'"']
\end{tikzcd}
$$

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

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

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

$$
\begin{tikzcd}
A \coprod_C B \arrow[dr, phantom, very near start, "\ulcorner"] \arrow[dr, dashed] & & B \arrow[ll] \arrow[dr, "\psi"] & \\
& A' \coprod_{C'} B' \arrow[dr, phantom, very near start, "\ulcorner"] & & B' \arrow[ll] \\
A \arrow[uu] \arrow[dr, "\phi"'] & & C \arrow[ll, "f"'] \arrow[uu, "g"] \arrow[dr, "\chi"] & \\
& A' \arrow[uu] & & C' \arrow[ll, "f'"] \arrow[uu, "g'"']
\end{tikzcd}
$$

commute.

2. *Adjointness.* We have an adjunction

$$
\left(-_1 \coprod_X -_2 \dashv \Delta_{\mathsf{Sets}_{X/}}\right) \colon \quad
\begin{tikzcd}
\mathsf{Sets}_{X/} \times \mathsf{Sets}_{X/} \arrow[r, bend left, "-_1 \coprod_X -_2"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}_{X/}, \arrow[l, bend left, "\Delta_{\mathsf{Sets}_{X/}}"]
\end{tikzcd}
$$

witnessed by a bijection

$$\mathsf{Sets}_{X/}(A \coprod{}_X B, C), \cong \mathrm{Hom}_{\mathsf{Sets}_{X/} \times \mathsf{Sets}_{X/}}((A,B),(C,C))$$

natural in $(A, B) \in \mathrm{Obj}(\mathsf{Sets}_{X/} \times \mathsf{Sets}_{X/})$ and in $C \in \mathrm{Obj}(\mathsf{Sets}_{X/})$.

3. *Associativity.* Given a diagram

$$\begin{tikzcd}
A & & B & & C \\
& X \arrow[ul, "f"] \arrow[ur, "g"'] & & Y \arrow[ul, "h"] \arrow[ur, "k"'] &
\end{tikzcd}$$

in Sets, we have isomorphisms of sets

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

where these pullbacks are built as in the diagrams

$$\begin{tikzcd}[column sep=small]
& & (A \coprod_X B) \coprod_Y C & & \\
& A \coprod_X B \arrow[ur] \arrow[dd, phantom, "\ulcorner" very near start] & & & \\
A \arrow[ur] & & B \arrow[ul] & & C \arrow[uull] \\
& X \arrow[ul, "f"] \arrow[ur, "g"'] & & Y \arrow[ul, "h"] \arrow[ur, "k"'] &
\end{tikzcd},
\begin{tikzcd}[column sep=small]
& & (A \coprod_X B) \coprod_B (B \coprod_Y C) & & \\
& A \coprod_X B \arrow[ur] \arrow[dd, phantom, "\ulcorner" very near start] & & B \coprod_Y C \arrow[ul] \arrow[dd, phantom, "\ulcorner" very near start] & \\
A \arrow[ur] & & B \arrow[ul] \arrow[ur] & & C \arrow[ul] \\
& X \arrow[ul, "f"] \arrow[ur, "g"'] & & Y \arrow[ul, "h"] \arrow[ur, "k"'] &
\end{tikzcd},
\begin{tikzcd}[column sep=small]
& & A \coprod_X (B \coprod_Y C) & & \\
& & & B \coprod_Y C \arrow[ul] \arrow[dd, phantom, "\ulcorner" very near start] & \\
A \arrow[uurr] & & B \arrow[ur] & & C \arrow[ul] \\
& X \arrow[ul, "f"] \arrow[ur, "g"'] & & Y \arrow[ul, "h"] \arrow[ur, "k"'] &
\end{tikzcd}.$$

4. *Interaction With Composition.* Given a diagram

$$\begin{tikzcd}
X & & & & Y \\
& A \arrow[ul, "\phi"] & & B \arrow[ur, "\psi"'] & \\
& & K \arrow[ul, "f"] \arrow[ur, "g"'] & &
\end{tikzcd}$$

in Sets, we have isomorphisms of sets

$$X \coprod{}_K^{\phi \circ f, \psi \circ g} Y \cong (X \coprod{}_A^{\phi, j_1} (A \coprod{}_K^{f,g} B)) \coprod{}_{A \coprod_K^{f,g} B}^{i_2, i_1} ((A \coprod{}_K^{f,g} B) \coprod{}_B^{j_2, \psi} Y)$$

$$
\begin{aligned}
&\cong X \coprod\nolimits_A^{\phi,i} ((A \coprod\nolimits_K^{f,g} B) \coprod\nolimits_B^{j_2,\psi} Y) \\
&\cong (X \coprod\nolimits_A^{\phi,i_1} (A \coprod\nolimits_K^{f,g} B)) \coprod\nolimits_B^{j,\psi} Y
\end{aligned}
$$

where

$$
\begin{aligned}
j_1 &= \mathrm{inj}_1^{A \times_K^{f,g} B}, & j_2 &= \mathrm{inj}_2^{A \times_K^{f,g} B}, \\
i_1 &= \mathrm{inj}_1^{(A \times_K^{f,g} B) \times_Y^{q_2,\psi}}, & i_2 &= \mathrm{inj}_2^{X \times_{A \times_K^{f,g} B}^{\phi,q_1} (A \times_K^{f,g} B)}, \\
i &= j_1 \circ \mathrm{inj}_1^{(A \times_K^{f,g} B) \times_B^{q_2,\psi} Y}, & j &= j_2 \circ \mathrm{inj}_2^{X \times_A^{\phi,q_1} (A \times_K^{f,g} B)},
\end{aligned}
$$

and where these pullbacks are built as in the diagrams

$$
\begin{tikzcd}
 & & (X \coprod_A (A \coprod_K B)) \coprod_{A \coprod_K B} ((A \coprod_K B) \coprod_B Y) & & \\
 & X \coprod_A (A \coprod_K B) \arrow[ur, hook] & & (A \coprod_K B) \coprod_B Y \arrow[ul, hook'] & \\
X \arrow[ur, hook] & & A \coprod_K B \arrow[ul, hook'] \arrow[ur, hook] \arrow[uu, phantom, "\wedge" near end] & & Y, \arrow[ul, hook'] \\
 & A \arrow[ul, "\phi"] \arrow[ur, hook] \arrow[uu, phantom, "\wedge" near end] & & B \arrow[ul, hook'] \arrow[ur, "\psi"'] \arrow[uu, phantom, "\wedge" near end] & \\
 & & K \arrow[ul, "f"] \arrow[ur, "g"'] \arrow[uu, phantom, "\wedge" near end] & &
\end{tikzcd}
\qquad
\begin{tikzcd}
 & & X \coprod_A ((A \coprod_K B) \coprod_B Y) & & \\
 & & & (A \coprod_K B) \coprod_B Y \arrow[ul, hook'] & \\
X \arrow[uurr, hook] & & A \coprod_K B \arrow[ur, hook] \arrow[uu, phantom, "\wedge" near end] & & Y, \arrow[ul, hook'] \\
 & A \arrow[ul, "\phi"] \arrow[ur, hook] & & B \arrow[ul, hook'] \arrow[ur, "\psi"'] \arrow[uu, phantom, "\wedge" near end] & \\
 & & K \arrow[ul, "f"] \arrow[ur, "g"'] \arrow[uu, phantom, "\wedge" near end] & &
\end{tikzcd}
$$

$$
\begin{tikzcd}
 & & (X \coprod_A (A \coprod_K B)) \coprod_B Y & & \\
 & X \coprod_A (A \coprod_K B) \arrow[ur, hook] & & & \\
X \arrow[ur, hook] & & A \coprod_K B \arrow[ul, hook'] & & Y, \arrow[uull, hook'] \\
 & A \arrow[ul, "\phi"] \arrow[ur, hook] \arrow[uu, phantom, "\wedge" near end] & & B \arrow[ur, "\psi"'] \arrow[ul, hook'] & \\
 & & K \arrow[ul, "f"] \arrow[ur, "g"'] \arrow[uu, phantom, "\wedge" near end] & &
\end{tikzcd}
\qquad
\begin{tikzcd}
 & & X \coprod_K Y & & \\
 & & & & \\
X \arrow[uurr, hook] & & & & Y. \arrow[uull, hook'] \\
 & A \arrow[ul, "\phi"] & & B \arrow[ur, "\psi"'] & \\
 & & K \arrow[ul, "f"] \arrow[ur, "g"'] \arrow[uuuu, phantom, "\wedge" near end] & &
\end{tikzcd}
$$

5. *Unitality.* We have isomorphisms of sets

$$
\begin{tikzcd}
A \arrow[r, equal] & A \\
X \arrow[u, "f"] \arrow[r, equal] \arrow[ur, phantom, "\ulcorner", very near end] & X \arrow[u, "f"']
\end{tikzcd}
\qquad
\begin{aligned}
\lambda^{\mathsf{Sets}_{X/}}_{A} &\colon X \textstyle\coprod_X A \overset{\sim}{\dashrightarrow} A,\\
\rho^{\mathsf{Sets}_{X/}}_{A} &\colon A \textstyle\coprod_X X \overset{\sim}{\dashrightarrow} A,
\end{aligned}
\qquad
\begin{tikzcd}
A & X \arrow[l, "f"'] \\
X \arrow[u, equal] \arrow[ur, phantom, "\ulcorner", very near end] & X, \arrow[l, "f"] \arrow[u, equal]
\end{tikzcd}
$$

natural in $(A, f) \in \mathrm{Obj}(\mathsf{Sets}_{X/})$.

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

$$
\begin{tikzcd}
A \coprod_X B & B \arrow[l] \\
A \arrow[u] \arrow[ur, phantom, "\ulcorner", very near end] & X, \arrow[l, "f"] \arrow[u, "g"']
\end{tikzcd}
\qquad
\sigma^{\mathsf{Sets}_{X/}}_{A} \colon A \textstyle\coprod_X B \overset{\sim}{\dashrightarrow} B \textstyle\coprod_X A
\qquad
\begin{tikzcd}
B \coprod_X A & A \arrow[l] \\
B \arrow[u] \arrow[ur, phantom, "\ulcorner", very near end] & X. \arrow[l, "g"] \arrow[u, "f"']
\end{tikzcd}
$$

natural in $(A, f), (B, g) \in \mathrm{Obj}(\mathsf{Sets}_{X/})$.

7. *Interaction With Coproducts.* We have

$$
A \textstyle\coprod_{\emptyset} B \cong A \textstyle\coprod B,
\qquad
\begin{tikzcd}
A \coprod B & B \arrow[l] \\
A \arrow[u] \arrow[ur, phantom, "\ulcorner", very near end] & \emptyset. \arrow[l, hook', "\iota_A"] \arrow[u, hook, "\iota_B"']
\end{tikzcd}
$$

8. *Symmetric Monoidality.* The triple $(\mathsf{Sets}_{X/}, \coprod_X, X)$ is a symmetric monoidal category.

PROOF 4.2.4.1.9 ► PROOF OF PROPOSITION 4.2.4.1.8

Item 1: Functoriality

This is a special case of functoriality of co/limits, Limits and Colimits, **??**

of **??**, with the explicit expression for ξ following from the commutativity of the cube pushout diagram.

Item 2: : Adjointness

This follows from the universal property of the coproduct (pushouts are coproducts in $\mathsf{Sets}_{X/}$).

Item 3: Associativity

Omitted.

Item 4: Interaction With Composition

Omitted.

Item 5: Unitality

Omitted.

Item 6: Commutativity

Omitted.

Item 7: Interaction With Coproducts

Omitted.

Item 8: Symmetric Monoidality

Omitted.

4.2.5 Coequalisers

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

Definition 4.2.5.1.1 ► Coequalisers of Sets

The **coequaliser of** f **and** g is the coequaliser of f and g in Sets as in Limits and Colimits, **??**.

Construction 4.2.5.1.2 ► Construction of Coequalisers of Sets

Concretely, the coequaliser of f and g is the pair $(\mathrm{CoEq}(f,g), \mathrm{coeq}(f,g))$ consisting of:

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

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

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

2. *The Cocone.* The map

$$\mathrm{coeq}(f,g)\colon B \twoheadrightarrow \mathrm{CoEq}(f,g)$$

given by the quotient map $\pi\colon B \twoheadrightarrow B/{\sim}$ with respect to the equivalence relation generated by $f(a) \sim g(a)$.

Proof 4.2.5.1.3 ▶ Proof of Construction 4.2.5.1.2

We claim that $\mathrm{CoEq}(f,g)$ 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

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

Indeed, we have

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

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

$$\begin{tikzcd}
A \arrow[r, shift left, "f"] \arrow[r, shift right, "g"'] & B \arrow[r, "\mathrm{coeq}(f,g)"] \arrow[rd, "c"'] & \mathrm{CoEq}(f,g) \\
& & C
\end{tikzcd}$$

in Sets. Then, since $c(f(a)) = c(g(a))$ for each $a \in A$, it follows from Conditions on Relations, Items 4 and 5 of Proposition 10.6.2.1.3 that there exists a unique map $\mathrm{CoEq}(f,g) \xrightarrow{\exists!} C$ making the diagram

$$\begin{tikzcd} A \arrow[r, shift left, "f"] \arrow[r, shift right, "g"'] & B \arrow[r, hook, "\mathrm{coeq}(f,g)"] \arrow[dr, "c"'] & \mathrm{CoEq}(f,g) \arrow[d, dashed, "\exists!"] \\ & & C \end{tikzcd}$$

commute.

Remark 4.2.5.1.4 ▶ Unwinding Definition 4.2.5.1.1

In detail, by Conditions on Relations, Construction 10.5.2.1.2, the relation $\sim$ of Definition 4.2.5.1.1 is given by declaring $a \sim b$ iff one of the following conditions is satisfied:

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

   In other words, there exist $x_1, \ldots, x_n \in B$ satisfying the following conditions:

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

i. We have $x_n = f(z_n)$ and $b = g(z_n)$.
ii. We have $x_n = g(z_n)$ and $b = f(z_n)$.

Example 4.2.5.1.5 ▶ Examples of Coequalisers of Sets

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

$$X/{\sim_R} \cong \mathrm{CoEq}(R \hookrightarrow X \times X \underset{\mathrm{pr}_2}{\overset{\mathrm{pr}_1}{\rightrightarrows}} X).$$

Proof 4.2.5.1.6 ▶ Proof of Example 4.2.5.1.5

Item 1: Quotients by Equivalence Relations

See [Pro25z]. □

Proposition 4.2.5.1.7 ▶ Properties of Coequalisers of Sets

Let A, B, and C be sets.

1. *Associativity.* We have isomorphisms of sets[1]

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

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

$$\begin{tikzcd} A \arrow[r, shift left=2, "f"] \arrow[r, "g" description] \arrow[r, shift right=2, "h"'] & B \end{tikzcd}$$

   in Sets.

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

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

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

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

4. *Interaction With Composition.* Let

$$A \underset{g}{\overset{f}{\rightrightarrows}} B \underset{k}{\overset{h}{\rightrightarrows}} C$$

be functions. We have a surjection

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

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

---

[1]That is, the following three ways of forming "the" coequaliser of (f, g, h) agree:

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

$$\begin{tikzcd} A \arrow[r, shift left=2, "f"] \arrow[r, "g" description] \arrow[r, shift right=2, "h"'] & B \end{tikzcd}$$

in Sets.

(b) First take the coequaliser of f and g, forming a diagram

$$A \underset{g}{\overset{f}{\rightrightarrows}} B \overset{\mathrm{coeq}(f,g)}{\twoheadrightarrow} \mathrm{CoEq}(f, g)$$

and then take the coequaliser of the composition

$$A \underset{h}{\overset{f}{\rightrightarrows}} B \overset{\mathrm{coeq}(f,g)}{\twoheadrightarrow} \mathrm{CoEq}(f, g),$$

obtaining a quotient

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

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

(c) First take the coequaliser of g and h, forming a diagram

$$A \underset{h}{\overset{g}{\rightrightarrows}} B \overset{\mathrm{coeq}(g,h)}{\twoheadrightarrow} \mathrm{CoEq}(g, h)$$

and then take the coequaliser of the composition

$$A \underset{g}{\overset{f}{\rightrightarrows}} B \overset{\mathrm{coeq}(g,h)}{\twoheadrightarrow} \mathrm{CoEq}(g, h),$$

obtaining a quotient

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

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

Proof 4.2.5.1.8 ▶ Proof of Proposition 4.2.5.1.7

Item 1: Associativity

Omitted.

Item 2: Unitality

Omitted.

Item 3: Commutativity

Omitted.

Item 4: Interaction With Composition

Omitted.

4.2.6 Direct Colimits

Let $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I} \colon (I, \preceq) \to \mathsf{Sets}$ be a direct system of sets.

Definition 4.2.6.1.1 ▶ Direct Colimits of Sets

The **direct colimit of** $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$ is the direct colimit of $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$ in Sets as in Limits and Colimits, **??**.

Construction 4.2.6.1.2 ▶ Construction of Direct Colimits of Sets

Concretely, the direct colimit of $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$ is the pair $\left(\underset{\substack{\longrightarrow \\ \alpha\in I}}{\mathrm{colim}}(X_\alpha), \{\mathrm{inj}_\alpha\}_{\alpha\in I}\right)$ consisting of:

1. *The Colimit.* The set $\underset{\substack{\longrightarrow \\ \alpha\in I}}{\mathrm{colim}}(X_\alpha)$ defined by

$$\underset{\substack{\longrightarrow \\ \alpha\in I}}{\mathrm{colim}}(X_\alpha) \overset{\text{def}}{=} \left(\coprod_{\alpha\in I} X_\alpha\right)\Big/\sim,$$

where $\sim$ is the equivalence relation on $\coprod_{\alpha\in I} X_\alpha$ generated by declaring $(\alpha, x) \sim (\beta, y)$ iff there exists some $\gamma \in I$ satisfying the following conditions:

(a) We have $\alpha \preceq \gamma$.

(b) We have $\beta \preceq \gamma$.

(c) We have $f_{\alpha\gamma}(x) = f_{\beta\gamma}(y)$.

2. *The Cocone.* The collection

$$\left\{ \mathrm{inj}_\gamma \colon X_\gamma \to \underset{\substack{\longrightarrow \\ \alpha \in I}}{\mathrm{colim}}(X_\alpha) \right\}_{\gamma \in I}$$

of maps of sets defined by

$$\mathrm{inj}_\gamma(x) \overset{\mathrm{def}}{=} [(\gamma, x)]$$

for each $\gamma \in I$ and each $x \in X_\gamma$.

Proof 4.2.6.1.3 ▶ Proof of Construction 4.2.6.1.2

We will prove Construction 4.2.6.1.2 below in a bit, but first we need a lemma (which is interesting in its own right).

Lemma 4.2.6.1.4 ▶ Identification of x with $f_{\alpha\beta}(x)$ in Direct Colimits

For each $\alpha, \beta \in I$ and each $x \in X_\alpha$, if $\alpha \preceq \beta$, then we have

$$(\alpha, x) \sim (\beta, f_{\alpha\beta}(x))$$

in $\underset{\substack{\longrightarrow \\ \alpha \in I}}{\mathrm{colim}}(X_\alpha)$.

Proof 4.2.6.1.5 ▶ Proof of Lemma 4.2.6.1.4

Taking $\gamma = \beta$, we have $f_{\alpha\gamma} = f_{\alpha\beta}$, we have $f_{\beta\gamma} = f_{\beta\beta} \overset{\mathrm{def}}{=} \mathrm{id}_{X_\beta}$, and we have

$$\begin{aligned} f_{\alpha\beta}(x) &= f_{\beta\beta}(f_{\alpha\beta}(x)) \\ &\overset{\mathrm{def}}{=} \mathrm{id}_{X_\beta}(f_{\alpha\beta}(x)), \end{aligned}$$

$$= f_{\alpha\beta}(x).$$

As a result, since $\alpha \preceq \beta$ and $\beta \preceq \beta$ as well, Items 1a to 1c of Construction 4.2.6.1.2 are met. Thus we have $(\alpha, x) \sim (\beta, f_{\alpha\beta}(x))$.

We can now prove Construction 4.2.6.1.2:

PROOF 4.2.6.1.6 ► PROOF OF CONSTRUCTION 4.2.6.1.2

We claim that $\underset{\alpha\in I}{\underrightarrow{\operatorname{colim}}}(X_\alpha)$ is the colimit of the direct system of sets $(X_\alpha, f_{\alpha\beta})_{\alpha,\beta\in I}$.

Commutativity of the Colimit Diagram

First, we need to check that the colimit diagram defined by $\underset{\alpha\in I}{\underrightarrow{\operatorname{colim}}}(X_\alpha)$ commutes, i.e. that we have

$$\operatorname{inj}_\alpha = \operatorname{inj}_\beta \circ f_{\alpha\beta}, \qquad \begin{tikzcd} & \underset{\alpha\in I}{\underrightarrow{\operatorname{colim}}}(X_\alpha) & \\ X_\alpha \arrow[ur, "\operatorname{inj}_\alpha"] \arrow[rr, "f_{\alpha\beta}"'] & & X_\beta \arrow[ul, "\operatorname{inj}_\beta"'] \end{tikzcd}$$

for each $\alpha, \beta \in I$ with $\alpha \preceq \beta$. Indeed, given $x \in X_\alpha$, we have

$$\begin{aligned} [\operatorname{inj}_\beta \circ f_{\alpha\beta}](x) &\overset{\text{def}}{=} \operatorname{inj}_\beta(f_{\alpha\beta}(x)) \\ &\overset{\text{def}}{=} [(\beta, f_{\alpha\beta}(x))] \\ &= [(\alpha, x)] \\ &\overset{\text{def}}{=} \operatorname{inj}_\alpha(x), \end{aligned}$$

where we have used Lemma 4.2.6.1.4 for the third equality.

Proof of the Universal Property of the Colimit

Next, we prove that $\underset{\alpha\in I}{\underrightarrow{\operatorname{colim}}}(X_\alpha)$ as constructed in Construction 4.2.6.1.2 satisfies the universal property of a direct colimit. Suppose that we have, for each $\alpha, \beta \in I$ with $\alpha \preceq \beta$, a diagram of the form

$$\begin{tikzcd}
 & C & \\
 & \underset{\alpha\in I}{\underrightarrow{\mathrm{colim}}}(X_\alpha) & \\
X_\alpha \arrow[ur, "\mathrm{inj}_\alpha"] \arrow[rr, "f_{\alpha\beta}"'] \arrow[uur, bend left, "i_\alpha"] & & X_\beta \arrow[ul, "\mathrm{inj}_\beta"'] \arrow[uul, bend right, "i_\beta"']
\end{tikzcd}$$

in Sets. We claim that there exists a unique map $\phi\colon \underset{\alpha\in I}{\underrightarrow{\mathrm{colim}}}(X_\alpha) \xrightarrow{\exists!} C$ making the diagram

$$\begin{tikzcd}
 & C & \\
 & \underset{\alpha\in I}{\underrightarrow{\mathrm{colim}}}(X_\alpha) \arrow[u, dashed, "\phi", "\exists!"'] & \\
X_\alpha \arrow[ur, "\mathrm{inj}_\alpha"] \arrow[rr, "f_{\alpha\beta}"'] \arrow[uur, bend left, "i_\alpha"] & & X_\beta \arrow[ul, "\mathrm{inj}_\beta"'] \arrow[uul, bend right, "i_\beta"']
\end{tikzcd}$$

commute. To this end, first consider the diagram

$$\begin{tikzcd}
\coprod_{\alpha\in I} X_\alpha \arrow[r, two heads, "\mathrm{pr}"] \arrow[dr, "\coprod_{\alpha\in I} i_\alpha"'] & \underset{\alpha\in I}{\underrightarrow{\mathrm{colim}}}(X_\alpha) \\
 & C.
\end{tikzcd}$$

Lemma. If $(\alpha, x) \sim (\beta, y)$, then we have

$$\left[\coprod_{\alpha\in I} i_\alpha\right](x) = \left[\coprod_{\alpha\in I} i_\alpha\right](y).$$

Proof. Indeed, if $(\alpha, x) \sim (\beta, y)$, then there exists some $\gamma \in I$ satisfying the following conditions:

1. We have $\alpha \preceq \gamma$.
2. We have $\beta \preceq \gamma$.
3. We have $f_{\alpha\gamma}(x) = f_{\beta\gamma}(y)$.

We then have

$$\begin{aligned}\left[\coprod_{\alpha\in I} i_\alpha\right](x) &\overset{\text{def}}{=} i_\alpha(x)\\ &\overset{\text{def}}{=} [i_\gamma \circ f_{\alpha\gamma}](x)\\ &\overset{\text{def}}{=} i_\gamma(f_{\alpha\gamma}(x))\\ &= i_\gamma(f_{\beta\gamma}(x))\\ &\overset{\text{def}}{=} [i_\gamma \circ f_{\beta\gamma}](x)\\ &= i_\beta(y)\\ &\overset{\text{def}}{=} \left[\coprod_{\alpha\in I} i_\alpha\right](y).\end{aligned}$$

This finishes the proof of the lemma. Continuing, by Conditions on Relations, **??** of Proposition 10.6.2.1.3, there then exists a map $\phi\colon \underset{\overrightarrow{\alpha\in I}}{\operatorname{colim}}(X_\alpha) \xrightarrow{\exists!} C$ making the diagram

$$\begin{tikzcd} \coprod_{\alpha\in I} X_\alpha \arrow[r, two heads, "\mathrm{pr}"] \arrow[dr, "\coprod_{\alpha\in I} i_\alpha"'] & \underset{\overrightarrow{\alpha\in I}}{\operatorname{colim}}(X_\alpha) \arrow[d, "\phi"] \\ & C \end{tikzcd}$$

commute. In particular, this implies that the diagram

$$\begin{tikzcd} X_\alpha \arrow[r, two heads, "\mathrm{inj}_\alpha"] \arrow[dr, "i_\alpha"'] & \underset{\overrightarrow{\alpha\in I}}{\mathrm{colim}}(X_\alpha) \arrow[d, "\phi"] \\ & C \end{tikzcd}$$

also commutes, and thus so does the diagram

$$\begin{tikzcd} & C & \\ & \underset{\overrightarrow{\alpha\in I}}{\mathrm{colim}}(X_\alpha) \arrow[u, dashed, "\phi", "\exists!"'] & \\ X_\alpha \arrow[uur, bend left, "i_\alpha"] \arrow[ur, "\mathrm{inj}_\alpha"] \arrow[rr, "f_{\alpha\beta}"'] & & X_\beta. \arrow[uul, bend right, "i_\beta"'] \arrow[ul, "\mathrm{inj}_\beta"'] \end{tikzcd}$$

This finishes the proof.[1]

[1] Incidentally, the conditions

$$\left\{i_\alpha = \phi \circ \mathrm{inj}_\alpha\right\}_{\alpha\in I}$$

show that ϕ must be given by

$$\phi([(\alpha, x)]) = (i_\alpha(x))_{\alpha\in I}$$

for each $[(\alpha, x)] \in \underset{\overrightarrow{\alpha\in I}}{\mathrm{colim}}(X_\alpha)$, although we would need to show that this assignment is well-defined were we to prove Construction 4.2.6.1.2 in this way. Instead, invoking Conditions on Relations, ?? of Proposition 10.6.2.1.3 gave us a way to avoid having to prove this, leading to a cleaner alternative proof.

Example 4.2.6.1.7 ▶ Examples of Direct Colimits of Sets

Here are some examples of direct colimits of sets.

1. *The Prüfer Group.* The Prüfer group $\mathbb{Z}(p^\infty)$ is defined as the direct

colimit

$$\mathbb{Z}(p^\infty) \stackrel{\text{def}}{=} \underset{\substack{\longrightarrow \\ n\in\mathbb{N}}}{\mathrm{colim}}(\mathbb{Z}_{/p^n});$$

see **??**.

4.3 Operations With Sets

4.3.1 The Empty Set

Definition 4.3.1.1.1 ► The Empty Set

The **empty set** is the set $\emptyset$ defined by

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

where X is the set in the set existence axiom, **??** of **??**.

4.3.2 Singleton Sets

Let X be a set.

Definition 4.3.2.1.1 ► Singleton Sets

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 of Definition 4.3.3.1.1.

4.3.3 Pairings of Sets

Let X and Y be sets.

Definition 4.3.3.1.1 ► Pairings of Sets

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 **??**.

4.3.4 Ordered Pairs

Let A and B be sets.

Definition 4.3.4.1.1 ► Ordered Pairs

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

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

Proposition 4.3.4.1.2 ► Properties of Ordered Pairs

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 4.3.4.1.3 ► Proof of Proposition 4.3.4.1.2

Item 1: Uniqueness

See [Cie97, Theorem 1.2.3]. □

4.3.5 Sets of Maps

Let A and B be sets.

Definition 4.3.5.1.1 ► Sets of Maps

The **set of maps from** A **to** B[1] is the set $\mathrm{Sets}(A, B)$[2] whose elements are the functions from A to B.

[1] *Further Terminology:* Also called the **Hom set from** A **to** B.

[2] *Further Notation:* Also written $\mathrm{Hom}_{\mathrm{Sets}}(A, B)$.

Proposition 4.3.5.1.2 ▶ Properties of Sets of Maps

Let A and B be sets.

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

$$\begin{aligned} \mathsf{Sets}(X, -) &\colon \quad \mathsf{Sets} \longrightarrow \mathsf{Sets},\\ \mathsf{Sets}(-, Y) &\colon \quad \mathsf{Sets}^{\mathsf{op}} \longrightarrow \mathsf{Sets},\\ \mathsf{Sets}(-_1, -_2) &\colon \mathsf{Sets}^{\mathsf{op}} \times \mathsf{Sets} \longrightarrow \mathsf{Sets}. \end{aligned}$$

2. *Adjointness.* We have adjunctions

$$(A \times - \dashv \mathsf{Sets}(A, -))\colon \quad \begin{tikzcd} \mathsf{Sets} \arrow[r, bend left, "A\times-"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}, \arrow[l, bend left, "\mathsf{Sets}(A,-)"] \end{tikzcd}$$

$$(- \times B \dashv \mathsf{Sets}(B, -))\colon \quad \begin{tikzcd} \mathsf{Sets} \arrow[r, bend left, "-\times B"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}, \arrow[l, bend left, "\mathsf{Sets}(B,-)"] \end{tikzcd}$$

witnessed by bijections

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

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

3. *Maps From the Punctual Set.* We have a bijection

$$\mathsf{Sets}(\mathrm{pt}, A) \cong A,$$

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

4. *Maps to the Punctual Set.* We have a bijection

$$\mathsf{Sets}(A, \mathrm{pt}) \cong \mathrm{pt},$$

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

Proof 4.3.5.1.3 ▶ Proof of Proposition 4.3.5.1.2

Item 1: Functoriality

This follows from Categories, Items 2 and 5 of Proposition 11.1.4.1.2.

Item 2: Adjointness

This is a repetition of Item 2 of Proposition 4.1.3.1.4 and is proved there.

Item 3: Maps From the Punctual Set

The bijection

$$\Phi_A \colon \mathsf{Sets}(\mathrm{pt}, A) \overset{\sim}{\dashrightarrow} A$$

is given by

$$\Phi_A(f) \overset{\text{def}}{=} f(\star)$$

for each $f \in \mathsf{Sets}(\mathrm{pt}, A)$, admitting an inverse

$$\Phi_A^{-1} \colon A \overset{\sim}{\dashrightarrow} \mathsf{Sets}(\mathrm{pt}, A)$$

given by

$$\Phi_A^{-1}(a) \overset{\text{def}}{=} [\![\star \mapsto a]\!]$$

for each $a \in A$. Indeed, we have

$$\begin{aligned}
[\Phi_A^{-1} \circ \Phi_A](f) &\overset{\text{def}}{=} \Phi_A^{-1}(\Phi_A(f)) \\
&\overset{\text{def}}{=} \Phi_A^{-1}(f(\star)) \\
&\overset{\text{def}}{=} [\![\star \mapsto f(\star)]\!] \\
&\overset{\text{def}}{=} f \\
&\overset{\text{def}}{=} [\mathrm{id}_{\mathsf{Sets}(\mathrm{pt},A)}](f)
\end{aligned}$$

for each $f \in \mathsf{Sets}(\mathrm{pt}, A)$ and

$$\begin{aligned}
[\Phi_A \circ \Phi_A^{-1}](a) &\overset{\text{def}}{=} \Phi_A(\Phi_A^{-1}(a)) \\
&\overset{\text{def}}{=} \Phi_A([\![\star \mapsto a]\!]) \\
&\overset{\text{def}}{=} \mathrm{ev}_\star([\![\star \mapsto a]\!]) \\
&\overset{\text{def}}{=} a \\
&\overset{\text{def}}{=} [\mathrm{id}_A](a)
\end{aligned}$$

for each $a \in A$, and thus we have

$$\begin{aligned}\Phi_A^{-1} \circ \Phi_A &= \mathrm{id}_{\mathsf{Sets}(\mathrm{pt},A)}\\ \Phi_A \circ \Phi_A^{-1} &= \mathrm{id}_A\,.\end{aligned}$$

To prove naturality, we need to show that the diagram

$$\begin{tikzcd} \mathsf{Sets}(\mathrm{pt},A) \arrow[r, "f_!"] \arrow[d, dashed, "\Phi_A"', "\wr"] & \mathsf{Sets}(\mathrm{pt},B) \arrow[d, dashed, "\Phi_B", "\wr"'] \\ A \arrow[r, "f"'] & B \end{tikzcd}$$

commutes. Indeed, we have

$$\begin{aligned}[f \circ \Phi_A](\phi) &\overset{\text{def}}{=} f(\Phi_A(\phi))\\ &\overset{\text{def}}{=} f(\phi(\star))\\ &\overset{\text{def}}{=} [f \circ \phi](\star)\\ &\overset{\text{def}}{=} \Phi_B(f \circ \phi)\\ &\overset{\text{def}}{=} \Phi_B(f_!(\phi))\\ &\overset{\text{def}}{=} [\Phi_B \circ f_!](\phi)\end{aligned}$$

for each $\phi \in \mathsf{Sets}(\mathrm{pt},A)$. This finishes the proof.

Item 4: Maps to the Punctual Set

This follows from the universal property of pt as the terminal set, Definition 4.1.1.1.1.

4.3.6 Unions of Families of Subsets

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

Definition 4.3.6.1.1 ▶ Unions of Families of Subsets

The **union of** $\mathcal{U}$ is the set $\bigcup_{U\in\mathcal{U}} U$ defined by

$$\bigcup_{U\in\mathcal{U}} U \overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l}\text{there exists some } U \in \mathcal{U}\\ \text{such that we have } x \in U\end{array} \right\}.$$

Proposition 4.3.6.1.2 ▶ Properties of Unions of Families of Subsets

Let X be a set.

1. *Functoriality.* The assignment $\mathcal{U} \mapsto \bigcup_{U\in\mathcal{U}} U$ defines a functor

   $$\bigcup\colon (\mathcal{P}(\mathcal{P}(X)), \subset) \to (\mathcal{P}(X), \subset).$$

   In particular, for each $\mathcal{U}, \mathcal{V} \in \mathcal{P}(\mathcal{P}(X))$, the following condition is satisfied:

   $(\star)$ If $\mathcal{U} \subset \mathcal{V}$, then $\displaystyle\bigcup_{U\in\mathcal{U}} U \subset \bigcup_{V\in\mathcal{V}} V$.

2. *Associativity.* The diagram

   $$\begin{tikzcd} \mathcal{P}(\mathcal{P}(\mathcal{P}(X))) \arrow[r, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcup"] \arrow[d, "\bigcup \star \mathrm{id}_{\mathcal{P}(X)}"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\ \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcup"'] & \mathcal{P}(X) \end{tikzcd}$$

   commutes, i.e. we have

   $$\bigcup_{U \in \bigcup_{A\in\mathcal{A}} A} U = \bigcup_{A\in\mathcal{A}} \left(\bigcup_{U\in A} U \right)$$

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

3. *Left Unitality.* The diagram

$$\begin{tikzcd} \mathcal{P}(X) \arrow[d, "\chi_{\mathcal{P}(X)}"'] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)}"] & \\ \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcup"'] & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{V\in\{U\}} V = U$$

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

4. *Right Unitality.* The diagram

$$\begin{tikzcd} \mathcal{P}(X) \arrow[d, "\mathcal{P}(\chi_X)"'] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)}"] & \\ \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcup"'] & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{\{u\}\in\chi_X(U)} \{u\} = U$$

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

5. *Interaction With Unions I.* The diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(X)) \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\cup"] \arrow[d, "\bigcup\times\bigcup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\ \mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\cup"'] & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{W\in\mathcal{U}\cup\mathcal{V}} W = \left(\bigcup_{U\in\mathcal{U}} U\right)\cup\left(\bigcup_{V\in\mathcal{V}} V\right)$$

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

6. *Interaction With Unions II.* The diagrams

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))\setminus\{\emptyset\} \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))}\times(U\cup-)"] \arrow[d, "\cup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cup"] \\
\mathcal{P}(X) \arrow[r, "U\cup-"'] & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))\setminus\{\emptyset\} \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))}\times(-\cup V)"] \arrow[d, "\cup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cup"] \\
\mathcal{P}(X) \arrow[r, "-\cup V"'] & \mathcal{P}(X)
\end{tikzcd}$$

commute, i.e. we have

$$\begin{aligned}
U\cup\left(\bigcup_{V\in\mathcal{V}} V\right) &= \bigcup_{V\in\mathcal{V}}(U\cup V),\\
\left(\bigcup_{U\in\mathcal{U}} U\right)\cup V &= \bigcup_{U\in\mathcal{U}}(U\cup V)
\end{aligned}$$

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

7. *Interaction With Intersections I.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))\times\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\cap"] \arrow[d, "\cup\times\cup"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cup"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[r, "\cap"'] & \mathcal{P}(X),
\end{tikzcd}$$

with components

$$\bigcup_{W\in\mathcal{U}\cap\mathcal{V}} W \subset \left(\bigcup_{U\in\mathcal{U}} U\right)\cap\left(\bigcup_{V\in\mathcal{V}} V\right)$$

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

8. *Interaction With Intersections II.* The diagrams

$$
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))}\times(U\cap-)"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\
\mathcal{P}(X) \arrow[r, "U\cap-"'] & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))}\times(-\cap V)"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\
\mathcal{P}(X) \arrow[r, "-\cap V"'] & \mathcal{P}(X)
\end{tikzcd}
$$

commute, i.e. we have

$$
\begin{aligned}
U \cap \left(\bigcup_{V\in\mathcal{V}} V\right) &= \bigcup_{V\in\mathcal{V}}(U\cap V),\\
\left(\bigcup_{U\in\mathcal{U}} U\right) \cap V &= \bigcup_{U\in\mathcal{U}}(U\cap V)
\end{aligned}
$$

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

9. *Interaction With Differences.* The diagram

$$
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\setminus"] \arrow[d, "\bigcup\times\bigcup"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\setminus"'] & \mathcal{P}(X),
\end{tikzcd}
$$

does not commute in general, i.e. we may have

$$
\bigcup_{W\in\mathcal{U}\setminus\mathcal{V}} W \neq \left(\bigcup_{U\in\mathcal{U}} U\right) \setminus \left(\bigcup_{V\in\mathcal{V}} V\right)
$$

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

10. *Interaction With Complements I.* The diagram

$$
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[r, "(-)^{\mathsf{c}}"] \arrow[d, "\bigcup^{\mathsf{op}}"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "(-)^{\mathsf{c}}"'] & \mathcal{P}(X),
\end{tikzcd}
$$

does not commute in general, i.e. we may have

$$\bigcup_{U\in\mathcal{U}^{\textsf{c}}} U \neq \bigcup_{U\in\mathcal{U}} U^{\textsf{c}}$$

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

11. *Interaction With Complements II.* The diagram

$$\begin{tikzcd}
& \mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[dr, dashed, "\sim"] & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)}\star(-)^{\textsf{c}}"] \arrow[d, "\bigcup"'] & & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[d, "\bigcap^{\mathsf{op}}"] \\
\mathcal{P}(X) \arrow[rr, "(-)^{\textsf{c}}"'] & & \mathcal{P}(X)^{\mathsf{op}},
\end{tikzcd}$$

commutes, i.e. we have

$$\left(\bigcup_{U\in\mathcal{U}} U\right)^{\textsf{c}} = \bigcap_{U\in\mathcal{U}} U^{\textsf{c}}$$

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

12. *Interaction With Complements III.* The diagram

$$\begin{tikzcd}
& \mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[dr, dashed, "\sim"] & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)}\star(-)^{\textsf{c}}"] \arrow[d, "\bigcap"'] & & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[d, "\bigcup^{\mathsf{op}}"] \\
\mathcal{P}(X) \arrow[rr, "(-)^{\textsf{c}}"'] & & \mathcal{P}(X)^{\mathsf{op}},
\end{tikzcd}$$

commutes, i.e. we have

$$\left(\bigcap_{U\in\mathcal{U}} U\right)^{\mathsf{c}} = \bigcup_{U\in\mathcal{U}} U^{\mathsf{c}}$$

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

13. *Interaction With Symmetric Differences.* The diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(X)) \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\triangle"] \arrow[d, "\bigcup\times\bigcup"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\ \mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\triangle"'] & \mathcal{P}(X), \end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcup_{W\in\mathcal{U}\triangle\mathcal{V}} W \neq \left(\bigcup_{U\in\mathcal{U}} U\right) \triangle \left(\bigcup_{V\in\mathcal{V}} V\right)$$

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

14. *Interaction With Internal Homs I.* The diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "{[-_1,-_2]_{\mathcal{P}(X)}}"] \arrow[d, "\bigcup^{\mathsf{op}}\times\bigcup^{\mathsf{op}}"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\ \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "{[-_1,-_2]_X}"'] & \mathcal{P}(X), \end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcup_{W\in[\mathcal{U},\mathcal{V}]_{\mathcal{P}(X)}} W \neq \left[\bigcup_{U\in\mathcal{U}} U, \bigcup_{V\in\mathcal{V}} V\right]_X$$

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

15. *Interaction With Internal Homs II.* The diagram

$$
\begin{tikzcd}
 & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[dr, "\bigcup^{\mathsf{op}}"] & \\
\mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[ur, dashed, "\sim"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \star [-,V]_X"'] & & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "{[-,V]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[rr, "\bigcap"'] & & \mathcal{P}(X)
\end{tikzcd}
$$

commutes, i.e. we have

$$\left[\bigcup_{U\in\mathcal{U}} U, V\right]_X = \bigcap_{U\in\mathcal{U}} [U, V]_X$$

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

16. *Interaction With Internal Homs III.* The diagram

$$
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcup"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \star [U,-]_X"'] & \mathcal{P}(X) \arrow[d, "{[U,-]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcup"'] & \mathcal{P}(X)
\end{tikzcd}
$$

commutes, i.e. we have

$$\left[U, \bigcup_{V\in\mathcal{V}} V\right]_X = \bigcup_{V\in\mathcal{V}} [U, V]_X$$

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

17. *Interaction With Direct Images.* Let $f : X \to Y$ be a map of sets. The

diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_!)_!"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\bigcup"] \\ \mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{U\in\mathcal{U}} f_!(U) = \bigcup_{V\in f_!(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_!(\mathcal{U}) \overset{\text{def}}{=} (f_!)_!(\mathcal{U})$.

18. *Interaction With Inverse Images.* Let $f : X \to Y$ be a map of sets. The diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(Y)) \arrow[r, "(f^{-1})^{-1}"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\ \mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{V\in\mathcal{V}} f^{-1}(V) = \bigcup_{U\in f^{-1}(\mathcal{U})} U$$

for each $\mathcal{V} \in \mathcal{P}(Y)$, where $f^{-1}(\mathcal{V}) \overset{\text{def}}{=} (f^{-1})^{-1}(\mathcal{V})$.

19. *Interaction With Codirect Images.* Let $f : X \to Y$ be a map of sets. The diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_*)_*"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\bigcup"] \\ \mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{U\in\mathcal{U}} f_*(U) = \bigcup_{V\in f_*(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_*(\mathcal{U}) \overset{\text{def}}{=} (f_*)_*(\mathcal{U})$.

20. *Interaction With Intersections of Families I.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcap"] \arrow[d, "\bigcup \star \mathrm{id}_{\mathcal{P}(X)}"'] & \mathcal{P}(\mathcal{P}(x)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \arrow[r, "\bigcap"'] & X
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{U\in \bigcup_{A\in\mathcal{A}} A} U = \bigcap_{A\in\mathcal{A}}\left(\bigcap_{U\in A} U\right)$$

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

21. *Interaction With Intersections of Families II.* Let X be a set and consider the compositions

$$\begin{tikzcd}
 & & \mathcal{P}(\mathcal{P}(\mathcal{P}(X))) \arrow[dll, "\bigcap \star \mathrm{id}_{\mathcal{P}(X)}"'] \arrow[dl, "\bigcup \star \mathrm{id}_{\mathcal{P}(X)}"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcap"] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcup"] & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[drr, "\bigcup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[dr, "\bigcap"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] & \mathcal{P}(\mathcal{P}(X)) \arrow[dl, "\bigcap"] \\
 & & \mathcal{P}(X) &
\end{tikzcd}$$

given by

$$\mathcal{A} \mapsto \bigcup_{U \in \bigcap_{A \in \mathcal{A}} A} U, \qquad \mathcal{A} \mapsto \bigcap_{U \in \bigcup_{A \in \mathcal{A}} A} U,$$

$$\mathcal{A} \mapsto \bigcup_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right), \quad \mathcal{A} \mapsto \bigcap_{A \in \mathcal{A}} \left(\bigcup_{U \in A} U \right)$$

for each $\mathcal{A} \in \mathcal{P}(\mathcal{P}(\mathcal{P}(X)))$. We have the following inclusions:

$$\begin{tikzcd}
 & \bigcup_{U \in \bigcap_{A \in \mathcal{A}} A} U \arrow[dr, hook] & \\
\bigcup_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right) & & \bigcap_{A \in \mathcal{A}} \left(\bigcup_{U \in A} U \right) \\
 & \bigcap_{U \in \bigcup_{A \in \mathcal{A}} A} U \arrow[ul, hook] \arrow[uu, hook] \arrow[ur, hook] &
\end{tikzcd}$$

All other possible inclusions fail to hold in general.

PROOF 4.3.6.1.3 ► PROOF OF PROPOSITION 4.3.6.1.2

Item 1: Functoriality

Since $\mathcal{P}(X)$ is posetal, it suffices to prove the condition $(\star)$. So let $\mathcal{U}, \mathcal{V} \in \mathcal{P}(\mathcal{P}(X))$ with $\mathcal{U} \subset \mathcal{V}$. We claim that

$$\bigcup_{U \in \mathcal{U}} U \subset \bigcup_{V \in \mathcal{V}} V.$$

Indeed, given $x \in \bigcup_{U\in\mathcal{U}} U$, there exists some $U \in \mathcal{U}$ such that $x \in U$, but since $\mathcal{U} \subset \mathcal{V}$, we have $U \in \mathcal{V}$ as well, and thus $x \in \bigcup_{V\in\mathcal{V}} V$, which gives our desired inclusion.

Item 2: Associativity

We have

$$\begin{aligned}
\bigcup_{U\in\bigcup_{A\in\mathcal{A}} A} U &\overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } U \in \bigcup\limits_{A\in\mathcal{A}} A \\ \text{such that we have } x \in U \end{array} \right\} \\
&= \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } A \in \mathcal{A} \\ \text{and some } U \in A \text{ such that} \\ \text{we have } x \in U \end{array} \right\} \\
&= \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } A \in \mathcal{A} \\ \text{such that we have } x \in \bigcup\limits_{U\in A} U \end{array} \right\} \\
&\overset{\text{def}}{=} \bigcup_{A\in\mathcal{A}} \left(\bigcup_{U\in A} U \right).
\end{aligned}$$

This finishes the proof.

Item 3: Left Unitality

We have

$$\begin{aligned}
\bigcup_{V\in\{U\}} V &\overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } V \in \{U\} \\ \text{such that we have } x \in U \end{array} \right\} \\
&= \{x \in X \mid x \in U\} \\
&= U.
\end{aligned}$$

This finishes the proof.

Item 4: Right Unitality

We have

$$\begin{aligned}\bigcup_{\{u\}\in\chi_X(U)}\{u\} &\stackrel{\text{def}}{=} \left\{x\in X \,\middle|\, \begin{array}{l}\text{there exists some } \{u\}\in\chi_X(U)\\ \text{such that we have } x\in\{u\}\end{array}\right\}\\ &= \left\{x\in X \,\middle|\, \begin{array}{l}\text{there exists some } \{u\}\in\chi_X(U)\\ \text{such that we have } x=u\end{array}\right\}\\ &= \left\{x\in X \,\middle|\, \begin{array}{l}\text{there exists some } u\in U\\ \text{such that we have } x=u\end{array}\right\}\\ &= \{x\in X \mid x\in U\}\\ &= U.\end{aligned}$$

This finishes the proof.

Item 5: Interaction With Unions I

We have

$$\begin{aligned}\bigcup_{W\in\mathcal{U}\cup\mathcal{V}} W &\stackrel{\text{def}}{=} \left\{x\in X \,\middle|\, \begin{array}{l}\text{there exists some } W\in\mathcal{U}\cup\mathcal{V}\\ \text{such that we have } x\in W\end{array}\right\}\\ &= \left\{x\in X \,\middle|\, \begin{array}{l}\text{there exists some } W\in\mathcal{U} \text{ or some}\\ W\in\mathcal{V} \text{ such that we have } x\in W\end{array}\right\}\\ &\stackrel{\text{def}}{=} \left\{x\in X \,\middle|\, \begin{array}{l}\text{there exists some } W\in\mathcal{U}\\ \text{such that we have } x\in W\end{array}\right\}\\ &\quad\cup \left\{x\in X \,\middle|\, \begin{array}{l}\text{there exists some } W\in\mathcal{V}\\ \text{such that we have } x\in W\end{array}\right\}\\ &\stackrel{\text{def}}{=} \left(\bigcup_{W\in\mathcal{U}} W\right)\cup\left(\bigcup_{W\in\mathcal{V}} W\right)\\ &= \left(\bigcup_{U\in\mathcal{U}} U\right)\cup\left(\bigcup_{V\in\mathcal{V}} V\right).\end{aligned}$$

This finishes the proof.

Item 6: Interaction With Unions II

Assume $\mathcal{V}$ is nonempty. We have

$$\begin{aligned}
U \cup \bigcup_{V\in\mathcal{V}} V &\overset{\text{def}}{=} \left\{ x \in X \;\middle|\; x \in U \text{ or } x \in \bigcup_{V\in\mathcal{V}} V \right\} \\
&= \left\{ x \in X \;\middle|\; \begin{array}{l} x \in U \text{ or there exists some} \\ V \in \mathcal{V} \text{ such that } x \in V \end{array} \right\} \\
&= \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } V \in \mathcal{V} \\ \text{such that } x \in U \text{ or } x \in V \end{array} \right\} \\
&= \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } V \in \mathcal{V} \\ \text{such that } x \in U \cup V \end{array} \right\} \\
&\overset{\text{def}}{=} \bigcup_{V\in\mathcal{V}} U \cup V.
\end{aligned}$$

This concludes the proof of the first statement. For the second statement, use Item 4 of Proposition 4.3.8.1.2 to rewrite

$$\begin{aligned}
\left(\bigcup_{U\in\mathcal{U}} U\right) \cup V &= V \cup \left(\bigcup_{U\in\mathcal{U}} U\right), \\
\bigcup_{U\in\mathcal{U}} (U \cup V) &= \bigcup_{U\in\mathcal{U}} (V \cup U).
\end{aligned}$$

But these two sets are equal by the first statement.

Item 7: Interaction With Intersections I

We have

$$\begin{aligned}
\bigcup_{W\in\mathcal{U}\cap\mathcal{V}} W &\overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } W \in \mathcal{U} \cap \mathcal{V} \\ \text{such that we have } x \in W \end{array} \right\} \\
&\subset \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some } U \in \mathcal{U} \text{ and some } V \in \mathcal{V} \\ \text{such that we have } x \in U \text{ and } x \in V \end{array} \right\}
\end{aligned}$$

$$
\begin{aligned}
&= \left\{ x \in X \,\middle|\, \begin{array}{l} \text{there exists some } U \in \mathcal{U} \\ \text{such that we have } x \in U \end{array} \right\} \\
&\quad \cup \left\{ x \in X \,\middle|\, \begin{array}{l} \text{there exists some } V \in \mathcal{V} \\ \text{such that we have } x \in V \end{array} \right\} \\
&\stackrel{\text{def}}{=} \left(\bigcup_{U \in \mathcal{U}} U \right) \cap \left(\bigcup_{V \in \mathcal{V}} V \right).
\end{aligned}
$$

This finishes the proof.

Item 8: Interaction With Intersections II

We have

$$
\begin{aligned}
U \cap \bigcup_{V \in \mathcal{V}} V &\stackrel{\text{def}}{=} \left\{ x \in X \,\middle|\, x \in U \text{ and } x \in \bigcup_{V \in \mathcal{V}} V \right\} \\
&= \left\{ x \in X \,\middle|\, \begin{array}{l} x \in U \text{ and there exists some} \\ V \in \mathcal{V} \text{ such that } x \in V \end{array} \right\} \\
&= \left\{ x \in X \,\middle|\, \begin{array}{l} \text{there exists some } V \in \mathcal{V} \\ \text{such that } x \in U \text{ and } x \in V \end{array} \right\} \\
&= \left\{ x \in X \,\middle|\, \begin{array}{l} \text{there exists some } V \in \mathcal{V} \\ \text{such that } x \in U \cap V \end{array} \right\} \\
&\stackrel{\text{def}}{=} \bigcup_{V \in \mathcal{V}} U \cap V.
\end{aligned}
$$

This concludes the proof of the first statement. For the second statement, use Item 5 of Proposition 4.3.9.1.2 to rewrite

$$
\begin{aligned}
\left(\bigcup_{U \in \mathcal{U}} U \right) \cap V &= V \cap \left(\bigcup_{U \in \mathcal{U}} U \right), \\
\bigcup_{U \in \mathcal{U}} (U \cap V) &= \bigcup_{U \in \mathcal{U}} (V \cap U).
\end{aligned}
$$

But these two sets are equal by the first statement.

Item 9: Interaction With Differences

Let $X = \{0, 1\}$, let $\mathcal{U} = \{\{0, 1\}\}$, and let $\mathcal{V} = \{\{0\}\}$. We have

$$\begin{aligned}\bigcup_{W\in\mathcal{U}\setminus\mathcal{V}} U &= \bigcup_{W\in\{\{0,1\}\}} W\\ &= \{0, 1\},\end{aligned}$$

whereas

$$\begin{aligned}\left(\bigcup_{U\in\mathcal{U}} U\right) \setminus \left(\bigcup_{V\in\mathcal{V}} V\right) &= \{0, 1\} \setminus \{0\}\\ &= \{1\}.\end{aligned}$$

Thus we have

$$\bigcup_{W\in\mathcal{U}\setminus\mathcal{V}} W = \{0, 1\} \neq \{1\} = \left(\bigcup_{U\in\mathcal{U}} U\right) \setminus \left(\bigcup_{V\in\mathcal{V}} V\right).$$

This finishes the proof.

Item 10: Interaction With Complements I

Let $X = \{0, 1\}$ and let $\mathcal{U} = \{0\}$. We have

$$\begin{aligned}\bigcup_{U\in\mathcal{U}^{\mathsf{c}}} U &= \bigcup_{U\in\{\emptyset,\{1\},\{0,1\}\}} U\\ &= \{0, 1\},\end{aligned}$$

whereas

$$\begin{aligned}\bigcup_{U\in\mathcal{U}} U^{\mathsf{c}} &= \{0\}^{\mathsf{c}}\\ &= \{1\}.\end{aligned}$$

Thus we have

$$\bigcup_{U\in\mathcal{U}^{\mathsf{c}}} U = \{0, 1\} \neq \{1\} = \bigcup_{U\in\mathcal{U}} U^{\mathsf{c}}.$$

This finishes the proof.

Item 11: Interaction With Complements II

We have

$$\begin{aligned}\left(\bigcup_{U\in\mathcal{U}} U\right)^{\textsf{c}} &\overset{\text{def}}{=} \left\{x \in X \,\middle|\, \begin{array}{l}\text{there exists no } U \in \mathcal{U}\\ \text{such that we have } x \in U\end{array}\right\}\\ &= \left\{x \in X \,\middle|\, \begin{array}{l}\text{for all } U \in \mathcal{U}\\ \text{we have } x \notin U\end{array}\right\}\\ &\overset{\text{def}}{=} \left\{x \in X \,\middle|\, \begin{array}{l}\text{for all } U \in \mathcal{U}\\ \text{we have } x \in U^{\textsf{c}}\end{array}\right\}\\ &\overset{\text{def}}{=} \bigcap_{U\in\mathcal{U}} U^{\textsf{c}}.\end{aligned}$$

Item 12: Interaction With Complements III

By Item 11 Item 3 of Proposition 4.3.11.1.2, we have

$$\begin{aligned}\left(\bigcap_{U\in\mathcal{U}} U\right)^{\textsf{c}} &= \left(\bigcap_{U\in\mathcal{U}} (U^{\textsf{c}})^{\textsf{c}}\right)^{\textsf{c}}\\ &= \left(\left(\bigcup_{U\in\mathcal{U}} U^{\textsf{c}}\right)^{\textsf{c}}\right)^{\textsf{c}}\\ &= \bigcup_{U\in\mathcal{U}} U^{\textsf{c}}.\end{aligned}$$

Item 13: Interaction With Symmetric Differences

Let $X = \{0, 1\}$, let $\mathcal{U} = \{\{0, 1\}\}$, and let $\mathcal{V} = \{\{0\}, \{0, 1\}\}$. We have

$$\begin{aligned}\bigcup_{W\in\mathcal{U}\triangle\mathcal{V}} W &= \bigcup_{W\in\{\{0\}\}} W\\ &= \{0\},\end{aligned}$$

whereas

$$
\begin{aligned}
\left(\bigcup_{U\in\mathcal{U}} U\right) \triangle \left(\bigcup_{V\in\mathcal{V}} V\right) &= \{0,1\} \triangle \{0,1\} \\
&= \emptyset,
\end{aligned}
$$

Thus we have

$$
\bigcup_{W\in\mathcal{U}\triangle\mathcal{V}} W = \{0\} \neq \emptyset = \left(\bigcup_{U\in\mathcal{U}} U\right) \triangle \left(\bigcup_{V\in\mathcal{V}} V\right).
$$

This finishes the proof.

Item 14: Interaction With Internal Homs I

This is a repetition of Item 7 of Proposition 4.4.7.1.4 and is proved there.

Item 15: Interaction With Internal Homs II

This is a repetition of Item 8 of Proposition 4.4.7.1.4 and is proved there.

Item 16: Interaction With Internal Homs III

This is a repetition of Item 9 of Proposition 4.4.7.1.4 and is proved there.

Item 17: Interaction With Direct Images

This is a repetition of Item 3 of Proposition 4.6.1.1.5 and is proved there.

Item 18: Interaction With Inverse Images

This is a repetition of Item 3 of Proposition 4.6.2.1.3 and is proved there.

Item 19: Interaction With Codirect Images

This is a repetition of Item 3 of Proposition 4.6.3.1.7 and is proved there.

Item 20: Interaction With Intersections of Families I

We have

$$
\bigcap_{U\in \bigcup_{A\in\mathcal{A}} A} U \overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } U \in \bigcup\limits_{A\in\mathcal{A}} A, \\ \text{we have } x \in U \end{array} \right\}
$$

$$= \left\{ x \in X \,\middle|\, \begin{array}{l} \text{for each } A \in \mathcal{A} \text{ and each} \\ U \in A, \text{ we have } x \in U \end{array} \right\}$$

$$\stackrel{\text{def}}{=} \bigcap_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right).$$

This finishes the proof.

Item 21: Interaction With Intersections of Families II

Omitted.

4.3.7 Intersections of Families of Subsets

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

Definition 4.3.7.1.1 ▶ Intersections of Families of Subsets

The **intersection of** $\mathcal{U}$ is the set $\bigcap_{U \in \mathcal{U}} U$ defined by

$$\bigcap_{U \in \mathcal{U}} U \stackrel{\text{def}}{=} \left\{ x \in X \,\middle|\, \begin{array}{l} \text{for each } U \in \mathcal{U}, \\ \text{we have } x \in U \end{array} \right\}.$$

Proposition 4.3.7.1.2 ▶ Properties of Intersections of Families of Subsets

Let X be a set.

1. *Functoriality*. The assignment $\mathcal{U} \mapsto \bigcap_{U \in \mathcal{U}} U$ defines a functor

$$\bigcap \colon (\mathcal{P}(\mathcal{P}(X)), \supset) \to (\mathcal{P}(X), \subset).$$

In particular, for each $\mathcal{U}, \mathcal{V} \in \mathcal{P}(\mathcal{P}(X))$, the following condition is satisfied:

(★) If $\mathcal{U} \subset \mathcal{V}$, then $\bigcap_{V \in \mathcal{V}} V \subset \bigcap_{U \in \mathcal{U}} U$.

2. *Oplax Associativity.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(\mathcal{P}(X))) \arrow[r, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcap"] \arrow[d, "\bigcap \star \mathrm{id}_{\mathcal{P}(X)}"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcap"'] & \mathcal{P}(X)
\end{tikzcd}$$

with components

$$\bigcap_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right) \subset \bigcap_{U \in \bigcap_{A \in \mathcal{A}} A} U$$

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

3. *Left Unitality.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \arrow[d, "\chi_{\mathcal{P}(X)}"'] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)}"] & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcap"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{V \in \{U\}} V = U.$$

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

4. *Oplax Right Unitality.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \arrow[d, "\mathcal{P}(\chi_X)"'] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)}"] & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcap"'] \arrow[ur, phantom, "\times"] & \mathcal{P}(X)
\end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcap_{\{x\}\in\chi_X(U)} \{x\} \neq U$$

in general, where $U \in \mathcal{P}(X)$. However, when U is nonempty, we have

$$\bigcap_{\{x\}\in\chi_X(U)} \{x\} \subset U.$$

5. *Interaction With Unions I.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\cup"] \arrow[d, "\bigcap\times\bigcap"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\cap"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{W\in\mathcal{U}\cup\mathcal{V}} W = \left(\bigcap_{U\in\mathcal{U}} U\right) \cap \left(\bigcap_{V\in\mathcal{V}} V\right)$$

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

6. *Interaction With Unions II.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))}\times(U\cup-)"] \arrow[d, "\bigcap"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \arrow[r, "U\cup-"'] & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))}\times(-\cup V)"] \arrow[d, "\bigcap"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \arrow[r, "-\cup V"'] & \mathcal{P}(X)
\end{tikzcd}$$

commute, i.e. we have

$$U \cup \left(\bigcap_{V\in\mathcal{V}} V\right) = \bigcap_{V\in\mathcal{V}} (U \cup V),$$

$$\left(\bigcap_{U\in\mathcal{U}} U\right) \cup V = \bigcap_{U\in\mathcal{U}} (U \cup V)$$

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

7. *Interaction With Intersections I.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\cap"] \arrow[d, "\cap \times \cap"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cap"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\cap"'] & \mathcal{P}(X),
\end{tikzcd}$$

with components

$$\left(\bigcap_{U \in \mathcal{U}} U\right) \cap \left(\bigcap_{V \in \mathcal{V}} V\right) \subset \bigcap_{W \in \mathcal{U} \cap \mathcal{V}} W$$

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

8. *Interaction With Intersections II.* The diagrams

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))} \times (U \cap -)"] \arrow[d, "\cap"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cap"] \\
\mathcal{P}(X) \arrow[r, "U \cap -"'] & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(\mathcal{P}(X))} \times (- \cap V)"] \arrow[d, "\cap"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cap"] \\
\mathcal{P}(X) \arrow[r, "- \cap V"'] & \mathcal{P}(X)
\end{tikzcd}$$

commute, i.e. we have

$$U \cup \left(\bigcap_{V \in \mathcal{V}} V\right) = \bigcap_{V \in \mathcal{V}} (U \cup V),$$

$$\left(\bigcap_{U \in \mathcal{U}} U\right) \cup V = \bigcap_{U \in \mathcal{U}} (U \cup V)$$

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

9. *Interaction With Differences.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\setminus"] \arrow[d, "\cap \times \cap"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cap"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\setminus"'] & \mathcal{P}(X),
\end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcap_{W\in\mathcal{U}\setminus\mathcal{V}} W \neq \left(\bigcap_{U\in\mathcal{U}} U\right) \setminus \left(\bigcap_{V\in\mathcal{V}} V\right)$$

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

10. *Interaction With Complements I.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[r, "(-)^{\mathsf{c}}"] \arrow[d, "\bigcap^{\mathsf{op}}"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "(-)^{\mathsf{c}}"'] & \mathcal{P}(X),
\end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcap_{W\in\mathcal{U}^{\mathsf{c}}} W \neq \bigcap_{U\in\mathcal{U}} U^{\mathsf{c}}$$

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

11. *Interaction With Complements II.* The diagram

$$\begin{tikzcd}
 & & \mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[drr, dashed, "\sim"] & & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[urr, "\mathrm{id}_{\mathcal{P}(X)}\star(-)^{\mathsf{c}}"] \arrow[dr, "\bigcap"'] & & & & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[dl, "\bigcup^{\mathsf{op}}"] \\
 & \mathcal{P}(X) \arrow[rr, "(-)^{\mathsf{c}}"'] & & \mathcal{P}(X)^{\mathsf{op}}, &
\end{tikzcd}$$

commutes, i.e. we have

$$\left(\bigcap_{U\in\mathcal{U}} U\right)^{\mathsf{c}} = \bigcup_{U\in\mathcal{U}} U^{\mathsf{c}}$$

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

12. *Interaction With Complements III.* The diagram

$$\begin{tikzcd}[column sep=small]
 & \mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[dr, dashed, "\sim"] & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)}\star(-)^{\mathsf{c}}"] \arrow[d, "\bigcup"'] & & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[d, "\bigcap^{\mathsf{op}}"] \\
\mathcal{P}(X) \arrow[rr, "(-)^{\mathsf{c}}"'] & & \mathcal{P}(X)^{\mathsf{op}},
\end{tikzcd}$$

commutes, i.e. we have

$$\left(\bigcup_{U\in\mathcal{U}} U\right)^{\mathsf{c}} = \bigcap_{U\in\mathcal{U}} U^{\mathsf{c}}$$

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

13. *Interaction With Symmetric Differences.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "\triangle"] \arrow[d, "\bigcap\times\bigcap"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\triangle"'] & \mathcal{P}(X),
\end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcap_{W\in\mathcal{U}\triangle\mathcal{V}} W \neq \left(\bigcap_{U\in\mathcal{U}} U\right) \triangle \left(\bigcap_{V\in\mathcal{V}} V\right)$$

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

14. *Interaction With Internal Homs I.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "{[-_1,-_2]_{\mathcal{P}(X)}}"] \arrow[d, "\bigcap^{\mathsf{op}}\times\bigcap^{\mathsf{op}}"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "{[-_1,-_2]_X}"'] & \mathcal{P}(X),
\end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcap_{W\in[\mathcal{U},\mathcal{V}]_{\mathcal{P}(X)}} W \neq \left[\bigcap_{U\in\mathcal{U}} U, \bigcap_{V\in\mathcal{V}} V\right]_X$$

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

15. *Interaction With Internal Homs II.* The diagram

$$\begin{tikzcd}
 & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[dr, "\bigcap^{\mathsf{op}}"] & \\
\mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[ur, dashed, "\sim"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\star[-,V]_X"'] & & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "{[-,V]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[rr, "\bigcup"'] & & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\left[\bigcap_{U\in\mathcal{U}} U, V\right]_X = \bigcup_{U\in\mathcal{U}} [U, V]_X$$

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

16. *Interaction With Internal Homs III.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcap"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\star[U,-]_X"'] & \mathcal{P}(X) \arrow[d, "{[U,-]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcap"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\left[U, \bigcap_{V\in\mathcal{V}} V\right]_X = \bigcap_{V\in\mathcal{V}} [U, V]_X$$

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

17. *Interaction With Direct Images.* Let $f\colon X \to Y$ be a map of sets. The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_!)_!"] \arrow[d, "\cap"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\cap"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{U\in\mathcal{U}} f_!(U) = \bigcap_{V\in f_!(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_!(\mathcal{U}) \overset{\text{def}}{=} (f_!)_!(\mathcal{U})$.

18. *Interaction With Inverse Images.* Let $f\colon X \to Y$ be a map of sets. The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(Y)) \arrow[r, "(f^{-1})^{-1}"] \arrow[d, "\cap"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\cap"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{V\in\mathcal{V}} f^{-1}(V) = \bigcap_{U\in f^{-1}(\mathcal{U})} U$$

for each $\mathcal{V} \in \mathcal{P}(Y)$, where $f^{-1}(\mathcal{V}) \overset{\text{def}}{=} (f^{-1})^{-1}(\mathcal{V})$.

19. *Interaction With Codirect Images.* Let $f\colon X \to Y$ be a map of sets. The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_*)_*"] \arrow[d, "\cap"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\cap"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{U \in \mathcal{U}} f_*(U) = \bigcap_{V \in f_*(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_*(\mathcal{U}) \stackrel{\text{def}}{=} (f_*)_*(\mathcal{U})$.

20. *Interaction With Unions of Families I.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcap"] \arrow[d, "\bigcup \star \mathrm{id}_{\mathcal{P}(X)}"'] & \mathcal{P}(\mathcal{P}(x)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \arrow[r, "\bigcap"'] & X
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{U \in \bigcup_{A \in \mathcal{A}} A} U = \bigcap_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right)$$

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

21. *Interaction With Unions of Families II.* Let X be a set and consider the compositions

$$\begin{tikzcd}
 & & & \mathcal{P}(\mathcal{P}(\mathcal{P}(X))) \arrow[dlll, "\bigcap \star \mathrm{id}_{\mathcal{P}(X)}"'] \arrow[dl, "\bigcup \star \mathrm{id}_{\mathcal{P}(X)}"] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcap"'] \arrow[drrr, "\mathrm{id}_{\mathcal{P}(X)} \star \bigcup"] & & & \\
\mathcal{P}(\mathcal{P}(X)) \arrow[drrr, "\bigcup"'] & & \mathcal{P}(\mathcal{P}(X)) \arrow[dr, "\bigcap"] & & \mathcal{P}(\mathcal{P}(X)) \arrow[dl, "\bigcup"'] & & \mathcal{P}(\mathcal{P}(X)) \arrow[dlll, "\bigcap"] \\
 & & & \mathcal{P}(X) & & &
\end{tikzcd}$$

given by

$$\mathcal{A} \mapsto \bigcup_{U \in \bigcap_{A \in \mathcal{A}} A} U, \qquad \mathcal{A} \mapsto \bigcap_{U \in \bigcup_{A \in \mathcal{A}} A} U,$$

$$\mathcal{A} \mapsto \bigcup_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right), \quad \mathcal{A} \mapsto \bigcap_{A \in \mathcal{A}} \left(\bigcup_{U \in A} U \right)$$

for each $\mathcal{A} \in \mathcal{P}(\mathcal{P}(\mathcal{P}(X)))$. We have the following inclusions:

$$\begin{tikzcd}
 & \displaystyle\bigcup_{U \in \bigcap_{A \in \mathcal{A}} A} U \arrow[dr, hook] & \\
\displaystyle\bigcup_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right) & & \displaystyle\bigcap_{A \in \mathcal{A}} \left(\bigcup_{U \in A} U \right) \\
 & \displaystyle\bigcap_{U \in \bigcup_{A \in \mathcal{A}} A} U \arrow[ul, hook] \arrow[uu, hook] \arrow[ur, hook] &
\end{tikzcd}$$

All other possible inclusions fail to hold in general.

PROOF 4.3.7.1.3 ► PROOF OF PROPOSITION 4.3.6.1.2

Item 1: Functoriality

Since $\mathcal{P}(X)$ is posetal, it suffices to prove the condition $(\star)$. So let $\mathcal{U}, \mathcal{V} \in$

$\mathcal{P}(\mathcal{P}(X))$ with $\mathcal{U} \subset \mathcal{V}$. We claim that

$$\bigcap_{V \in \mathcal{V}} V \subset \bigcap_{U \in \mathcal{U}} U.$$

Indeed, if $x \in \bigcap_{V \in \mathcal{V}} V$, then $x \in V$ for all $V \in \mathcal{V}$. But since $\mathcal{U} \subset \mathcal{V}$, it follows that $x \in U$ for all $U \in \mathcal{U}$ as well. Thus $x \in \bigcap_{U \in \mathcal{U}} U$, which gives our desired inclusion.

Item 2: Oplax Associativity

We have

$$\begin{aligned}
\bigcap_{A \in \mathcal{A}} \left(\bigcap_{U \in A} U \right) &\overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } A \in \mathcal{A}, \\ \text{we have } x \in \bigcap_{U \in A} U \end{array} \right\} \\
&\overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } A \in \mathcal{A} \text{ and each} \\ U \in A, \text{ we have } x \in U \end{array} \right\} \\
&= \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } U \in \bigcup_{A \in \mathcal{A}} A, \\ \text{we have } x \in U \end{array} \right\} \\
&\subset \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } U \in \bigcap_{A \in \mathcal{A}} A, \\ \text{we have } x \in U \end{array} \right\} \\
&\overset{\text{def}}{=} \bigcap_{U \in \bigcap_{A \in \mathcal{A}} A} U.
\end{aligned}$$

Since $\mathcal{P}(X)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2). This finishes the proof.

Item 3: Left Unitality

We have

$$\bigcap_{V \in \{U\}} V \overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } V \in \{U\}, \\ \text{we have } x \in U \end{array} \right\}$$

$$
\begin{aligned}
&= \{x \in X \mid x \in U\} \\
&= U.
\end{aligned}
$$

This finishes the proof.

Item 4: Oplax Right Unitality

If $U = \emptyset$, then we have

$$
\begin{aligned}
\bigcap_{\{u\} \in \chi_X(U)} \{u\} &= \bigcap_{\{u\} \in \emptyset} \{u\} \\
&= X,
\end{aligned}
$$

so $\bigcap_{\{u\} \in \chi_X(U)} \{u\} = X \neq \emptyset = U$. When U is nonempty, we have two cases:

1. If U is a singleton, say $U = \{u\}$, we have

$$
\begin{aligned}
\bigcap_{\{u\} \in \chi_X(U)} \{u\} &= \{u\} \\
&\overset{\text{def}}{=} U.
\end{aligned}
$$

2. If U contains at least two elements, we have

$$
\begin{aligned}
\bigcap_{\{u\} \in \chi_X(U)} \{u\} &= \emptyset \\
&\subset U.
\end{aligned}
$$

This finishes the proof.

Item 5: Interaction With Unions I

We have

$$
\begin{aligned}
\bigcap_{W \in \mathcal{U} \cup \mathcal{V}} W &\overset{\text{def}}{=} \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } W \in \mathcal{U} \cup \mathcal{V}, \\ \text{we have } x \in W \end{array} \right\} \\
&= \left\{ x \in X \;\middle|\; \begin{array}{l} \text{for each } W \in \mathcal{U} \text{ and each} \\ W \in \mathcal{V}, \text{ we have } x \in W \end{array} \right\}
\end{aligned}
$$

$$
\begin{aligned}
&\overset{\text{def}}{=} \left\{x \in X \;\middle|\; \begin{array}{l}\text{for each } W \in \mathcal{U},\\ \text{we have } x \in W\end{array}\right\}\\
&\quad \cap \left\{x \in X \;\middle|\; \begin{array}{l}\text{for each } W \in \mathcal{V},\\ \text{we have } x \in W\end{array}\right\}\\
&\overset{\text{def}}{=} \left(\bigcap_{W \in \mathcal{U}} W\right) \cap \left(\bigcap_{W \in \mathcal{V}} W\right)\\
&= \left(\bigcap_{U \in \mathcal{U}} U\right) \cap \left(\bigcap_{V \in \mathcal{V}} V\right).
\end{aligned}
$$

This finishes the proof.

Item 6: Interaction With Unions II

Omitted.

Item 7: Interaction With Intersections I

We have

$$
\begin{aligned}
\left(\bigcap_{U \in \mathcal{U}} U\right) \cap \left(\bigcap_{V \in \mathcal{V}} V\right) &\overset{\text{def}}{=} \left\{x \in X \;\middle|\; \begin{array}{l}\text{for each } U \in \mathcal{U},\\ \text{we have } x \in U\end{array}\right\}\\
&\quad \cup \left\{x \in X \;\middle|\; \begin{array}{l}\text{for each } V \in \mathcal{V},\\ \text{we have } x \in V\end{array}\right\}\\
&= \left\{x \in X \;\middle|\; \begin{array}{l}\text{for each } W \in \mathcal{U} \cap \mathcal{V},\\ \text{we have } x \in W\end{array}\right\}\\
&\subset \left\{x \in X \;\middle|\; \begin{array}{l}\text{for each } W \in \mathcal{U} \cup \mathcal{V},\\ \text{we have } x \in W\end{array}\right\}\\
&\overset{\text{def}}{=} \bigcap_{W \in \mathcal{U} \cap \mathcal{V}} W.
\end{aligned}
$$

Since $\mathcal{P}(X)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2). This finishes the proof.

Item 8: Interaction With Intersections II

Omitted.

Item 9: Interaction With Differences

Let $X = \{0, 1\}$, let $\mathcal{U} = \{\{0\}, \{0, 1\}\}$, and let $\mathcal{V} = \{\{0\}\}$. We have

$$\begin{aligned}\bigcap_{W \in \mathcal{U} \setminus \mathcal{V}} U &= \bigcap_{W \in \{\{0,1\}\}} W \\ &= \{0, 1\},\end{aligned}$$

whereas

$$\begin{aligned}\left(\bigcap_{U \in \mathcal{U}} U\right) \setminus \left(\bigcap_{V \in \mathcal{V}} V\right) &= \{0\} \setminus \{0\} \\ &= \emptyset.\end{aligned}$$

Thus we have

$$\bigcap_{W \in \mathcal{U} \setminus \mathcal{V}} W = \{0, 1\} \neq \emptyset = \left(\bigcap_{U \in \mathcal{U}} U\right) \setminus \left(\bigcap_{V \in \mathcal{V}} V\right).$$

This finishes the proof.

Item 10: Interaction With Complements I

Let $X = \{0, 1\}$ and let $\mathcal{U} = \{\{0\}\}$. We have

$$\begin{aligned}\bigcap_{W \in \mathcal{U}^{\mathsf{c}}} U &= \bigcap_{W \in \{\emptyset, \{1\}, \{0,1\}\}} W \\ &= \emptyset,\end{aligned}$$

whereas

$$\begin{aligned}\bigcap_{U \in \mathcal{U}} U^{\mathsf{c}} &= \{0\}^{\mathsf{c}} \\ &= \{1\}.\end{aligned}$$

Thus we have

$$\bigcap_{W \in \mathcal{U}^{\mathsf{c}}} U = \emptyset \neq \{1\} = \bigcap_{U \in \mathcal{U}} U^{\mathsf{c}}.$$

This finishes the proof.

Item 11: Interaction With Complements II

This is a repetition of Item 12 of Proposition 4.3.6.1.2 and is proved there.

Item 12: Interaction With Complements III

This is a repetition of Item 11 of Proposition 4.3.6.1.2 and is proved there.

Item 13: Interaction With Symmetric Differences

Let $X = \{0, 1\}$, let $\mathcal{U} = \{\{0, 1\}\}$, and let $\mathcal{V} = \{\{0\}, \{0, 1\}\}$. We have

$$\begin{aligned}\bigcap_{W\in\mathcal{U}\triangle\mathcal{V}} W &= \bigcap_{W\in\{\{0\}\}} W\\ &= \{0\},\end{aligned}$$

whereas

$$\begin{aligned}\left(\bigcap_{U\in\mathcal{U}} U\right) \triangle \left(\bigcap_{V\in\mathcal{V}} V\right) &= \{0, 1\} \triangle \{0\}\\ &= \emptyset,\end{aligned}$$

Thus we have

$$\bigcap_{W\in\mathcal{U}\triangle\mathcal{V}} W = \{0\} \neq \emptyset = \left(\bigcap_{U\in\mathcal{U}} U\right) \triangle \left(\bigcap_{V\in\mathcal{V}} V\right).$$

This finishes the proof.

Item 14: Interaction With Internal Homs I

This is a repetition of Item 10 of Proposition 4.4.7.1.4 and is proved there.

Item 15: Interaction With Internal Homs II

This is a repetition of Item 11 of Proposition 4.4.7.1.4 and is proved there.

Item 16: Interaction With Internal Homs III

This is a repetition of Item 12 of Proposition 4.4.7.1.4 and is proved there.

Item 17: Interaction With Direct Images

This is a repetition of Item 4 of Proposition 4.6.1.1.5 and is proved there.

Item 18: Interaction With Inverse Images

This is a repetition of Item 4 of Proposition 4.6.2.1.3 and is proved there.

Item 19: Interaction With Codirect Images

This is a repetition of Item 4 of Proposition 4.6.3.1.7 and is proved there.

Item 20: Interaction With Unions of Families I

This is a repetition of Item 20 of Proposition 4.3.6.1.2 and is proved there.

Item 21: Interaction With Unions of Families II

This is a repetition of Item 21 of Proposition 4.3.6.1.2 and is proved there.

4.3.8 Binary Unions

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

Definition 4.3.8.1.1 ► Binary Unions

The **union of** U **and** V is the set $U \cup V$ defined by

$$\begin{aligned} U \cup V &\overset{\text{def}}{=} \bigcup_{z \in \{U,V\}} z \\ &\overset{\text{def}}{=} \{x \in X \mid x \in U \text{ or } x \in V\}. \end{aligned}$$

Proposition 4.3.8.1.2 ► Properties of Binary Unions

Let X be a set.

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

$$\begin{aligned} U \cup - \colon & \quad (\mathcal{P}(X), \subset) && \to (\mathcal{P}(X), \subset), \\ - \cup V \colon & \quad (\mathcal{P}(X), \subset) && \to (\mathcal{P}(X), \subset), \\ -_1 \cup -_2 \colon & \quad (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \subset) && \to (\mathcal{P}(X), \subset). \end{aligned}$$

   In particular, the following statements hold for each $U, V, A, B \in \mathcal{P}(X)$:

   (a) If $U \subset A$, then $U \cup V \subset A \cup V$.

(b) If $V \subset B$, then $U \cup V \subset U \cup B$.

(c) If $U \subset A$ and $V \subset B$, then $U \cup V \subset A \cup B$.

2. *Associativity*. The diagram

$$
\begin{tikzcd}
 & \mathcal{P}(X) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)} \times \cup"] & \\
(\mathcal{P}(X) \times \mathcal{P}(X)) \times \mathcal{P}(X) \arrow[ur, dashed, "\alpha^{\mathsf{Sets}}_{\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}", "\sim"'] \arrow[dr, "\cup \times \mathrm{id}_{\mathcal{P}(X)}"'] & & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cup"] \\
 & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\cup"'] & \mathcal{P}(X),
\end{tikzcd}
$$

commutes, i.e. we have an equality of sets

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

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

3. *Unitality*. The diagrams

$$
\begin{tikzcd}
\mathrm{pt} \times \mathcal{P}(X) \arrow[r, "{[\emptyset] \times \mathrm{id}_{\mathcal{P}(X)}}"] \arrow[dr, dashed, "\sim", "\lambda^{\mathsf{Sets}}_{\mathcal{P}(X)}"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cup"] \\
 & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(X) \times \mathrm{pt} \arrow[r, "{\mathrm{id}_{\mathcal{P}(X)} \times [\emptyset]}"] \arrow[dr, dashed, "\sim", "\rho^{\mathsf{Sets}}_{\mathcal{P}(X)}"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cup"] \\
 & \mathcal{P}(X)
\end{tikzcd}
$$

commute, i.e. we have equalities of sets

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

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

4. *Commutativity*. The diagram

$$
\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\sigma^{\mathsf{Sets}}_{\mathcal{P}(X),\mathcal{P}(X)}"] \arrow[dr, "\cup"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cup"] \\
 & \mathcal{P}(X)
\end{tikzcd}
$$

commutes, i.e. we have an equality of sets

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

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

5. *Annihilation With X.* The diagrams

$$\begin{tikzcd}
 & \mathrm{pt} \times \mathrm{pt} \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathrm{pt} \times \mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathrm{pt}} \times \epsilon^{\mathsf{Sets}}_{\mathcal{P}(X)}"] \arrow[d, "{[X]} \times \mathrm{id}_{\mathcal{P}(X)}"'] & & \mathrm{pt} \arrow[d, "{[X]}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[rr, "\cup"'] & & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
 & \mathrm{pt} \times \mathrm{pt} \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathcal{P}(X) \times \mathrm{pt} \arrow[ur, "\epsilon^{\mathsf{Sets}}_{\mathcal{P}(X)} \times \mathrm{id}_{\mathrm{pt}}"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \times {[X]}"'] & & \mathrm{pt} \arrow[d, "{[X]}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[rr, "\cup"'] & & \mathcal{P}(X)
\end{tikzcd}$$

commute, i.e. we have equalities of sets

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

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

6. *Distributivity of Unions Over Intersections.* The diagrams

$$\begin{tikzcd}
 & (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathcal{P}(X) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)} \times (\mathrm{id}_{\mathcal{P}(X)} \times \mathrm{id}_{\mathcal{P}(X)})"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \times \cap"'] & & (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[d, "\cup \times \cup"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[dr, "\cup"'] & & \mathcal{P}(X) \times \mathcal{P}(X), \arrow[dl, "\cap"] \\
 & \mathcal{P}(X) &
\end{tikzcd}
\qquad
\begin{tikzcd}
 & (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
(\mathcal{P}(X) \times \mathcal{P}(X)) \times \mathcal{P}(X) \arrow[ur, "(\mathrm{id}_{\mathcal{P}(X)} \times \mathrm{id}_{\mathcal{P}(X)}) \times \Delta_{\mathcal{P}(X)}"] \arrow[d, "\cap \times \mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X) \times \mathcal{P}(X)) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[d, "\cup \times \cup"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[dr, "\cup"'] & & \mathcal{P}(X) \times \mathcal{P}(X), \arrow[dl, "\cap"] \\
 & \mathcal{P}(X) &
\end{tikzcd}$$

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

7. *Distributivity of Intersections Over Unions.* The diagrams

$$
\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathcal{P}(X)\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)}\times(\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)})"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\times\cup"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\cap\times\cap"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\cap"'] & & \mathcal{P}(X)\times\mathcal{P}(X), \arrow[dl, "\cup"] \\
 & \mathcal{P}(X) &
\end{tikzcd}
\qquad
\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
(\mathcal{P}(X)\times\mathcal{P}(X))\times\mathcal{P}(X) \arrow[ur, "(\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)})\times\Delta_{\mathcal{P}(X)}"] \arrow[d, "\cup\times\mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\cap\times\cap"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\cap"'] & & \mathcal{P}(X)\times\mathcal{P}(X), \arrow[dl, "\cup"] \\
 & \mathcal{P}(X) &
\end{tikzcd}
$$

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

8. *Idempotency.* The diagram

$$
\begin{tikzcd}
\mathcal{P}(X) \arrow[r, "\Delta_{\mathcal{P}(X)}"] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)}"'] & \mathcal{P}(X)\times\mathcal{P}(X) \arrow[d, "\cup"] \\
 & \mathcal{P}(X)
\end{tikzcd}
$$

commutes, i.e. we have an equality of sets

$$
U \cup U = U
$$

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

9. *Via Intersections and Symmetric Differences.* The diagram

$$
\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[r, "\triangle\times\cap"] & \mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\triangle"] & \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[ur, "\Delta_{\mathcal{P}(X)\times\mathcal{P}(X)}"] \arrow[rrr, "\cup"'] & & & \mathcal{P}(X)
\end{tikzcd}
$$

commutes, i.e. we have an equality of sets

$$
U \cup V = (U \mathbin{\triangle} V) \mathbin{\triangle} (U \cap V)
$$

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

10. *Interaction With Characteristic Functions I.* We have

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

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

11. *Interaction With Characteristic Functions II.* We have

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

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

12. *Interaction With Direct Images.* Let $f : X \to Y$ be a function. The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_! \times f_!"] \arrow[d, "\cup"'] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cup"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_!(U \cup V) = f_!(U) \cup f_!(V)$$

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

13. *Interaction With Inverse Images.* Let $f : X \to Y$ be a function. The diagram

$$\begin{tikzcd}
\mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[r, "f^{-1} \times f^{-1}"] \arrow[d, "\cup"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cup"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U \cup V) = f^{-1}(U) \cup f^{-1}(V)$$

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

14. *Interaction With Codirect Images.* Let $f \colon X \to Y$ be a function. We have a natural transformation

$$\begin{tikzcd} \mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_* \times f_*"] \arrow[d, "\cup"'] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cup"] \\ \mathcal{P}(X) \arrow[r, "f_*"'] \arrow[ur, phantom, "\subset"] & \mathcal{P}(Y) \end{tikzcd}$$

with components

$$f_*(U) \cup f_*(V) \subset f_*(U \cup V)$$

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

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

Proof 4.3.8.1.3 ► Proof of Proposition 4.3.8.1.2

Item 1: Functoriality

See [Pro25an].

Item 2: Associativity

See [Pro25ba].

Item 3: Unitality

This follows from [Pro25bd] and Item 4.

Item 4: Commutativity

See [Pro25bb].

Item 5: Annihilation With X

We have

$$\begin{aligned} U \cup X &\stackrel{\text{def}}{=} \{x \in X \mid x \in U \text{ or } x \in X\} \\ &= \{x \in X \mid x \in X\}, \end{aligned}$$

$$= X$$

and

$$\begin{aligned} X \cup V &\stackrel{\text{def}}{=} \{x \in X \mid x \in X \text{ or } x \in V\} \\ &= \{x \in X \mid x \in X\} \\ &= X. \end{aligned}$$

This finishes the proof.

Item 6: Distributivity of Unions Over Intersections

See [Pro25az].

Item 7: Distributivity of Intersections Over Unions

See [Pro25aj].

Item 8: Idempotency

See [Pro25am].

Item 9: Via Intersections and Symmetric Differences

See [Pro25ay].

Item 10: Interaction With Characteristic Functions I

See [Pro25h].

Item 11: Interaction With Characteristic Functions II

See [Pro25h].

Item 12: Interaction With Direct Images

See [Pro25p].

Item 13: Interaction With Inverse Images

See [Pro25y].

Item 14: Interaction With Codirect Images

This is a repetition of Item 5 of Proposition 4.6.3.1.7 and is proved there.

Item 15: Interaction With Powersets and Semirings

This follows from Items 2 to 4 and 8 of this propostition and Items 3 to 6 and 8 of Proposition 4.3.9.1.2. □

4.3.9 Binary Intersections

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

Definition 4.3.9.1.1 ▶ Binary Intersections

The **intersection of** U **and** V is the set $U \cap V$ defined by

$$\begin{aligned} U \cap V &\overset{\text{def}}{=} \bigcap_{z \in \{U,V\}} z \\ &\overset{\text{def}}{=} \{x \in X \mid x \in U \text{ or } x \in V\}. \end{aligned}$$

Proposition 4.3.9.1.2 ▶ Properties of Binary Intersections

Let X be a set.

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

$$\begin{aligned} U \cap - \colon & \quad (\mathcal{P}(X), \subset) && \to (\mathcal{P}(X), \subset), \\ - \cap V \colon & \quad (\mathcal{P}(X), \subset) && \to (\mathcal{P}(X), \subset), \\ -_1 \cap -_2 \colon & \quad (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \subset) && \to (\mathcal{P}(X), \subset). \end{aligned}$$

   In particular, the following statements hold for each $U, V, A, B \in \mathcal{P}(X)$:

   (a) If $U \subset A$, then $U \cap V \subset A \cap V$.

   (b) If $V \subset B$, then $U \cap V \subset U \cap B$.

   (c) If $U \subset A$ and $V \subset B$, then $U \cap V \subset A \cap B$.

2. *Adjointness.* We have adjunctions

$$(U \cap - \dashv [U, -]_X) \colon \quad \begin{tikzcd} \mathcal{P}(X) \arrow[r, bend left, "U \cap -"] \arrow[r, phantom, "\perp"] & \mathcal{P}(X), \arrow[l, bend left, "{[U,-]_X}"] \end{tikzcd}$$

$$(- \cap V \dashv [V, -]_X) \colon \quad \begin{tikzcd} \mathcal{P}(X) \arrow[r, bend left, "- \cap V"] \arrow[r, phantom, "\perp"] & \mathcal{P}(X), \arrow[l, bend left, "{[V,-]_X}"] \end{tikzcd}$$

   witnessed by bijections

$$\mathrm{Hom}_{\mathcal{P}(X)}(U \cap V, W) \cong \mathrm{Hom}_{\mathcal{P}(X)}(U, [V, W]_X),$$

$$\mathrm{Hom}_{\mathcal{P}(X)}(U \cap V, W) \cong \mathrm{Hom}_{\mathcal{P}(X)}(V, [U, W]_X),$$

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

$$[-_1, -_2]_X \colon \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \to \mathcal{P}(X)$$

is the bifunctor of Section 4.4.7. In particular, the following statements hold for each $U, V, W \in \mathcal{P}(X)$:

(a) The following conditions are equivalent:

i. We have $U \cap V \subset W$.

ii. We have $U \subset [V, W]_X$.

(b) The following conditions are equivalent:

i. We have $U \cap V \subset W$.

ii. We have $V \subset [U, W]_X$.

3. *Associativity.* The diagram

$$\begin{tikzcd}
 & \mathcal{P}(X) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)} \times \cap"] & \\
(\mathcal{P}(X) \times \mathcal{P}(X)) \times \mathcal{P}(X) \arrow[ur, dashed, "\alpha^{\mathsf{Sets}}_{\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}", "\sim"'] \arrow[d, "\cap \times \mathrm{id}_{\mathcal{P}(X)}"'] & & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cap"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[rr, "\cap"'] & & \mathcal{P}(X),
\end{tikzcd}$$

commutes, i.e. we have an equality of sets

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

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

4. *Unitality.* The diagrams

$$\begin{tikzcd}
\mathrm{pt} \times \mathcal{P}(X) \arrow[r, "{[X] \times \mathrm{id}_{\mathcal{P}(X)}}"] \arrow[dr, dashed, "\lambda^{\mathsf{Sets}}_{\mathcal{P}(X)}"', "\sim"] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cap"] \\
 & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(X) \times \mathrm{pt} \arrow[r, "{\mathrm{id}_{\mathcal{P}(X)} \times [X]}"] \arrow[dr, dashed, "\rho^{\mathsf{Sets}}_{\mathcal{P}(X)}"', "\sim"] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cap"] \\
 & \mathcal{P}(X)
\end{tikzcd}$$

commute, i.e. we have equalities of sets

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

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

5. *Commutativity.* The diagram

$$
\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\sigma^{\mathsf{Sets}}_{\mathcal{P}(X),\mathcal{P}(X)}"] \arrow[dr, "\cap"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cap"] \\
 & \mathcal{P}(X)
\end{tikzcd}
$$

commutes, i.e. we have an equality of sets

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

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

6. *Annihilation With the Empty Set.* The diagrams

$$
\begin{tikzcd}[column sep=tiny]
 & \mathrm{pt} \times \mathrm{pt} \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathrm{pt} \times \mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathrm{pt}} \times \epsilon^{\mathsf{Sets}}_{\mathcal{P}(X)}"] \arrow[d, "{[\emptyset]} \times \mathrm{id}_{\mathcal{P}(X)}"'] & & \mathrm{pt} \arrow[d, "{[\emptyset]}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[rr, "\cap"'] & & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}[column sep=tiny]
 & \mathrm{pt} \times \mathrm{pt} \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathcal{P}(X) \times \mathrm{pt} \arrow[ur, "\epsilon^{\mathsf{Sets}}_{\mathcal{P}(X)} \times \mathrm{id}_{\mathrm{pt}}"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \times {[\emptyset]}"'] & & \mathrm{pt} \arrow[d, "{[\emptyset]}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[rr, "\cap"'] & & \mathcal{P}(X)
\end{tikzcd}
$$

commute, i.e. we have equalities of sets

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

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

7. *Distributivity of Unions Over Intersections.* The diagrams

$$
\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathcal{P}(X)\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)}\times(\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)})"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\times\cap"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\cup\times\cup"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\cup"'] & & \mathcal{P}(X)\times\mathcal{P}(X), \arrow[dl, "\cap"] \\
 & \mathcal{P}(X) &
\end{tikzcd}
\qquad
\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
(\mathcal{P}(X)\times\mathcal{P}(X))\times\mathcal{P}(X) \arrow[ur, "(\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)})\times\Delta_{\mathcal{P}(X)}"] \arrow[d, "\cap\times\mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\cup\times\cup"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\cup"'] & & \mathcal{P}(X)\times\mathcal{P}(X), \arrow[dl, "\cap"] \\
 & \mathcal{P}(X) &
\end{tikzcd}
$$

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

8. *Distributivity of Intersections Over Unions.* The diagrams

$$
\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
\mathcal{P}(X)\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[ur, "\Delta_{\mathcal{P}(X)}\times(\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)})"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)}\times\cup"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\cap\times\cap"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\cap"'] & & \mathcal{P}(X)\times\mathcal{P}(X), \arrow[dl, "\cup"] \\
 & \mathcal{P}(X) &
\end{tikzcd}
\qquad
\begin{tikzcd}
 & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[dr, "\mu^{\mathsf{Sets}}_{4|\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}"] & \\
(\mathcal{P}(X)\times\mathcal{P}(X))\times\mathcal{P}(X) \arrow[ur, "(\mathrm{id}_{\mathcal{P}(X)}\times\mathrm{id}_{\mathcal{P}(X)})\times\Delta_{\mathcal{P}(X)}"] \arrow[d, "\cup\times\mathrm{id}_{\mathcal{P}(X)}"'] & & (\mathcal{P}(X)\times\mathcal{P}(X))\times(\mathcal{P}(X)\times\mathcal{P}(X)) \arrow[d, "\cap\times\cap"] \\
\mathcal{P}(X)\times\mathcal{P}(X) \arrow[dr, "\cap"'] & & \mathcal{P}(X)\times\mathcal{P}(X), \arrow[dl, "\cup"] \\
 & \mathcal{P}(X) &
\end{tikzcd}
$$

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

9. *Idempotency.* The diagram

$$
\begin{tikzcd}
\mathcal{P}(X) \arrow[r, "\Delta_{\mathcal{P}(X)}"] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)}"'] & \mathcal{P}(X)\times\mathcal{P}(X) \arrow[d, "\cap"] \\
 & \mathcal{P}(X)
\end{tikzcd}
$$

commutes, i.e. we have an equality of sets

$$U \cap U = U$$

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

10. *Interaction With Characteristic Functions I.* We have

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

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

11. *Interaction With Characteristic Functions II.* We have

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

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

12. *Interaction With Direct Images.* Let $f : X \to Y$ be a function. We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_! \times f_!"] \arrow[d, "\cap"'] \arrow[dr, phantom, "\subset"] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cap"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_!(U \cap V) \subset f_!(U) \cap f_!(V)$$

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

13. *Interaction With Inverse Images.* Let $f : X \to Y$ be a function. The diagram

$$\begin{tikzcd}
\mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[r, "f^{-1} \times f^{-1}"] \arrow[d, "\cap"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cap"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U \cap V) = f^{-1}(U) \cap f^{-1}(V)$$

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

14. *Interaction With Codirect Images.* Let $f \colon X \to Y$ be a function. The diagram

$$\begin{tikzcd} \mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_* \times f_*"] \arrow[d, "\cap"'] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cap"] \\ \mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y) \end{tikzcd}$$

commutes, i.e. we have

$$f_*(U) \cap f_*(V) = f_*(U \cap V)$$

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

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

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

Proof 4.3.9.1.3 ► Proof of Proposition 4.3.9.1.2

Item 1: Functoriality

See [Pro25al].

Item 2: Adjointness

See [MSE 267469].

Item 3: Associativity

See [Pro25r].

Item 4: Unitality

This follows from [Pro25v] and Item 5.

Item 5: Commutativity

See [Pro25s].

Item 6: Annihilation With the Empty Set

This follows from [Pro25t] and Item 5.

Item 7: Distributivity of Unions Over Intersections

See [Pro25az].

Item 8: Distributivity of Intersections Over Unions

See [Pro25aj].

Item 9: Idempotency

See [Pro25ak].

Item 10: Interaction With Characteristic Functions I

See [Pro25e].

Item 11: Interaction With Characteristic Functions II

See [Pro25e].

Item 12: Interaction With Direct Images

See [Pro25n].

Item 13: Interaction With Inverse Images

See [Pro25w].

Item 14: Interaction With Codirect Images

This is a repetition of Item 6 of Proposition 4.6.3.1.7 and is proved there.

Item 15: Interaction With Powersets and Monoids With Zero

This follows from Items 3 to 6.

Item 16: Interaction With Powersets and Semirings

This follows from Items 2 to 4 and 8 and Items 3 to 6 and 8 of Proposition 4.3.9.1.2.

4.3.10 Differences

Let X and Y be sets.

Definition 4.3.10.1.1 ▶ Differences

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

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

Proposition 4.3.10.1.2 ▶ Properties of Differences

Let X be a set.

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

$$\begin{aligned} U \setminus -\colon \quad & (\mathcal{P}(X), \supset) && \to (\mathcal{P}(X), \subset), \\ - \setminus V\colon \quad & (\mathcal{P}(X), \subset) && \to (\mathcal{P}(X), \subset), \\ -_1 \setminus -_2\colon \quad & (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \supset) && \to (\mathcal{P}(X), \subset). \end{aligned}$$

   In particular, the following statements hold for each $U, V, A, B \in \mathcal{P}(X)$:

   (a) If $U \subset A$, then $U \setminus V \subset A \setminus V$.

   (b) If $V \subset B$, then $U \setminus B \subset U \setminus V$.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$U \setminus V = U \cap V^{\mathsf{c}}$$

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

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

$$U \setminus V = U \mathbin{\triangle} (U \cap V)$$

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

11. *Left Annihilation.* We have

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

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

12. *Right Unitality.* We have

$$U \setminus \emptyset = U$$

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

13. *Right Annihilation.* We have

$$U \setminus X = \emptyset$$

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

14. *Invertibility.* We have

$$U \setminus U = \emptyset$$

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

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

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

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

16. *Interaction With Characteristic Functions.* We have

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

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

17. *Interaction With Direct Images.* We have a natural transformation

$$\begin{tikzcd} \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_!^{\mathsf{op}} \times f_!"] \arrow[d, "\setminus"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "\setminus"] \\ \mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y) \end{tikzcd}$$

with components

$$f_!(U) \setminus f_!(V) \subset f_!(U \setminus V)$$

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

18. *Interaction With Inverse Images.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[r, "f^{\mathsf{op},-1} \times f^{-1}"] \arrow[d, "\setminus"'] & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[d, "\setminus"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U \setminus V) = f^{-1}(U) \setminus f^{-1}(V)$$

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

19. *Interaction With Codirect Images.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_!^{\mathsf{op}} \times f_!"] \arrow[d, "\setminus"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "\setminus"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_!(U) \setminus f_!(V) \subset f_!(U \setminus V)$$

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

Proof 4.3.10.1.3 ► Proof of Proposition 4.3.10.1.2

Item 1: Functoriality

See [Pro25ad] and [Pro25ah].

Item 2: De Morgan's Laws

See [Pro25k].

Item 3: Interaction With Unions I

See [Pro25l].

Item 4: Interaction With Unions II

We have

$$\begin{aligned}(U \setminus V) \cup W &\overset{\text{def}}{=} \{x \in X \mid (x \in U \text{ and } x \notin V) \text{ or } x \in W\} \\ &= \{x \in X \mid (x \in U \text{ or } x \in W) \text{ and } (x \notin V \text{ or } x \in W)\} \\ &= \{x \in X \mid (x \in U \cup W) \text{ and not } (x \in V \text{ and } x \notin W)\} \\ &= \{x \in X \mid (x \in U \cup W) \text{ and not } (x \in V \setminus W)\} \\ &= \{x \in X \mid (x \in (U \cup W) \setminus (V \setminus W))\} \\ &= (U \cup W) \setminus (V \setminus W).\end{aligned}$$

Item 5: Interaction With Unions III

See [Pro25ai].

Item 6: Interaction With Unions IV

See [Pro25ac].

Item 7: Interaction With Intersections

See [Pro25u].

Item 8: Interaction With Complements

See [Pro25aa].

Item 9: Interaction With Symmetric Differences

See [Pro25ab].

Item 10: Triple Differences

See [Pro25ag].

Item 11: Left Annihilation

The direction $\emptyset \subset \emptyset \setminus U$ always holds. Now assume $x \in \emptyset \setminus U$. Then, $x \in \emptyset$ and $x \notin U$. Hence $\emptyset \setminus U \subset \emptyset$ must hold and the sets are equal.

Item 12: Right Unitality

See [Pro25ae].

Item 13: Right Annihilation

It suffices to show that no $x \in X$ can be an element of $U \setminus X$. Assume $x \in U \setminus X$. Then $x \notin X$, contradicting $x \in X$. This completes the proof.

Item 14: Invertibility

See [Pro25af].

Item 15: Interaction With Containment

The conditions are symmetric in U, W, hence it suffices to show that $V \setminus U \subset W$ implies $V \setminus W \subset U$. So assume $V \setminus U \subset W, x \in V \setminus W$. Then $x \in V, x \notin W$. So by contraposition, $x \notin V \setminus U$. But $x \in V$, so we must have $x \in U$, completing the proof.

Item 16: Interaction With Characteristic Functions

See [Pro25f].

Item 17: Interaction With Direct Images

See [Pro25o].

Item 18: Interaction With Inverse Images

See [Pro25x].

4.3.11 Complements

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

Definition 4.3.11.1.1 ▶ Complements

The **complement of** U is the set U^{c} defined by

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

Proposition 4.3.11.1.2 ▶ Properties of Complements

Let X be a set.

1. *Functoriality.* The assignment $U \mapsto U^{\mathsf{c}}$ defines a functor

$$(-)^{\mathsf{c}} \colon \mathcal{P}(X)^{\mathsf{op}} \to \mathcal{P}(X).$$

In particular, the following statements hold for each $U, V \in \mathcal{P}(X)$:

($\star$) If $U \subset V$, then $V^{\mathsf{c}} \subset U^{\mathsf{c}}$.

2. *De Morgan's Laws.* The diagrams

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X)^{\mathsf{op}} \arrow[r, "\cup^{\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}} \times (-)^{\mathsf{c}}"'] & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\cap"'] & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X)^{\mathsf{op}} \arrow[r, "\cap^{\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}} \times (-)^{\mathsf{c}}"'] & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\cup"'] & \mathcal{P}(X)
\end{tikzcd}$$

commute, i.e. we have equalities of sets

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

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

3. *Involutority.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "(-)^{\mathsf{c}}"] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)^{\mathsf{op}}}"'] & \mathcal{P}(X) \arrow[d, "(-)^{\mathsf{c},\mathsf{op}}"] \\
 & \mathcal{P}(X)^{\mathsf{op}}
\end{tikzcd}$$

commutes, i.e. we have

$$(U^{\mathsf{c}})^{\mathsf{c}} = U$$

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

4. *Interaction With Characteristic Functions.* We have

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

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

5. *Interaction With Direct Images.* Let $f: X \to Y$ be a function. The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_*^{\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}}"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_!(U^{\mathsf{c}}) = f_*(U)^{\mathsf{c}}$$

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

6. *Interaction With Inverse Images.* Let $f: X \to Y$ be a function. The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \arrow[r, "f^{-1,\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}}"'] & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U^{\mathsf{c}}) = f^{-1}(U)^{\mathsf{c}}$$

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

7. *Interaction With Codirect Images.* Let $f: X \to Y$ be a function. The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_!^{\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}}"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_*(U^{\mathsf{c}}) = f_!(U)^{\mathsf{c}}$$

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

Proof 4.3.11.1.3 ▶ Proof of Proposition 4.3.11.1.2

Item 1: Functoriality

This follows from Item 1 of Proposition 4.3.10.1.2.

Item 2: De Morgan's Laws

See [Pro25k].

Item 3: Involutority

See [Pro25i].

Item 4: Interaction With Characteristic Functions

We consider the two cases $x \in U, x \notin U$.

1. If $x \in U$, then $x \notin U^{\mathsf{c}}$. So $\chi_U(x) = 1$ and
$$\begin{aligned} \chi_{U^{\mathsf{c}}}(x) &= 0 \\ &= 1 - \chi_U(x). \end{aligned}$$
2. If $x \notin U$, then $x \in U^{\mathsf{c}}$. So $\chi_U(x) = 0$ and
$$\begin{aligned} \chi_{U^{\mathsf{c}}}(x) &= 1 \\ &= 1 - \chi_U(x). \end{aligned}$$

Hence, the equation holds for all $x \in X$.

Item 5: Interaction With Direct Images

This is a repetition of Item 8 of Proposition 4.6.1.1.5 and is proved there.

Item 6: Interaction With Inverse Images

This is a repetition of Item 8 of Proposition 4.6.2.1.3 and is proved there.

Item 7: Interaction With Codirect Images

This is a repetition of Item 7 of Proposition 4.6.3.1.7 and is proved there.

4.3.12 Symmetric Differences

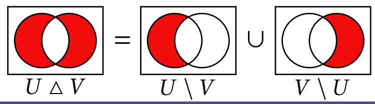
Let X be a set and let $U, V \in \mathcal{P}(X)$.

Definition 4.3.12.1.1 ▶ Symmetric Differences

The **symmetric difference of** U **and** V is the set $U \bigtriangleup V$ defined by[1]

$$U \bigtriangleup V \stackrel{\text{def}}{=} (U \setminus V) \cup (V \setminus U).$$

[1] *Illustration:*



Proposition 4.3.12.1.2 ▶ Properties of Symmetric Differences

Let X be a set.

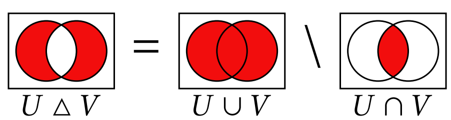
1. *Lack of Functoriality.* The assignment $(U, V) \mapsto U \bigtriangleup V$ ***does not*** in general define functors

$$\begin{aligned} U \bigtriangleup - \colon & \quad (\mathcal{P}(X), \subset) && \to (\mathcal{P}(X), \subset), \\ - \bigtriangleup V \colon & \quad (\mathcal{P}(X), \subset) && \to (\mathcal{P}(X), \subset), \\ -_1 \bigtriangleup -_2 \colon & \quad (\mathcal{P}(X) \times \mathcal{P}(X), \subset \times \subset) && \to (\mathcal{P}(X), \subset). \end{aligned}$$

2. *Via Unions and Intersections.* We have

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

for each $U, V \in \mathcal{P}(X)$, as in the Venn diagram



3. *Symmetric Differences of Disjoint Sets.* If U and V are disjoint, then we have

$$U \bigtriangleup V = U \cup V.$$

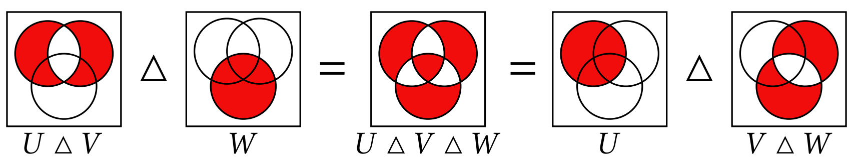
4. *Associativity*. The diagram

$$\begin{tikzcd}
 & \mathcal{P}(X) \times (\mathcal{P}(X) \times \mathcal{P}(X)) \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)} \times \triangle"] & \\
(\mathcal{P}(X) \times \mathcal{P}(X)) \times \mathcal{P}(X) \arrow[ur, dashed, "\alpha^{\mathsf{Sets}}_{\mathcal{P}(X),\mathcal{P}(X),\mathcal{P}(X)}", "\sim"'] \arrow[d, "\triangle \times \mathrm{id}_{\mathcal{P}(X)}"'] & & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\triangle"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[rr, "\triangle"'] & & \mathcal{P}(X),
\end{tikzcd}$$

commutes, i.e. we have

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

for each $U, V, W \in \mathcal{P}(X)$, as in the Venn diagram



5. *Unitality*. The diagrams

$$\begin{tikzcd}
\mathrm{pt} \times \mathcal{P}(X) \arrow[r, "{[\emptyset] \times \mathrm{id}_{\mathcal{P}(X)}}"] \arrow[dr, dashed, "\lambda^{\mathsf{Sets}}_{\mathcal{P}(X)}"', "\sim"] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\triangle"] \\
 & \mathcal{P}(X)
\end{tikzcd}
\qquad
\begin{tikzcd}
\mathcal{P}(X) \times \mathrm{pt} \arrow[r, "{\mathrm{id}_{\mathcal{P}(X)} \times [\emptyset]}"] \arrow[dr, dashed, "\rho^{\mathsf{Sets}}_{\mathcal{P}(X)}"', "\sim"] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\triangle"] \\
 & \mathcal{P}(X)
\end{tikzcd}$$

commute, i.e. we have

$$U \triangle \emptyset = U,$$
$$\emptyset \triangle U = U$$

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

6. *Commutativity.* The diagram

$$\begin{tikzcd} \mathcal{P}(X)\times\mathcal{P}(X) \arrow[r, "\sigma^{\mathsf{Sets}}_{\mathcal{P}(X),\mathcal{P}(X)}"] \arrow[dr, "\triangle"'] & \mathcal{P}(X)\times\mathcal{P}(X) \arrow[d, "\triangle"] \\ & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$U \triangle V = V \triangle U$$

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

7. *Invertibility.* We have

$$U \triangle U = \emptyset$$

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

8. *Interaction With Unions.* We have

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

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

9. *Interaction With Complements I.* We have

$$U \triangle U^{\mathsf{c}} = X$$

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

10. *Interaction With Complements II.* We have

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

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

11. *Interaction With Complements III*. The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\triangle"] \arrow[d, "(-)^{\mathsf{c}} \times (-)^{\mathsf{c}}"'] & \mathcal{P}(X) \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\triangle"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$U^{\mathsf{c}} \triangle V^{\mathsf{c}} = U \triangle V$$

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

12. *"Transitivity"*. We have

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

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

13. *The Triangle Inequality for Symmetric Differences*. We have

$$U \triangle W \subset U \triangle V \cup V \triangle W$$

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

14. *Distributivity Over Intersections*. We have

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

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

15. *Interaction With Characteristic Functions*. We have

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

and thus, in particular, we have

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

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

16. *Bijectivity.* Given $U, V \in \mathcal{P}(X)$, the maps

$$\begin{aligned} U \mathbin{\triangle} -\colon \mathcal{P}(X) &\to \mathcal{P}(X), \\ - \mathbin{\triangle} V\colon \mathcal{P}(X) &\to \mathcal{P}(X) \end{aligned}$$

are self-inverse bijections. Moreover, the map

$$\begin{aligned} \mathcal{P}(X) &\longrightarrow \mathcal{P}(X) \\ C &\longmapsto C \mathbin{\triangle} (U \mathbin{\triangle} V) \end{aligned}$$

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

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

    (a) The quadruple $(\mathcal{P}(X), \triangle, \emptyset, \mathrm{id}_{\mathcal{P}(X)})$ is an abelian group.[1]

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

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

    - The group $\mathcal{P}(X)$ of Item 17;
    - The map $\alpha_{\mathcal{P}(X)}\colon \mathbb{F}_2 \times \mathcal{P}(X) \to \mathcal{P}(X)$ defined by

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

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

19. *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 18.

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

20. *Interaction With Powersets and Rings.* The quintuple $(\mathcal{P}(X), \triangle, \cap, \emptyset, X)$ is a commutative ring.[2]

21. *Interaction With Direct Images.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_!^{\mathsf{op}} \times f_!"] \arrow[d, "\triangle"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "\triangle"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_!(U) \triangle f_!(V) \subset f_!(U \triangle V)$$

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

22. *Interaction With Inverse Images.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[r, "f^{\mathsf{op},-1} \times f^{-1}"] \arrow[d, "\triangle"'] & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[d, "\triangle"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

i.e. we have

$$f^{-1}(U) \triangle f^{-1}(V) = f^{-1}(U \triangle V)$$

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

23. *Interaction With Codirect Images.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_*^{\mathsf{op}} \times f_*"] \arrow[d, "\triangle"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "\triangle"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_*(U \triangle V) \subset f_*(U) \triangle f_*(V)$$

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

[1]Here are some examples:

i. When $X = \emptyset$, we have an isomorphism of groups between $\mathcal{P}(\emptyset)$ and the trivial group:
$$(\mathcal{P}(\emptyset), \triangle, \emptyset, \mathrm{id}_{\mathcal{P}(\emptyset)}) \cong \mathrm{pt}.$$
ii. When $X = \mathrm{pt}$, we have an isomorphism of groups between $\mathcal{P}(\mathrm{pt})$ and $\mathbb{Z}_{/2}$:
$$(\mathcal{P}(\mathrm{pt}), \triangle, \emptyset, \mathrm{id}_{\mathcal{P}(\mathrm{pt})}) \cong \mathbb{Z}_{/2}.$$
iii. When $X = \{0, 1\}$, we have an isomorphism of groups between $\mathcal{P}(\{0, 1\})$ and $\mathbb{Z}_{/2} \times \mathbb{Z}_{/2}$:
$$(\mathcal{P}(\{0, 1\}), \triangle, \emptyset, \mathrm{id}_{\mathcal{P}(\{0,1\})}) \cong \mathbb{Z}_{/2} \times \mathbb{Z}_{/2}.$$

[2] *Warning:* The analogous statement replacing intersections by unions (i.e. that the quintuple $(\mathcal{P}(X), \triangle, \cup, \emptyset, X)$ is a ring) is false, however. See [Pro25aw] for a proof.

Proof 4.3.12.1.3 ▶ Proof of Proposition 4.3.12.1.2

Item 1: Lack of Functoriality

Let $X = \{0, 1\}$, $U = \{0\}$. Then $\emptyset \subset U$, but $U \triangle \emptyset = U \not\subset \emptyset = U \triangle U$ from Item 5 and Item 7. This gives a counterexample to the first statement. By using Item 6, we can adapt it to the second and third statement.

Item 2: Via Unions and Intersections

See [Pro25m].

Item 3: Symmetric Differences of Disjoint Sets

Since U and V are disjoint, we have $U \cap V = \emptyset$, and therefore we have
$$\begin{aligned} U \triangle V &= (U \cup V) \setminus (U \cap V) \\ &= (U \cup V) \setminus \emptyset \\ &= U \cup V, \end{aligned}$$
where we've used Item 2 and Item 12 of Proposition 4.3.10.1.2.

Item 4: Associativity

See [Pro25ao].

Item 5: Unitality

This follows from Item 6 and [Pro25at].

Item 6: Commutativity

See [Pro25ap].

Item 7: Invertibility

See [Pro25av].

Item 8: Interaction With Unions

See [Pro25bc].

Item 9: Interaction With Complements I

See [Pro25as].

Item 10: Interaction With Complements II

This follows from Item 6 and [Pro25ax].

Item 11: Interaction With Complements III

See [Pro25aq].

Item 12: "Transitivity"

We have

$$\begin{aligned}(U \vartriangle V) \vartriangle (V \vartriangle W) &= U \vartriangle (V \vartriangle (V \vartriangle W)) && \text{(by Item 4)}\\ &= U \vartriangle ((V \vartriangle V) \vartriangle W) && \text{(by Item 4)}\\ &= U \vartriangle (\emptyset \vartriangle W) && \text{(by Item 7)}\\ &= U \vartriangle W. && \text{(by Item 5)}\end{aligned}$$

This finishes the proof.

Item 13: The Triangle Inequality for Symmetric Differences

This follows from Items 2 and 12.

Item 14: Distributivity Over Intersections

See [Pro25q].

Item 15: Interaction With Characteristic Functions

See [Pro25g].

Item 16: Bijectivity

- We show that

$$(U \triangle -)\colon \mathcal{P}(X) \to \mathcal{P}(X)$$

is self-inverse.

Let $W \in \mathcal{P}(X)$. Then,

$$\begin{aligned} U \triangle (U \triangle W) &= (U \triangle U) \triangle W && \text{(by Item 4)} \\ &= \emptyset \triangle W && \text{(by Item 7)} \\ &= W. && \text{(by Item 5)} \end{aligned}$$

- By Item 6, $(- \triangle V) = (V \triangle -)$, hence the former is also self-inverse by the first point.

- The map $- \triangle (U \triangle V)$ is a bijection as a special case of the second point. From the first two points and Item 6, we get

$$U \triangle (U \triangle V) = V, \; V \triangle (U \triangle V) = V \triangle (V \triangle U) = U.$$

Hence the function maps U to V and V to U.

Item 17: Interaction With Powersets and Groups

Item 17a follows from Items 4 to 7, while Item 17b follows from Item 7.[1]

Item 18: Interaction With Powersets and Vector Spaces I

See [MSE 2719059].

Item 19: Interaction With Powersets and Vector Spaces II

See [MSE 2719059].

Item 20: Interaction With Powersets and Rings

This follows from Items 6 and 15 of Proposition 4.3.9.1.2 and Items 14 and 17.[2]

Item 21: Interaction With Direct Images

This is a repetition of Item 9 of Proposition 4.6.1.1.5 and is proved there.

Item 22: Interaction With Inverse Images

This is a repetition of Item 9 of Proposition 4.6.2.1.3 and is proved there.

Item 23: Interaction With Codirect Images

This is a repetition of Item 8 of Proposition 4.6.3.1.7 and is proved there.

[1] *Reference:* [Pro25ar].
[2] *Reference:* [Pro25au].

4.4 Powersets

4.4.1 Foundations

Let X be a set.

Definition 4.4.1.1.1 ► Powersets

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 4.4.1.1.2 ► Powersets as Decategorifications of Co/Presheaf Categories

Under the analogy that $\{\mathrm{t}, \mathrm{f}\}$ should be the (-1)-categorical analogue of Sets, we may view the powerset of a set as a decategorification of the category of presheaves of a category (or of the category of copresheaves):

- The powerset of a set X is equivalently (Item 2 of Proposition 4.5.1.1.4) the set

  $$\mathsf{Sets}(X, \{\mathrm{t}, \mathrm{f}\})$$

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

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

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

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

NOTATION 4.4.1.1.3 ▶ FURTHER NOTATION FOR POWERSETS

Let X be a set.

1. We write $\mathcal{P}_0(X)$ for the set of nonempty subsets of X.
2. We write $\mathcal{P}_{\text{fin}}(X)$ for the set of finite subsets of X.

PROPOSITION 4.4.1.1.4 ▶ ELEMENTARY PROPERTIES OF POWERSETS

Let X be a set.

1. *Co/Completeness.* The (posetal) category (associated to) $(\mathcal{P}(X), \subset)$ is complete and cocomplete:
   (a) *Products.* The products in $\mathcal{P}(X)$ are given by intersection of subsets.
   (b) *Coproducts.* The coproducts in $\mathcal{P}(X)$ are given by union of subsets.
   (c) *Co/Equalisers.* Being a posetal category, $\mathcal{P}(X)$ only has at most one morphisms between any two objects, so co/equalisers are trivial.
2. *Cartesian Closedness.* The category $\mathcal{P}(X)$ is Cartesian closed.
3. *Powersets as Sets of Relations.* We have bijections
$$\begin{aligned}\mathcal{P}(X) &\cong \mathrm{Rel}(\mathrm{pt}, X),\\ \mathcal{P}(X) &\cong \mathrm{Rel}(X, \mathrm{pt}),\end{aligned}$$
natural in $X \in \mathrm{Obj}(\mathsf{Sets})$.
4. *Interaction With Products I.* The map
$$\begin{aligned}\mathcal{P}(X) \times \mathcal{P}(Y) &\longrightarrow \mathcal{P}(X \textstyle\coprod Y)\\ (U, V) &\longmapsto U \cup V\end{aligned}$$
is an isomorphism of sets, natural in $X, Y \in \mathrm{Obj}(\mathsf{Sets})$ with respect to each of the functor structures $\mathcal{P}_!$, $\mathcal{P}^{-1}$, and $\mathcal{P}_*$ on $\mathcal{P}$ of Proposition 4.4.2.1.1. Moreover, this makes each of $\mathcal{P}_!$, $\mathcal{P}^{-1}$, and $\mathcal{P}_*$ into a symmetric monoidal functor.

5. *Interaction With Products II.* The map

$$\begin{aligned}\mathcal{P}(X)\times\mathcal{P}(Y) &\longrightarrow \mathcal{P}(X\textstyle\coprod Y)\\ (U,V) &\longmapsto U\boxtimes_{X\times Y}V,\end{aligned}$$

where[1]

$$U\boxtimes_{X\times Y}V \overset{\text{def}}{=} \{(u,v)\in X\times Y \mid u\in U \text{ and } v\in V\}$$

is an inclusion of sets, natural in $X, Y \in \mathrm{Obj}(\mathsf{Sets})$ with respect to each of the functor structures $\mathcal{P}_!$, $\mathcal{P}^{-1}$, and $\mathcal{P}_*$ on $\mathcal{P}$ of Proposition 4.4.2.1.1. Moreover, this makes each of $\mathcal{P}_!$, $\mathcal{P}^{-1}$, and $\mathcal{P}_*$ into a symmetric monoidal functor.

6. *Interaction With Products III.* We have an isomorphism

$$\mathcal{P}(X)\otimes\mathcal{P}(Y)\cong\mathcal{P}(X\times Y),$$

natural in $X, Y \in \mathrm{Obj}(\mathsf{Sets})$ with respect to each of the functor structures $\mathcal{P}_!$, $\mathcal{P}^{-1}$, and $\mathcal{P}_*$ on $\mathcal{P}$ of Proposition 4.4.2.1.1, where $\otimes$ denotes the tensor product of suplattices of **??**. Moreover, this makes each of $\mathcal{P}_!$, $\mathcal{P}^{-1}$, and $\mathcal{P}_*$ into a symmetric monoidal functor.

[1]The set $U\boxtimes_{X\times Y}V$ is usually denoted simply $U\times V$. Here we denote it in this somewhat weird way to highlight the similarity to external tensor products in six-functor formalisms (see also Section 4.6.4).

Proof 4.4.1.1.5 ▶ Proof of Proposition 4.4.1.1.4

Item 1: Co/Completeness

Omitted.

Item 2: Cartesian Closedness

See Section 4.4.7.

Item 3: Powersets as Sets of Relations

Indeed, we have

$$\begin{aligned}\mathrm{Rel}(\mathrm{pt}, X) &\stackrel{\mathrm{def}}{=} \mathcal{P}(\mathrm{pt} \times X)\\ &\cong \mathcal{P}(X)\end{aligned}$$

and

$$\begin{aligned}\mathrm{Rel}(X, \mathrm{pt}) &\stackrel{\mathrm{def}}{=} \mathcal{P}(X \times \mathrm{pt})\\ &\cong \mathcal{P}(X),\end{aligned}$$

where we have used Item 5 of Proposition 4.1.3.1.4.

Item 4: Interaction With Products I

The inverse of the map in the statement is the map

$$\Phi\colon \mathcal{P}(X \textstyle\coprod Y) \to \mathcal{P}(X) \times \mathcal{P}(Y)$$

defined by

$$\Phi(S) \stackrel{\mathrm{def}}{=} (S_X, S_Y)$$

for each $S \in \mathcal{P}(X \coprod Y)$, where

$$\begin{aligned}S_X &\stackrel{\mathrm{def}}{=} \{x \in X \mid (0, x) \in S\}\\ S_Y &\stackrel{\mathrm{def}}{=} \{y \in Y \mid (1, y) \in S\}.\end{aligned}$$

The rest of the proof is omitted.

Item 5: Interaction With Products II

Omitted.

Item 6: Interaction With Products III

Omitted.

4.4.2 Functoriality of Powersets

Proposition 4.4.2.1.1 ► Functoriality of Powersets

Let X be a set.

1. *Functoriality I.* The assignment $X \mapsto \mathcal{P}(X)$ defines a functor

$$\mathcal{P}_!\colon \mathsf{Sets} \to \mathsf{Sets},$$

where

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

$$\mathcal{P}_!(A) \overset{\text{def}}{=} \mathcal{P}(A).$$

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

$$\mathcal{P}_{*|A,B}\colon \mathsf{Sets}(A, B) \to \mathsf{Sets}(\mathcal{P}(A), \mathcal{P}(B))$$

of $\mathcal{P}_!$ at (A, B) is the map defined by by sending a map of sets $f\colon A \to B$ to the map

$$\mathcal{P}_!(f)\colon \mathcal{P}(A) \to \mathcal{P}(B)$$

defined by

$$\mathcal{P}_!(f) \overset{\text{def}}{=} f_!,$$

as in Definition 4.6.1.1.1.

2. *Functoriality II.* The assignment $X \mapsto \mathcal{P}(X)$ defines a functor

$$\mathcal{P}^{-1}\colon \mathsf{Sets}^{\mathsf{op}} \to \mathsf{Sets},$$

where

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

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

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

$$\mathcal{P}^{-1}_{A,B} \colon \mathsf{Sets}(A, B) \to \mathsf{Sets}(\mathcal{P}(B), \mathcal{P}(A))$$

  of $\mathcal{P}^{-1}$ at (A, B) is the map defined by by sending a map of sets $f \colon A \to B$ to the map

$$\mathcal{P}^{-1}(f) \colon \mathcal{P}(B) \to \mathcal{P}(A)$$

  defined by

$$\mathcal{P}^{-1}(f) \overset{\text{def}}{=} f^{-1},$$

  as in Definition 4.6.2.1.1.

3. *Functoriality III.* The assignment $X \mapsto \mathcal{P}(X)$ defines a functor

$$\mathcal{P}_* \colon \mathsf{Sets} \to \mathsf{Sets},$$

where

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

$$\mathcal{P}_*(A) \overset{\text{def}}{=} \mathcal{P}(A).$$

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

$$\mathcal{P}_{!|A,B} \colon \mathsf{Sets}(A, B) \to \mathsf{Sets}(\mathcal{P}(A), \mathcal{P}(B))$$

  of $\mathcal{P}_*$ at (A, B) is the map defined by by sending a map of sets $f \colon A \to B$ to the map

$$\mathcal{P}_*(f) \colon \mathcal{P}(A) \to \mathcal{P}(B)$$

  defined by

$$\mathcal{P}_*(f) \overset{\text{def}}{=} f_*,$$

  as in Definition 4.6.3.1.1.

Proof 4.4.2.1.2 ▶ Proof of Proposition 4.4.2.1.1

Item 1: Functoriality I

This follows from Items 3 and 4 of Proposition 4.6.1.1.7.

Item 2: Functoriality II

This follows from Items 3 and 4 of Proposition 4.6.2.1.5.

Item 3: Functoriality III

This follows from Items 3 and 4 of Proposition 4.6.3.1.9.

4.4.3 Adjointness of Powersets I

Proposition 4.4.3.1.1 ▶ Adjointness of Powersets I

We have an adjunction

$$\left(\mathcal{P}^{-1} \dashv \mathcal{P}^{-1,\mathrm{op}}\right): \quad \begin{tikzcd} \mathsf{Sets}^{\mathrm{op}} \arrow[r, bend left, "\mathcal{P}^{-1}"] \arrow[r, phantom, "\perp"] & \mathsf{Sets}, \arrow[l, bend left, "\mathcal{P}^{-1,\mathrm{op}}"] \end{tikzcd}$$

witnessed by a bijection

$$\underbrace{\mathsf{Sets}^{\mathrm{op}}(\mathcal{P}(X), Y)}_{\overset{\mathrm{def}}{=} \mathsf{Sets}(Y, \mathcal{P}(X))} \cong \mathsf{Sets}(X, \mathcal{P}(Y)),$$

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

Proof 4.4.3.1.2 ▶ Proof of Proposition 4.4.3.1.1

We have

$$\begin{aligned}
\mathsf{Sets}^{\mathsf{op}}(\mathcal{P}(A), B) &\overset{\text{def}}{=} \mathsf{Sets}(B, \mathcal{P}(A)) \\
&\cong \mathsf{Sets}(B, \mathsf{Sets}(A, \{\mathsf{t}, \mathsf{f}\})) && \text{(by Item 2 of Proposition 4.5.1.1.4)} \\
&\cong \mathsf{Sets}(A \times B, \{\mathsf{t}, \mathsf{f}\}) && \text{(by Item 2 of Proposition 4.1.3.1.4)} \\
&\cong \mathsf{Sets}(A, \mathsf{Sets}(B, \{\mathsf{t}, \mathsf{f}\})) && \text{(by Item 2 of Proposition 4.1.3.1.4)} \\
&\cong \mathsf{Sets}(A, \mathcal{P}(B)), && \text{(by Item 2 of Proposition 4.5.1.1.4)}
\end{aligned}$$

where all bijections are natural in A and B.[1]

[1] Here we are using Item 3 of Proposition 4.5.1.1.4.

4.4.4 Adjointness of Powersets II

Proposition 4.4.4.1.1 ▶ Adjointness of Powersets II

We have an adjunction

$$
(\mathrm{Gr} \dashv \mathcal{P}_!) : \quad
\begin{tikzcd}
\mathsf{Sets} \arrow[r, bend left, "\mathrm{Gr}"] \arrow[r, phantom, "\perp"] & \mathrm{Rel}, \arrow[l, bend left, "\mathcal{P}_!"]
\end{tikzcd}
$$

witnessed by a bijection of sets

$$\mathrm{Rel}(\mathrm{Gr}(X), Y) \cong \mathsf{Sets}(X, \mathcal{P}(Y))$$

natural in $X \in \mathrm{Obj}(\mathsf{Sets})$ and $Y \in \mathrm{Obj}(\mathrm{Rel})$, where Gr is the graph functor of Relations, Item 1 of Proposition 8.2.2.1.2 and $\mathcal{P}_!$ is the functor of Relations, Proposition 8.7.5.1.1.

Proof 4.4.4.1.2 ▶ Proof of Proposition 4.4.4.1.1

We have

$$\begin{aligned}
\mathrm{Rel}(\mathrm{Gr}(A), B) &\cong \mathcal{P}(A \times B) \\
&\cong \mathsf{Sets}(A \times B, \{\mathsf{t}, \mathsf{f}\}) && \text{(by Item 2 of Proposition 4.5.1.1.4)} \\
&\cong \mathsf{Sets}(A, \mathsf{Sets}(B, \{\mathsf{t}, \mathsf{f}\})) && \text{(by Item 2 of Proposition 4.1.3.1.4)} \\
&\cong \mathsf{Sets}(A, \mathcal{P}(B)), && \text{(by Item 2 of Proposition 4.5.1.1.4)}
\end{aligned}$$

where all bijections are natural in A, (where we are using Item 3 of Proposition 4.5.1.1.4). Explicitly, this isomorphism is given by sending a relation $R\colon \mathrm{Gr}(A) \nrightarrow B$ to the map $R^\dagger\colon A \to \mathcal{P}(B)$ sending a to the subset $R(a)$ of B, as in Relations, Definition 8.1.1.1.1.
Naturality in B is then the statement that given a relation $R\colon B \nrightarrow B'$, the diagram

$$\begin{tikzcd}
\mathrm{Rel}(\mathrm{Gr}(A), B) \arrow[r, "R\diamond-"] \arrow[d, dashed, "\wr"'] & \mathrm{Rel}(\mathrm{Gr}(A), B') \arrow[d, dashed, "\wr"] \\
\mathsf{Sets}(A, \mathcal{P}(B)) \arrow[r, "R_!"'] & \mathsf{Sets}(A, \mathcal{P}(B'))
\end{tikzcd}$$

commutes, which follows from Relations, Remark 8.7.1.1.3.

4.4.5 Powersets as Free Cocompletions

Let X be a set.

Proposition 4.4.5.1.1 ► Powersets as Free Cocompletions: Universal Property

The pair $(\mathcal{P}(X), \chi_{(-)})$ consisting of

- The powerset $(\mathcal{P}(X), \subset)$ of X of Definition 4.4.1.1.1;
- The characteristic embedding $\chi_{(-)}\colon X \hookrightarrow \mathcal{P}(X)$ of X into $\mathcal{P}(X)$ of Definition 4.5.4.1.1;

satisfies the following universal property:

(★) Given another pair (Y, f) consisting of

  - A suplattice $(Y, \preceq)$;
  - A function $f\colon X \to Y$;

  there exists a unique morphism of suplattices

$$(\mathcal{P}(X), \subset) \xrightarrow{\exists!} (Y, \preceq)$$

making the diagram

$$\begin{tikzcd} & \mathcal{P}(X) \arrow[d, dashed, "\exists!"] \\ X \arrow[ur, "\chi_X"] \arrow[r, "f"'] & Y \end{tikzcd}$$

commute.

Proof 4.4.5.1.2 ► Proof of Proposition 4.4.5.1.1

This is a rephrasing of Proposition 4.4.5.1.3, which we prove below.[1]

[1] Here we only remark that the unique morphism of suplattices in the statement is given by the left Kan extension $\mathrm{Lan}_{\chi_X}(f)$ of f along χ_X.

Proposition 4.4.5.1.3 ► Powersets as Free Cocompletions: Adjointness

We have an adjunction

$$(\mathcal{P} \dashv 忘)\colon \quad \begin{tikzcd} \mathsf{Sets} \arrow[r, bend left, "\mathcal{P}"] \arrow[r, phantom, "\perp"] & \mathsf{SupLat}, \arrow[l, bend left, "忘"] \end{tikzcd}$$

witnessed by a bijection

$$\mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq)) \cong \mathsf{Sets}(X, Y),$$

natural in $X \in \mathrm{Obj}(\mathsf{Sets})$ and $(Y, \preceq) \in \mathrm{Obj}(\mathsf{SupLat})$, where:

- The category SupLat is the category of suplattices of **??**.
- The map
  $$\chi_X^*\colon \mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq)) \to \mathsf{Sets}(X, Y)$$
  witnessing the above bijection is defined by
  $$\chi_X^*(f) \overset{\mathrm{def}}{=} f \circ \chi_X,$$
  i.e. by sending a morphism of suplattices $f\colon \mathcal{P}(X) \to Y$ to the composition
  $$X \overset{\chi_X}{\hookrightarrow} \mathcal{P}(X) \xrightarrow{f} Y.$$

- The map

$$\mathrm{Lan}_{\chi_X} \colon \mathsf{Sets}(X, Y) \to \mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq))$$

witnessing the above bijection is given by sending a function $f \colon X \to Y$ to its left Kan extension along χ_X,

$$\mathrm{Lan}_{\chi_X}(f) \colon \mathcal{P}(X) \to Y, \qquad \begin{tikzcd} & \mathcal{P}(X) \arrow[d, dashed, "\mathrm{Lan}_{\chi_X}(f)"] \\ X \arrow[ur, "\chi_X"] \arrow[r, "f"'] \arrow[ur, phantom, shift left=3, "\Uparrow"] & Y. \end{tikzcd}$$

Moreover, invoking the bijection $\mathcal{P}(X) \cong \mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})$ of Item 2 of Proposition 4.5.1.1.4, $\mathrm{Lan}_{\chi_X}(f)$ can be explicitly computed by

$$\begin{aligned} [\mathrm{Lan}_{\chi_X}(f)](U) &= \int^{x \in X} \chi_{\mathcal{P}(X)}(\chi_x, U) \odot f(x) \\ &= \int^{x \in X} \chi_U(x) \odot f(x) \\ &= \bigvee_{x \in X} (\chi_U(x) \odot f(x)) \\ &= \left(\bigvee_{x \in U} (\chi_U(x) \odot f(x)) \right) \vee \left(\bigvee_{x \in U^{\mathsf{c}}} (\chi_U(x) \odot f(x)) \right) \\ &= \left(\bigvee_{x \in U} f(x) \right) \vee \left(\bigvee_{x \in U^{\mathsf{c}}} \varnothing_Y \right) \\ &= \bigvee_{x \in U} f(x) \end{aligned}$$

for each $U \in \mathcal{P}(X)$, where:

  - We have used **??** for the first equality.
  - We have used Proposition 4.5.5.1.1 for the second equality.
  - We have used **??** for the third equality.
  - The symbol $\bigvee$ denotes the join in $(Y, \preceq)$.

– The symbol $\odot$ denotes the tensor of an element of Y by a truth value as in **??**. In particular, we have

$$\begin{aligned}\mathsf{true}\odot f(x) &\stackrel{\mathrm{def}}{=} f(x),\\ \mathsf{false}\odot f(x) &\stackrel{\mathrm{def}}{=} \varnothing_Y,\end{aligned}$$

where $\varnothing_Y$ is the bottom element of $(Y,\preceq)$.

In particular, when $(Y,\preceq_Y) = (\mathcal{P}(B),\subset)$ for some set B, the Kan extension $\mathrm{Lan}_{\chi_X}(f)$ is given by

$$\begin{aligned}[\mathrm{Lan}_{\chi_X}(f)](U) &= \bigvee_{x\in U} f(x)\\ &= \bigcup_{x\in U} f(x)\end{aligned}$$

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

Proof 4.4.5.1.4 ► **Proof of Proposition 4.4.5.1.3**

Map I

We define a map

$$\Phi_{X,Y}\colon \mathsf{SupLat}((\mathcal{P}(X),\subset),(Y,\preceq)) \longrightarrow \mathsf{Sets}(X,Y)$$

as in the statement, i.e. by

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

for each $f \in \mathsf{SupLat}((\mathcal{P}(X),\subset),(Y,\preceq))$.

Map II

We define a map

$$\Psi_{X,Y}\colon \mathsf{Sets}(X,Y) \longrightarrow \mathsf{SupLat}((\mathcal{P}(X),\subset),(Y,\preceq))$$

as in the statement, i.e. by

$$\Psi_{X,Y}(f) \overset{\text{def}}{=} \mathrm{Lan}_{\chi_X}(f), \qquad \begin{tikzcd} & \mathcal{P}(X) \arrow[d, dashed, "\mathrm{Lan}_{\chi_X}(f)"] \\ X \arrow[ur, "\chi_X"] \arrow[r, "f"'] \arrow[ur, phantom, "\Uparrow"] & Y, \end{tikzcd}$$

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

Invertibility I

We claim that

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \mathrm{id}_{\mathsf{SupLat}((\mathcal{P}(X),\subset),(Y,\preceq))}.$$

We have

$$\begin{aligned} [\Psi_{X,Y} \circ \Phi_{X,Y}](f) &\overset{\text{def}}{=} \Psi_{X,Y}(\Phi_{X,Y}(f)) \\ &\overset{\text{def}}{=} \Psi_{X,Y}(f \circ \chi_X) \\ &\overset{\text{def}}{=} \mathrm{Lan}_{\chi_X}(f \circ \chi_X) \end{aligned}$$

for each $f \in \mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq))$. We now claim that

$$\mathrm{Lan}_{\chi_X}(f \circ \chi_X) = f$$

for each $f \in \mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq))$. Indeed, we have

$$\begin{aligned} \left[\mathrm{Lan}_{\chi_X}(f \circ \chi_X)\right](U) &= \bigvee_{x \in U} f(\chi_X(x)) \\ &= f\left(\bigvee_{x \in U} \chi_X(x)\right) \\ &= f\left(\bigcup_{x \in U} \{x\}\right) \\ &= f(U) \end{aligned}$$

for each $U \in \mathcal{P}(X)$, where we have used that f is a morphism of suplattices and hence preserves joins for the second equality. This proves our claim. Since we have shown that

$$[\Psi_{X,Y} \circ \Phi_{X,Y}](f) = f$$

for each $f \in \mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq))$, it follows that $\Psi_{X,Y} \circ \Phi_{X,Y}$ must be equal to the identity map $\mathrm{id}_{\mathsf{SupLat}((\mathcal{P}(X),\subset),(Y,\preceq))}$ of $\mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq))$.

Invertibility II

We claim that

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

We have

$$\begin{aligned}
[\Phi_{X,Y} \circ \Psi_{X,Y}](f) &\overset{\text{def}}{=} \Phi_{X,Y}(\Psi_{X,Y}(f)) \\
&\overset{\text{def}}{=} \Phi_{X,Y}(\mathrm{Lan}_{\chi_X}(f)) \\
&\overset{\text{def}}{=} \mathrm{Lan}_{\chi_X}(f) \circ \chi_X
\end{aligned}$$

for each $f \in \mathsf{Sets}(X, Y)$. We now claim that

$$\mathrm{Lan}_{\chi_X}(f) \circ \chi_X = f$$

for each $f \in \mathsf{Sets}(X, Y)$. Indeed, we have

$$\begin{aligned}
[\mathrm{Lan}_{\chi_X}(f) \circ \chi_X](x) &= \bigvee_{y \in \{x\}} f(y) \\
&= f(x)
\end{aligned}$$

for each $x \in X$. This proves our claim. Since we have shown that

$$[\Phi_{X,Y} \circ \Psi_{X,Y}](f) = f$$

for each $f \in \mathsf{Sets}(X, Y)$, it follows that $\Phi_{X,Y} \circ \Psi_{X,Y}$ must be equal to the identity map $\mathrm{id}_{\mathsf{Sets}(X,Y)}$ of $\mathsf{Sets}(X, Y)$.

Naturality for Φ, Part I

We need to show that, given a function $f: X \to X'$, the diagram

$$\begin{tikzcd} \mathsf{SupLat}((\mathcal{P}(X'),\subset),(Y,\preceq)) \arrow[r, "\Phi_{X',Y}"] \arrow[d, "\mathcal{P}_!(f)^*"'] & \mathsf{Sets}(X',Y) \arrow[d, "f^*"] \\ \mathsf{SupLat}((\mathcal{P}(X),\subset),(Y,\preceq)) \arrow[r, "\Phi_{X,Y}"'] & \mathsf{Sets}(X,Y) \end{tikzcd}$$

commutes. Indeed, we have

$$\begin{aligned} [\Phi_{X,Y}\circ\mathcal{P}_!(f)^*](\xi) &\overset{\text{def}}{=} \Phi_{X,Y}(\mathcal{P}_!(f)^*(\xi)) \\ &\overset{\text{def}}{=} \Phi_{X,Y}(\xi\circ f_!) \\ &\overset{\text{def}}{=} (\xi\circ f_!)\circ\chi_X \\ &= \xi\circ(f_!\circ\chi_X) \\ &\overset{(\dagger)}{=} \xi\circ(\chi_{X'}\circ f) \\ &= (\xi\circ\chi_{X'})\circ f \\ &\overset{\text{def}}{=} \Phi_{X',Y}(\xi)\circ f \\ &\overset{\text{def}}{=} f^*(\Phi_{X',Y}(\xi)) \\ &\overset{\text{def}}{=} [f^*\circ\Phi_{X',Y}](\xi), \end{aligned}$$

for each $\xi \in \mathsf{SupLat}((\mathcal{P}(X'),\subset),(Y,\preceq))$, where we have used Item 1 of Proposition 4.5.4.1.3 for the fifth equality above.

Naturality for Φ, Part II

We need to show that, given a morphism of suplattices

$$g\colon (Y,\preceq_Y)\to(Y',\preceq_{Y'}),$$

the diagram

$$\begin{tikzcd} \mathsf{SupLat}((\mathcal{P}(X),\subset),(Y,\preceq)) \arrow[r, "\Phi_{X,Y}"] \arrow[d, "g_!"'] & \mathsf{Sets}(X,Y) \arrow[d, "g_!"] \\ \mathsf{SupLat}((\mathcal{P}(X),\subset),(Y',\preceq)) \arrow[r, "\Phi_{X,Y'}"'] & \mathsf{Sets}(X,Y') \end{tikzcd}$$

commutes. Indeed, we have

$$\begin{aligned}
[\Phi_{X,Y'} \circ g_!](\xi) &\overset{\text{def}}{=} \Phi_{X,Y'}(g_!(\xi)) \\
&\overset{\text{def}}{=} \Phi_{X,Y'}(g \circ \xi) \\
&\overset{\text{def}}{=} (g \circ \xi) \circ \chi_X \\
&= g \circ (\xi \circ \chi_X) \\
&\overset{\text{def}}{=} g \circ (\Phi_{X,Y}(\xi)) \\
&\overset{\text{def}}{=} g_!(\Phi_{X,Y}(\xi)) \\
&\overset{\text{def}}{=} [g_! \circ \Phi_{X,Y}](\xi).
\end{aligned}$$

for each $\xi \in \mathsf{SupLat}((\mathcal{P}(X), \subset), (Y, \preceq))$.

Naturality for Ψ

Since Φ is natural in each argument and Φ is a componentwise inverse to Ψ in each argument, it follows from Categories, Item 2 of Proposition 11.9.7.1.2 that Ψ is also natural in each argument.

Warning 4.4.5.1.5 ▶ Free Cocompletion Is Not an Idempotent Operation

Although the assignment $X \mapsto \mathcal{P}(X)$ is called the *free cocompletion of* X, it is not an idempotent operation, i.e. we have $\mathcal{P}(\mathcal{P}(X)) \neq \mathcal{P}(X)$.

4.4.6 Powersets as Free Completions

Let X be a set.

Proposition 4.4.6.1.1 ▶ Powersets as Free Completions: Universal Property

The pair $(\mathcal{P}(X), \chi_{(-)})$ consisting of

- The powerset of X together with reverse inclusion $\mathcal{P}(X)^{\mathsf{op}} = (\mathcal{P}(X), \supset)$ of Definition 4.4.1.1.1;
- The characteristic embedding $\chi_{(-)} \colon X \hookrightarrow \mathcal{P}(X)$ of X into $\mathcal{P}(X)$ of Definition 4.5.4.1.1;

satisfies the following universal property:

(★) Given another pair (Y, f) consisting of

- An inflattice $(Y, \preceq)$;
- A function $f \colon X \to Y$;

there exists a unique morphism of inflattices

$$(\mathcal{P}(X), \supset) \xrightarrow{\exists!} (Y, \preceq)$$

making the diagram

$$\begin{tikzcd} & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, dashed, "\exists!"] \\ X \arrow[ur, "\chi_X"] \arrow[r, "f"'] & Y \end{tikzcd}$$

commute.

Proof 4.4.6.1.2 ▶ Proof of Proposition 4.4.6.1.1

This is a rephrasing of Proposition 4.4.6.1.3, which we prove below.[1]

[1] Here we only remark that the unique morphism of inflattices in the statement is given by the right Kan extension $\mathrm{Ran}_{\chi_X}(f)$ of f along χ_X.

Proposition 4.4.6.1.3 ▶ Powersets as Free Completions: Adjointness

We have an adjunction

$$(\mathcal{P} \dashv 忘)\colon\quad \begin{tikzcd} \mathsf{Sets} \arrow[r, bend left, "\mathcal{P}"] \arrow[r, phantom, "\perp"] & \mathsf{InfLat}, \arrow[l, bend left, "忘"] \end{tikzcd}$$

witnessed by a bijection

$$\mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq)) \cong \mathsf{Sets}(X, Y),$$

natural in $X \in \mathrm{Obj}(\mathsf{Sets})$ and $(Y, \preceq) \in \mathrm{Obj}(\mathsf{InfLat})$, where:

- The category InfLat is the category of inflattices of **??**.
- The map

$$\chi_X^*\colon \mathsf{InfLat}((\mathcal{P}(X),\supset),(Y,\preceq)) \to \mathsf{Sets}(X,Y)$$

witnessing the above bijection is defined by

$$\chi_X^*(f) \stackrel{\text{def}}{=} f \circ \chi_X,$$

i.e. by sending a morphism of inflattices $f\colon \mathcal{P}(X)^{\mathsf{op}} \to Y$ to the composition

$$X \overset{\chi_X}{\hookrightarrow} \mathcal{P}(X)^{\mathsf{op}} \xrightarrow{f} Y.$$

- The map

$$\mathrm{Ran}_{\chi_X}\colon \mathsf{Sets}(X,Y) \to \mathsf{InfLat}((\mathcal{P}(X),\supset),(Y,\preceq))$$

witnessing the above bijection is given by sending a function $f\colon X \to Y$ to its right Kan extension along χ_X,

$$\mathrm{Ran}_{\chi_X}(f)\colon \mathcal{P}(X)^{\mathsf{op}} \to Y, \qquad \begin{tikzcd} & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, dashed, "\mathrm{Ran}_{\chi_X}(f)"] \\ X \arrow[ur, "\chi_X"] \arrow[r, "f"'] \arrow[ur, phantom, shift right=3, "\Downarrow"] & Y. \end{tikzcd}$$

Moreover, invoking the bijection $\mathcal{P}(X) \cong \mathsf{Sets}(X,\{\mathsf{t},\mathsf{f}\})$ of Item 2 of Proposition 4.5.1.1.4, $\mathrm{Ran}_{\chi_X}(f)$ can be explicitly computed by

$$\begin{aligned}
[\mathrm{Ran}_{\chi_X}(f)](U) &= \int_{x\in X} \chi_{\mathcal{P}(X)^{\mathsf{op}}}(\chi_x, U) \pitchfork f(x)\\
&= \int_{x\in X} \chi_{\mathcal{P}(X)}(U, \chi_x) \pitchfork f(x)\\
&= \int_{x\in X} \chi_U(x) \pitchfork f(x)\\
&= \bigwedge_{x\in X} \chi_U(x) \pitchfork f(x)
\end{aligned}$$

$$
\begin{aligned}
&= \left(\bigwedge_{x\in U} \chi_U(x) \pitchfork f(x)\right) \wedge \left(\bigwedge_{x\in U^{\mathsf{c}}} \chi_U(x) \pitchfork f(x)\right) \\
&= \left(\bigwedge_{x\in U} f(x)\right) \wedge \left(\bigwedge_{x\in U^{\mathsf{c}}} \infty_Y\right) \\
&= \left(\bigwedge_{x\in U} f(x)\right) \wedge \infty_Y \\
&= \bigwedge_{x\in U} f(x)
\end{aligned}
$$

for each $U \in \mathcal{P}(X)$, where:

- We have used **??** for the first equality.
- We have used Proposition 4.5.5.1.1 for the second equality.
- We have used **??** for the third equality.
- The symbol $\bigwedge$ denotes the meet in $(Y, \preceq)$.
- The symbol $\pitchfork$ denotes the cotensor of an element of Y by a truth value as in **??**. In particular, we have

$$
\begin{aligned}
\mathsf{true} \pitchfork f(x) &\stackrel{\text{def}}{=} f(x), \\
\mathsf{false} \pitchfork f(x) &\stackrel{\text{def}}{=} \infty_Y,
\end{aligned}
$$

  where ∞_Y is the top element of $(Y, \preceq)$.

In particular, when $(Y, \preceq_Y) = (\mathcal{P}(B), \subset)$ for some set B, the Kan extension $\mathrm{Ran}_{\chi_X}(f)$ is given by

$$
\begin{aligned}
[\mathrm{Ran}_{\chi_X}(f)](U) &= \bigwedge_{x\in U} f(x) \\
&= \bigcap_{x\in U} f(x)
\end{aligned}
$$

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

Proof 4.4.6.1.4 ► Proof of Proposition 4.4.5.1.3

Map I

We define a map

$$\Phi_{X,Y}\colon \mathsf{InfLat}((\mathcal{P}(X),\supset),(Y,\preceq)) \to \mathsf{Sets}(X,Y)$$

as in the statement, i.e. by

$$\Phi_{X,Y}(f) \overset{\mathrm{def}}{=} f \circ \chi_X$$

for each $f \in \mathsf{InfLat}((\mathcal{P}(X),\supset),(Y,\preceq))$.

Map II

We define a map

$$\Psi_{X,Y}\colon \mathsf{Sets}(X,Y) \to \mathsf{InfLat}((\mathcal{P}(X),\supset),(Y,\preceq))$$

as in the statement, i.e. by

$$\Psi_{X,Y}(f) \overset{\mathrm{def}}{=} \mathrm{Ran}_{\chi_X}(f), \qquad \begin{tikzcd} & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, dashed, "\mathrm{Ran}_{\chi_X}(f)"] \\ X \arrow[ur, "\chi_X"] \arrow[r, "f"'] \arrow[ur, phantom, "\Leftarrow" description, shift right=3] & Y, \end{tikzcd}$$

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

Invertibility I

We claim that

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \mathrm{id}_{\mathsf{InfLat}((\mathcal{P}(X),\supset),(Y,\preceq))}.$$

We have

$$\begin{aligned}[\Psi_{X,Y} \circ \Phi_{X,Y}](f) &\overset{\mathrm{def}}{=} \Psi_{X,Y}(\Phi_{X,Y}(f))\\ &\overset{\mathrm{def}}{=} \Psi_{X,Y}(f \circ \chi_X)\\ &\overset{\mathrm{def}}{=} \mathrm{Ran}_{\chi_X}(f \circ \chi_X)\end{aligned}$$

for each $f \in \mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq))$. We now claim that

$$\mathrm{Ran}_{\chi_X}(f \circ \chi_X) = f$$

for each $f \in \mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq))$. Indeed, we have

$$\begin{aligned}\left[\mathrm{Ran}_{\chi_X}(f \circ \chi_X)\right](U) &= \bigwedge_{x\in U} f(\chi_X(x)) \\ &= f\left(\bigwedge_{x\in U} \chi_X(x)\right) \\ &= f\left(\bigcup_{x\in U}\{x\}\right) \\ &= f(U)\end{aligned}$$

for each $U \in \mathcal{P}(X)$, where we have used that f is a morphism of inflattices and hence preserves meets in $(\mathcal{P}(X), \supset)$ (i.e. joins in $(\mathcal{P}(X), \subset)$) for the second equality. This proves our claim. Since we have shown that

$$[\Psi_{X,Y} \circ \Phi_{X,Y}](f) = f$$

for each $f \in \mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq))$, it follows that $\Psi_{X,Y} \circ \Phi_{X,Y}$ must be equal to the identity map $\mathrm{id}_{\mathsf{InfLat}((\mathcal{P}(X),\supset),(Y,\preceq))}$ of $\mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq))$.

Invertibility II

We claim that

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

We have

$$\begin{aligned}[\Phi_{X,Y} \circ \Psi_{X,Y}](f) &\stackrel{\text{def}}{=} \Phi_{X,Y}(\Psi_{X,Y}(f)) \\ &\stackrel{\text{def}}{=} \Phi_{X,Y}(\mathrm{Ran}_{\chi_X}(f)) \\ &\stackrel{\text{def}}{=} \mathrm{Ran}_{\chi_X}(f) \circ \chi_X\end{aligned}$$

for each $f \in \mathsf{Sets}(X, Y)$. We now claim that

$$\mathrm{Ran}_{\chi_X}(f) \circ \chi_X = f$$

for each $f \in \mathsf{Sets}(X, Y)$. Indeed, we have

$$\begin{aligned}[\mathrm{Ran}_{\chi_X}(f) \circ \chi_X](x) &= \bigwedge_{y \in \{x\}} f(y) \\ &= f(x)\end{aligned}$$

for each $x \in X$. This proves our claim. Since we have shown that

$$[\Phi_{X,Y} \circ \Psi_{X,Y}](f) = f$$

for each $f \in \mathsf{Sets}(X, Y)$, it follows that $\Phi_{X,Y} \circ \Psi_{X,Y}$ must be equal to the identity map $\mathrm{id}_{\mathsf{Sets}(X,Y)}$ of $\mathsf{Sets}(X, Y)$.

Naturality for Φ, Part I

We need to show that, given a function $f : X \to X'$, the diagram

$$\begin{tikzcd} \mathsf{InfLat}((\mathcal{P}(X'), \supset), (Y, \preceq)) \arrow[r, "\Phi_{X',Y}"] \arrow[d, "\mathcal{P}_!(f)^*"'] & \mathsf{Sets}(X', Y) \arrow[d, "f^*"] \\ \mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq)) \arrow[r, "\Phi_{X,Y}"'] & \mathsf{Sets}(X, Y) \end{tikzcd}$$

commutes. Indeed, we have

$$\begin{aligned}[\Phi_{X,Y} \circ \mathcal{P}_!(f)^*](\xi) &\overset{\text{def}}{=} \Phi_{X,Y}(\mathcal{P}_!(f)^*(\xi)) \\ &\overset{\text{def}}{=} \Phi_{X,Y}(\xi \circ f_!) \\ &\overset{\text{def}}{=} (\xi \circ f_!) \circ \chi_X \\ &= \xi \circ (f_! \circ \chi_X) \\ &\overset{(\dagger)}{=} \xi \circ (\chi_{X'} \circ f) \\ &= (\xi \circ \chi_{X'}) \circ f \\ &\overset{\text{def}}{=} \Phi_{X',Y}(\xi) \circ f\end{aligned}$$

$$\begin{aligned}&\overset{\text{def}}{=} f^*(\Phi_{X',Y}(\xi))\\&\overset{\text{def}}{=} [f^* \circ \Phi_{X',Y}](\xi),\end{aligned}$$

for each $\xi \in \mathsf{InfLat}((\mathcal{P}(X'), \supset), (Y, \preceq))$, where we have used Item 1 of Proposition 4.5.4.1.3 for the fifth equality above.

Naturality for Φ, Part II

We need to show that, given a cocontinuous morphism of posets

$$g\colon (Y, \preceq_Y) \to (Y', \preceq_{Y'}),$$

the diagram

$$\begin{tikzcd}
\mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq)) \arrow[r, "\Phi_{X,Y}"] \arrow[d, "g_!"'] & \mathsf{Sets}(X, Y) \arrow[d, "g_!"] \\
\mathsf{InfLat}((\mathcal{P}(X), \supset), (Y', \preceq)) \arrow[r, "\Phi_{X,Y'}"'] & \mathsf{Sets}(X, Y')
\end{tikzcd}$$

commutes. Indeed, we have

$$\begin{aligned}[\Phi_{X,Y'} \circ g_!](\xi) &\overset{\text{def}}{=} \Phi_{X,Y'}(g_!(\xi))\\&\overset{\text{def}}{=} \Phi_{X,Y'}(g \circ \xi)\\&\overset{\text{def}}{=} (g \circ \xi) \circ \chi_X\\&= g \circ (\xi \circ \chi_X)\\&\overset{\text{def}}{=} g \circ (\Phi_{X,Y}(\xi))\\&\overset{\text{def}}{=} g_!(\Phi_{X,Y}(\xi))\\&\overset{\text{def}}{=} [g_! \circ \Phi_{X,Y}](\xi).\end{aligned}$$

for each $\xi \in \mathsf{InfLat}((\mathcal{P}(X), \supset), (Y, \preceq))$.

Naturality for Ψ

Since Φ is natural in each argument and Φ is a componentwise inverse to Ψ in each argument, it follows from Categories, Item 2 of Proposition 11.9.7.1.2 that Ψ is also natural in each argument. □

WARNING 4.4.6.1.5 ► FREE COMPLETION IS NOT AN IDEMPOTENT OPERATION

Although the assignment $X \mapsto \mathcal{P}(X)^{\mathrm{op}}$ is called the *free completion of* X, it is not an idempotent operation, i.e. we have $\mathcal{P}(\mathcal{P}(X)^{\mathrm{op}})^{\mathrm{op}} \neq \mathcal{P}(X)^{\mathrm{op}}$.

4.4.7 The Internal Hom of a Powerset

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

PROPOSITION 4.4.7.1.1 ► THE INTERNAL HOM OF A POWERSET

The **internal Hom of** $\mathcal{P}(X)$ **from** U **to** V is the subset $[U, V]_X$[1] of X given by

$$\begin{aligned} [U, V]_X &= U^{\mathsf{c}} \cup V \\ &= (U \setminus V)^{\mathsf{c}} \end{aligned}$$

where U^{c} is the complement of U of Definition 4.3.11.1.1.

[1] *Further Notation:* Also written $\mathbf{Hom}_{\mathcal{P}(X)}(U, V)$.

PROOF 4.4.7.1.2 ► PROOF OF PROPOSITION 4.4.7.1.1

Proof of the Equality $U^{\mathsf{c}} \cup V = (U \setminus V)^{\mathsf{c}}$

We have

$$\begin{aligned} (U \setminus V)^{\mathsf{c}} &\stackrel{\text{def}}{=} X \setminus (U \setminus V) \\ &= (X \cap V) \cup (X \setminus U) \\ &= V \cup (X \setminus U) \\ &\stackrel{\text{def}}{=} V \cup U^{\mathsf{c}} \\ &= U^{\mathsf{c}} \cup V, \end{aligned}$$

where we have used:

1. Item 10 of Proposition 4.3.10.1.2 for the second equality.

2. Item 4 of Proposition 4.3.9.1.2 for the third equality.
3. Item 4 of Proposition 4.3.8.1.2 for the last equality.

This finishes the proof.

Proof that $U^{\mathsf{c}} \cup V$ Is Indeed the Internal Hom

This follows from Item 2 of Proposition 4.3.9.1.2.

Remark 4.4.7.1.3 ► Intuition for the Internal Hom of $\mathcal{P}(X)$

Henning Makholm suggests the following heuristic intuition for the internal Hom of $\mathcal{P}(X)$ from U to V ([MSE 267365]):

1. Since products in $\mathcal{P}(X)$ are given by binary intersections (Item 1 of Proposition 4.4.1.1.4), the right adjoint $\mathbf{Hom}_{\mathcal{P}(X)}(U,-)$ of $U \cap -$ may be thought of as a function type $[U,V]$.
2. Under the Curry–Howard correspondence (**??**), the function type $[U,V]$ corresponds to implication $U \Rightarrow V$.
3. Implication $U \Rightarrow V$ is logically equivalent to $\neg U \vee V$.
4. The expression $\neg U \vee V$ then corresponds to the set $U^{\mathsf{c}} \cup V$ in $\mathcal{P}(X)$.
5. The set $U^{\mathsf{c}} \vee V$ turns out to indeed be the internal Hom of $\mathcal{P}(X)$.

Proposition 4.4.7.1.4 ► Properties of Internal Homs of Powersets

Let X be a set.

1. *Functoriality.* The assignments $U, V, (U,V) \mapsto \mathbf{Hom}_{\mathcal{P}(X)}$ define functors

$$\begin{aligned}
[U,-]_X &\colon & (\mathcal{P}(X),\supset) &\to (\mathcal{P}(X),\subset),\\
[-,V]_X &\colon & (\mathcal{P}(X),\subset) &\to (\mathcal{P}(X),\subset),\\
[-_1,-_2]_X &\colon & (\mathcal{P}(X)\times\mathcal{P}(X),\subset\times\supset) &\to (\mathcal{P}(X),\subset).
\end{aligned}$$

   In particular, the following statements hold for each $U, V, A, B \in \mathcal{P}(X)$:

   (a) If $U \subset A$, then $[A,V]_X \subset [U,V]_X$.

   (b) If $V \subset B$, then $[U, V]_X \subset [U, B]_X$.
   (c) If $U \subset A$ and $V \subset B$, then $[A, V]_X \subset [U, B]_X$.

2. *Adjointness.* We have adjunctions

$$
\begin{tikzcd}
(U \cap - \dashv [U, -]_X)\colon \quad \mathcal{P}(X) \arrow[r, bend left, "U\cap -"] \arrow[r, phantom, "\perp"] & \mathcal{P}(X) \arrow[l, bend left, "{[U,-]_X}"],
\end{tikzcd}
$$

$$
\begin{tikzcd}
(- \cap V \dashv [V, -]_X)\colon \quad \mathcal{P}(X) \arrow[r, bend left, "-\cap V"] \arrow[r, phantom, "\perp"] & \mathcal{P}(X) \arrow[l, bend left, "{[V,-]_X}"],
\end{tikzcd}
$$

   witnessed by bijections

$$
\begin{aligned}
\mathrm{Hom}_{\mathcal{P}(X)}(U \cap V, W) &\cong \mathrm{Hom}_{\mathcal{P}(X)}(U, [V, W]_X),\\
\mathrm{Hom}_{\mathcal{P}(X)}(U \cap V, W) &\cong \mathrm{Hom}_{\mathcal{P}(X)}(V, [U, W]_X).
\end{aligned}
$$

   In particular, the following statements hold for each $U, V, W \in \mathcal{P}(X)$:

   (a) The following conditions are equivalent:
      i. We have $U \cap V \subset W$.
      ii. We have $U \subset [V, W]_X$.
   (b) The following conditions are equivalent:
      i. We have $U \cap V \subset W$.
      ii. We have $V \subset [U, W]_X$.

3. *Interaction With the Empty Set I.* We have

$$
\begin{aligned}
[U, \emptyset]_X &= U^{\mathsf{c}},\\
[\emptyset, V]_X &= X,
\end{aligned}
$$

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

4. *Interaction With X.* We have

$$
\begin{aligned}
[U, X]_X &= X,\\
[X, V]_X &= V,
\end{aligned}
$$

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

5. *Interaction With the Empty Set II.* The functor

$$D_X : \mathcal{P}(X)^{\mathsf{op}} \to \mathcal{P}(X)$$

defined by

$$\begin{aligned} D_X &\overset{\text{def}}{=} [-, \emptyset]_X \\ &= (-)^{\mathsf{c}} \end{aligned}$$

is an involutory isomorphism of categories, making $\emptyset$ into a dualising object for $(\mathcal{P}(X), \cap, X, [-,-]_X)$ in the sense of **??**. In particular:

(a) The diagram

$$\begin{tikzcd} \mathcal{P}(X)^{\mathsf{op}} \arrow[r, "D_X"] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)^{\mathsf{op}}}"'] & \mathcal{P}(X) \arrow[d, "D_X"] \\ & \mathcal{P}(X)^{\mathsf{op}} \end{tikzcd}$$

commutes, i.e. we have

$$\underbrace{D_X(D_X(U))}_{\overset{\text{def}}{=}[[U,\emptyset]_X,\emptyset]_X} = U$$

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

(b) The diagram

$$\begin{tikzcd} & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X)^{\mathsf{op}} \arrow[r, "\cap^{\mathsf{op}}"] & \mathcal{P}(X)^{\mathsf{op}} \arrow[dr, "D_X"] & \\ \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)^{\mathsf{op}}} \times D_X"] \arrow[rrr, "{[-_1,-_2]_X}"'] & & & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\underbrace{D_X(U \cap D_X(V))}_{\overset{\text{def}}{=}[U\cap[V,\emptyset]_X,\emptyset]_X} = [U, V]_X$$

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

6. *Interaction With the Empty Set III.* Let $f\colon X \to Y$ be a function.

   (a) *Interaction With Direct Images.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_*^{\mathsf{op}}"] \arrow[d, "D_X"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "D_Y"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

   commutes, i.e. we have

$$f_!(D_X(U)) = D_Y(f_*(U))$$

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

   (b) *Interaction With Inverse Images.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \arrow[r, "f^{-1,\mathsf{op}}"] \arrow[d, "D_Y"'] & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "D_X"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

   commutes, i.e. we have

$$f^{-1}(D_Y(U)) = D_X(f^{-1}(U))$$

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

   (c) *Interaction With Codirect Images.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_!^{\mathsf{op}}"] \arrow[d, "D_X"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "D_Y"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

   commutes, i.e. we have

$$f_*(D_X(U)) = D_Y(f_!(U))$$

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

7. *Interaction With Unions of Families of Subsets I.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "{[-_1,-_2]_{\mathcal{P}(X)}}"] \arrow[d, "\bigcup^{\mathsf{op}} \times \bigcup^{\mathsf{op}}"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "{[-_1,-_2]_X}"'] & \mathcal{P}(X),
\end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcup_{W \in [\mathcal{U},\mathcal{V}]_{\mathcal{P}(X)}} W \neq \left[\bigcup_{U \in \mathcal{U}} U, \bigcup_{V \in \mathcal{V}} V\right]_X$$

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

8. *Interaction With Unions of Families of Subsets II.* The diagram

$$\begin{tikzcd}
 & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[dr, "\bigcup^{\mathsf{op}}"] & \\
\mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[ur, dashed, "\sim"] \arrow[d, "{\mathrm{id}_{\mathcal{P}(X)} \star [-,V]_X}"'] & & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "{[-,V]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[rr, "\bigcap"'] & & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\left[\bigcup_{U \in \mathcal{U}} U, V\right]_X = \bigcap_{U \in \mathcal{U}} [U, V]_X$$

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

9. *Interaction With Unions of Families of Subsets III.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcup"] \arrow[d, "{\mathrm{id}_{\mathcal{P}(X)} \star [U,-]_X}"'] & \mathcal{P}(X) \arrow[d, "{[U,-]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcup"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\left[U, \bigcup_{V \in \mathcal{V}} V\right]_X = \bigcup_{V \in \mathcal{V}} [U, V]_X$$

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

10. *Interaction With Intersections of Families of Subsets I.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \times \mathcal{P}(\mathcal{P}(X)) \arrow[r, "{[-_1,-_2]_{\mathcal{P}(X)}}"] \arrow[d, "\bigcap^{\mathsf{op}} \times \bigcap^{\mathsf{op}}"'] \arrow[dr, phantom, "\times"] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "{[-_1,-_2]_X}"'] & \mathcal{P}(X),
\end{tikzcd}$$

does not commute in general, i.e. we may have

$$\bigcap_{W \in [\mathcal{U},\mathcal{V}]_{\mathcal{P}(X)}} W \neq \left[\bigcap_{U \in \mathcal{U}} U, \bigcap_{V \in \mathcal{V}} V\right]_X$$

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

11. *Interaction With Intersections of Families of Subsets II.* The diagram

$$\begin{tikzcd}
 & \mathcal{P}(\mathcal{P}(X))^{\mathsf{op}} \arrow[dr, "\bigcap^{\mathsf{op}}"] & \\
\mathcal{P}(\mathcal{P}(X)^{\mathsf{op}}) \arrow[ur, dashed, "\sim"] \arrow[d, "{\mathrm{id}_{\mathcal{P}(X)} \star [-,V]_X}"'] & & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "{[-,V]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[rr, "\bigcup"'] & & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\left[\bigcap_{U \in \mathcal{U}} U, V\right]_X = \bigcup_{U \in \mathcal{U}} [U, V]_X$$

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

12. *Interaction With Intersections of Families of Subsets III.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcap"] \arrow[d, "\mathrm{id}_{\mathcal{P}(X)} \star [U,-]_X"'] & \mathcal{P}(X) \arrow[d, "{[U,-]_X}"] \\
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "\bigcap"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$\left[U, \bigcap_{V \in \mathcal{V}} V\right]_X = \bigcap_{V \in \mathcal{V}} [U, V]_X$$

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

13. *Interaction With Binary Unions.* We have equalities of sets

$$\begin{aligned}
[U \cap V, W]_X &= [U, W]_X \cup [V, W]_X, \\
[U, V \cap W]_X &= [U, V]_X \cap [U, W]_X
\end{aligned}$$

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

14. *Interaction With Binary Intersections.* We have equalities of sets

$$\begin{aligned}
[U \cup V, W]_X &= [U, W]_X \cap [V, W]_X, \\
[U, V \cup W]_X &= [U, V]_X \cup [U, W]_X
\end{aligned}$$

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

15. *Interaction With Differences.* We have equalities of sets

$$\begin{aligned}
[U \setminus V, W]_X &= [U, W]_X \cup [V^{\mathsf{c}}, W]_X \\
&= [U, W]_X \cup [U, V]_X, \\
[U, V \setminus W]_X &= [U, V]_X \setminus (U \cap W)
\end{aligned}$$

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

16. *Interaction With Complements.* We have equalities of sets

$$\begin{aligned}[U^{\mathsf{c}}, V]_X &= U \cup V, \\ [U, V^{\mathsf{c}}]_X &= U \cap V, \\ [U, V]^{\mathsf{c}}_X &= U \setminus V\end{aligned}$$

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

17. *Interaction With Characteristic Functions.* We have

$$\chi_{[U,V]_{\mathcal{P}(X)}}(x) = \max(1 - \chi_U \pmod{2}, \chi_V)$$

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

18. *Interaction With Direct Images.* Let $f \colon X \to Y$ be a function. The diagram

$$\begin{tikzcd}\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_*^{\mathsf{op}} \times f_!"] \arrow[d, "{[-_1,-_2]_X}"'] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "{[-_1,-_2]_Y}"] \\ \mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)\end{tikzcd}$$

commutes, i.e. we have an equality of sets

$$f_!([U, V]_X) = [f_*(U), f_!(V)]_Y,$$

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

19. *Interaction With Inverse Images.* Let $f \colon X \to Y$ be a function. The diagram

$$\begin{tikzcd}\mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[r, "f^{-1,\mathsf{op}} \times f^{-1}"] \arrow[d, "{[-_1,-_2]_Y}"'] & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[d, "{[-_1,-_2]_X}"] \\ \mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)\end{tikzcd}$$

commutes, i.e. we have an equality of sets

$$f^{-1}([U, V]_Y) = [f^{-1}(U), f^{-1}(V)]_X,$$

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

20. *Interaction With Codirect Images.* Let $f\colon X \to Y$ be a function. We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_!^{\mathsf{op}} \times f_*"] \arrow[d, "{[-_1,-_2]_X}"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "{[-_1,-_2]_Y}"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$[f_!(U), f_*(V)]_Y \subset f_*([U,V]_X)$$

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

Proof 4.4.7.1.5 ▶ Proof of Proposition 4.4.7.1.4

Item 1: Functoriality

Since $\mathcal{P}(X)$ is posetal, it suffices to prove Items 1a to 1c.

1. *Proof of Item 1a:* We have

$$\begin{aligned}
[A, V]_X &\overset{\text{def}}{=} A^{\mathsf{c}} \cup V \\
&\subset U^{\mathsf{c}} \cup V \\
&\overset{\text{def}}{=} [U, V]_X,
\end{aligned}$$

where we have used:

   (a) Item 1 of Proposition 4.3.11.1.2, which states that if $U \subset A$, then $A^{\mathsf{c}} \subset U^{\mathsf{c}}$.

   (b) Item 1a of Item 1 of Proposition 4.3.11.1.2, which states that if $A^{\mathsf{c}} \subset U^{\mathsf{c}}$, then $A^{\mathsf{c}} \cup K \subset U^{\mathsf{c}} \cup K$ for any $K \in \mathcal{P}(X)$.

2. *Proof of Item 1b:* We have

$$[U, V]_X \overset{\text{def}}{=} U^{\mathsf{c}} \cup V$$

$$\begin{aligned} &\subset U^{\mathsf{c}} \cup B \\ &\overset{\text{def}}{=} [U, B]_X, \end{aligned}$$

where we have used Item 1b of Item 1 of Proposition 4.3.11.1.2, which states that if $V \subset B$, then $K \cup V \subset K \cup B$ for any $K \in \mathcal{P}(X)$.

3. *Proof of Item 1c:* We have

$$\begin{aligned} [A, V]_X &\subset [U, V]_X \\ &\subset [U, B]_X, \end{aligned}$$

where we have used Items 1a and 1b.

This finishes the proof.

Item 2: Adjointness

This is a repetition of Item 2 of Proposition 4.3.9.1.2 and is proved there.

Item 3: Interaction With the Empty Set I

We have

$$\begin{aligned} [U, \emptyset]_X &\overset{\text{def}}{=} U^{\mathsf{c}} \cup \emptyset \\ &= U^{\mathsf{c}}, \end{aligned}$$

where we have used Item 3 of Proposition 4.3.8.1.2, and we have

$$\begin{aligned} [\emptyset, V]_X &\overset{\text{def}}{=} \emptyset^{\mathsf{c}} \cup V \\ &\overset{\text{def}}{=} (X \setminus \emptyset) \cup V \\ &= X \cup V \\ &= X, \end{aligned}$$

where we have used:

1. Item 12 of Proposition 4.3.10.1.2 for the first equality.

2. Item 5 of Proposition 4.3.8.1.2 for the last equality.

Since $\mathcal{P}(X)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2).

Item 4: Interaction With X

We have

$$\begin{aligned}[U, X]_X &\stackrel{\text{def}}{=} U^{\mathsf{c}} \cup X \\ &= X,\end{aligned}$$

where we have used Item 5 of Proposition 4.3.8.1.2, and we have

$$\begin{aligned}[X, V]_X &\stackrel{\text{def}}{=} X^{\mathsf{c}} \cup V \\ &\stackrel{\text{def}}{=} (X \setminus X) \cup V \\ &= \emptyset \cup V \\ &= V,\end{aligned}$$

where we have used Item 3 of Proposition 4.3.8.1.2 for the last equality. Since $\mathcal{P}(X)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2).

Item 5: Interaction With the Empty Set II

We have

$$\begin{aligned}D_X(D_X(U)) &\stackrel{\text{def}}{=} [[U, \emptyset]_X, \emptyset]_X \\ &= [U^{\mathsf{c}}, \emptyset]_X \\ &= (U^{\mathsf{c}})^{\mathsf{c}} \\ &= U,\end{aligned}$$

where we have used:

1. Item 3 for the second and third equalities.
2. Item 3 of Proposition 4.3.11.1.2 for the fourth equality.

Since $\mathcal{P}(X)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2), and thus we have

$$[[-, \emptyset]_X, \emptyset]_X \cong \mathrm{id}_{\mathcal{P}(X)}$$

This finishes the proof.

Item 6: Interaction With the Empty Set III

Since $D_X = (-)^{\mathsf{c}}$, this is essentially a repetition of the corresponding results for $(-)^{\mathsf{c}}$, namely Items 5 to 7 of Proposition 4.3.11.1.2.

Item 7: Interaction With Unions of Families of Subsets I

By Item 3 of Proposition 4.4.7.1.4, we have

$$\begin{aligned}[\mathcal{U}, \emptyset]_{\mathcal{P}(X)} &= \mathcal{U}^{\mathsf{c}},\\ [U, \emptyset]_X &= U^{\mathsf{c}}.\end{aligned}$$

With this, the counterexample given in the proof of Item 10 of Proposition 4.3.6.1.2 then applies.

Item 8: Interaction With Unions of Families of Subsets II

We have

$$\begin{aligned}\left[\bigcup_{U\in\mathcal{U}} U, V\right]_X &\overset{\text{def}}{=} \left(\bigcup_{U\in\mathcal{U}} U\right)^{\mathsf{c}} \cup V\\ &= \left(\bigcap_{U\in\mathcal{U}} U^{\mathsf{c}}\right) \cup V\\ &= \bigcap_{U\in\mathcal{U}} (U^{\mathsf{c}} \cup V)\\ &\overset{\text{def}}{=} \bigcap_{U\in\mathcal{U}} [U, V]_X,\end{aligned}$$

where we have used:

1. Item 11 of Proposition 4.3.6.1.2 for the second equality.
2. Item 6 of Proposition 4.3.7.1.2 for the third equality.

This finishes the proof.

Item 9: Interaction With Unions of Families of Subsets III

We have

$$\begin{aligned}\bigcup_{V\in\mathcal{V}}[U,V]_X &\overset{\text{def}}{=} \bigcup_{V\in\mathcal{V}}(U^{\mathsf{c}}\cup V)\\ &= U^{\mathsf{c}}\cup\left(\bigcup_{V\in\mathcal{V}}V\right)\\ &\overset{\text{def}}{=}\left[U,\bigcup_{V\in\mathcal{V}}V\right]_X.\end{aligned}$$

where we have used Item 6. This finishes the proof.

Item 10: Interaction With Intersections of Families of Subsets I

Let $X = \{0,1\}$, let $\mathcal{U} = \{\{0,1\}\}$, and let $\mathcal{V} = \{\{0\},\{0,1\}\}$. We have

$$\begin{aligned}\bigcap_{W\in[\mathcal{U},\mathcal{V}]_{\mathcal{P}(X)}} W &= \bigcap_{W\in\mathcal{P}(X)} W\\ &= \{0,1\},\end{aligned}$$

whereas

$$\begin{aligned}\left[\bigcap_{U\in\mathcal{U}}U,\bigcap_{V\in\mathcal{V}}V\right]_X &= [\{0,1\},\{0\}]\\ &= \{0\},\end{aligned}$$

Thus we have

$$\bigcap_{W\in[\mathcal{U},\mathcal{V}]_{\mathcal{P}(X)}} W = \{0,1\} \neq \{0\} = \left[\bigcap_{U\in\mathcal{U}}U,\bigcap_{V\in\mathcal{V}}V\right]_X.$$

This finishes the proof.

Item 11: Interaction With Intersections of Families of Subsets II

We have

$$\left[\bigcap_{U\in\mathcal{U}}U,V\right]_X \overset{\text{def}}{=} \left(\bigcap_{U\in\mathcal{U}}U\right)^{\mathsf{c}}\cup V$$

$$
\begin{aligned}
&= \left(\bigcup_{U\in\mathcal{U}} U^{\mathsf{c}}\right) \cup V \\
&= \bigcup_{U\in\mathcal{U}} (U^{\mathsf{c}} \cup V) \\
&\stackrel{\text{def}}{=} \bigcup_{U\in\mathcal{U}} [U, V]_X,
\end{aligned}
$$

where we have used:

1. Item 12 of Proposition 4.3.6.1.2 for the second equality.

2. Item 6 of Proposition 4.3.7.1.2 for the third equality.

This finishes the proof.

Item 12: Interaction With Intersections of Families of Subsets III

We have

$$
\begin{aligned}
\bigcap_{V\in\mathcal{V}} [U, V]_X &\stackrel{\text{def}}{=} \bigcap_{V\in\mathcal{V}} (U^{\mathsf{c}} \cup V) \\
&= U^{\mathsf{c}} \cup \left(\bigcap_{V\in\mathcal{V}} V\right) \\
&\stackrel{\text{def}}{=} \left[U, \bigcap_{V\in\mathcal{V}} V\right]_X.
\end{aligned}
$$

where we have used Item 6. This finishes the proof.

Item 13: Interaction With Binary Unions

We have

$$
\begin{aligned}
[U \cap V, W]_X &\stackrel{\text{def}}{=} (U \cap V)^{\mathsf{c}} \cup W \\
&= (U^{\mathsf{c}} \cup V^{\mathsf{c}}) \cup W \\
&= (U^{\mathsf{c}} \cup V^{\mathsf{c}}) \cup (W \cup W) \\
&= (U^{\mathsf{c}} \cup W) \cup (V^{\mathsf{c}} \cup W) \\
&\stackrel{\text{def}}{=} [U, W]_X \cup [V, W]_X,
\end{aligned}
$$

where we have used:

1. Item 2 of Proposition 4.3.11.1.2 for the second equality.
2. Item 8 of Proposition 4.3.8.1.2 for the third equality.
3. Several applications of Items 2 and 4 of Proposition 4.3.8.1.2 and for the fourth equality.

For the second equality in the statement, we have

$$\begin{aligned}[U, V \cap W]_X &\overset{\text{def}}{=} U^{\mathsf{c}} \cup (V \cap W) \\ &= (U^{\mathsf{c}} \cup V) \cap (U^{\mathsf{c}} \cap W) \\ &\overset{\text{def}}{=} [U, V]_X \cap [U, W]_X,\end{aligned}$$

where we have used Item 6 of Proposition 4.3.8.1.2 for the second equality.

Item 14: Interaction With Binary Intersections

We have

$$\begin{aligned}[U \cup V, W]_X &\overset{\text{def}}{=} (U \cup V)^{\mathsf{c}} \cup W \\ &= (U^{\mathsf{c}} \cap V^{\mathsf{c}}) \cup W \\ &= (U^{\mathsf{c}} \cup W) \cap (V^{\mathsf{c}} \cup W) \\ &\overset{\text{def}}{=} [U, W]_X \cap [V, W]_X,\end{aligned}$$

where we have used:

1. Item 2 of Proposition 4.3.11.1.2 for the second equality.
2. Item 6 of Proposition 4.3.8.1.2 for the third equality.

Now, for the second equality in the statement, we have

$$\begin{aligned}[U, V \cup W]_X &\overset{\text{def}}{=} U^{\mathsf{c}} \cup (V \cup W) \\ &= (U^{\mathsf{c}} \cup U^{\mathsf{c}}) \cup (V \cup W) \\ &= (U^{\mathsf{c}} \cup V) \cup (U^{\mathsf{c}} \cup W) \\ &\overset{\text{def}}{=} [U, V]_X \cup [U, W]_X,\end{aligned}$$

where we have used:

1. Item 8 of Proposition 4.3.8.1.2 for the second equality.
2. Several applications of Items 2 and 4 of Proposition 4.3.8.1.2 and for the third equality.

This finishes the proof.

Item 15: Interaction With Differences

We have

$$\begin{aligned}
[U \setminus V, W]_X &\overset{\text{def}}{=} (U \setminus V)^{\mathsf{c}} \cup W \\
&\overset{\text{def}}{=} (X \setminus (U \setminus V)) \cup W \\
&= ((X \cap V) \cup (X \setminus U)) \cup W \\
&= (V \cup (X \setminus U)) \cup W \\
&\overset{\text{def}}{=} (V \cup U^{\mathsf{c}}) \cup W \\
&= (V \cup (U^{\mathsf{c}} \cup U^{\mathsf{c}})) \cup W \\
&= (U^{\mathsf{c}} \cup W) \cup (U^{\mathsf{c}} \cup V) \\
&\overset{\text{def}}{=} [U, W]_X \cup [U, V]_X,
\end{aligned}$$

where we have used:

1. Item 10 of Proposition 4.3.10.1.2 for the third equality.
2. Item 4 of Proposition 4.3.9.1.2 for the fourth equality.
3. Item 8 of Proposition 4.3.8.1.2 for the sixth equality.
4. Several applications of Items 2 and 4 of Proposition 4.3.8.1.2 and for the seventh equality.

We also have

$$\begin{aligned}
[U \setminus V, W]_X &\overset{\text{def}}{=} (U \setminus V)^{\mathsf{c}} \cup W \\
&\overset{\text{def}}{=} (X \setminus (U \setminus V)) \cup W \\
&= ((X \cap V) \cup (X \setminus U)) \cup W \\
&= (V \cup (X \setminus U)) \cup W
\end{aligned}$$

$$
\begin{aligned}
&\overset{\text{def}}{=} (V \cup U^{\mathsf{c}}) \cup W \\
&= (V \cup U^{\mathsf{c}}) \cup (W \cup W) \\
&= (U^{\mathsf{c}} \cup W) \cup (V \cup W) \\
&= (U^{\mathsf{c}} \cup W) \cup ((V^{\mathsf{c}})^{\mathsf{c}} \cup W) \\
&\overset{\text{def}}{=} [U, W]_X \cup [V^{\mathsf{c}}, W]_X,
\end{aligned}
$$

where we have used:

1. Item 10 of Proposition 4.3.10.1.2 for the third equality.
2. Item 4 of Proposition 4.3.9.1.2 for the fourth equality.
3. Item 8 of Proposition 4.3.8.1.2 for the sixth equality.
4. Several applications of Items 2 and 4 of Proposition 4.3.8.1.2 and for the seventh equality.
5. Item 3 of Proposition 4.3.11.1.2 for the eighth equality.

Now, for the second equality in the statement, we have

$$
\begin{aligned}
[U, V \setminus W]_X &\overset{\text{def}}{=} U^{\mathsf{c}} \cup (V \setminus W) \\
&= (V \setminus W) \cup U^{\mathsf{c}} \\
&= (V \cup U^{\mathsf{c}}) \setminus (W \setminus U^{\mathsf{c}}) \\
&\overset{\text{def}}{=} (V \cup U^{\mathsf{c}}) \setminus (W \setminus (X \setminus U)) \\
&= (V \cup U^{\mathsf{c}}) \setminus ((W \cap U) \cup (W \setminus X)) \\
&= (V \cup U^{\mathsf{c}}) \setminus ((W \cap U) \cup \emptyset) \\
&= (V \cup U^{\mathsf{c}}) \setminus (W \cap U) \\
&= (V \cup U^{\mathsf{c}}) \setminus (U \cap W) \\
&\overset{\text{def}}{=} [U, V]_X \setminus (U \cap W)
\end{aligned}
$$

where we have used:

1. Item 4 of Proposition 4.3.8.1.2 for the second equality.
2. Item 4 of Proposition 4.3.10.1.2 for the third equality.

3. Item 10 of Proposition 4.3.10.1.2 for the fifth equality.
4. Item 13 of Proposition 4.3.10.1.2 for the sixth equality.
5. Item 3 of Proposition 4.3.8.1.2 for the seventh equality.
6. Item 5 of Proposition 4.3.9.1.2 for the eighth equality.

This finishes the proof.

Item 16: Interaction With Complements

We have

$$\begin{aligned}[U^{\mathsf{c}}, V]_X &\stackrel{\text{def}}{=} (U^{\mathsf{c}})^{\mathsf{c}} \cup V, \\ &= U \cup V,\end{aligned}$$

where we have used Item 3 of Proposition 4.3.11.1.2. We also have

$$\begin{aligned}[U, V^{\mathsf{c}}]_X &\stackrel{\text{def}}{=} U^{\mathsf{c}} \cup V^{\mathsf{c}} \\ &= U \cap V\end{aligned}$$

where we have used Item 2 of Proposition 4.3.11.1.2. Finally, we have

$$\begin{aligned}[U, V]_X^{\mathsf{c}} &= ((U \setminus V)^{\mathsf{c}})^{\mathsf{c}} \\ &= U \setminus V,\end{aligned}$$

where we have used Item 2 of Proposition 4.3.11.1.2.

Item 17: Interaction With Characteristic Functions

We have

$$\begin{aligned}\chi_{[U,V]_{\mathcal{P}(X)}}(x) &\stackrel{\text{def}}{=} \chi_{U^{\mathsf{c}} \cup V}(x) \\ &= \max(\chi_{U^{\mathsf{c}}}, \chi_V) \\ &= \max(1 - \chi_U \pmod 2, \chi_V),\end{aligned}$$

where we have used:

1. Item 10 of Proposition 4.3.8.1.2 for the second equality.
2. Item 4 of Proposition 4.3.11.1.2 for the third equality.

This finishes the proof.

Item 18: Interaction With Direct Images

This is a repetition of Item 10 of Proposition 4.6.1.1.5 and is proved there.

Item 19: Interaction With Inverse Images

This is a repetition of Item 10 of Proposition 4.6.2.1.3 and is proved there.

Item 20: Interaction With Codirect Images

This is a repetition of Item 9 of Proposition 4.6.3.1.7 and is proved there.

4.4.8 Isbell Duality for Sets

Let X be a set.

Definition 4.4.8.1.1 ▶ The Isbell Function

The **Isbell function** of X is the map

$$\mathsf{I}\colon \mathcal{P}(X) \to \mathsf{Sets}(X, \mathcal{P}(X))$$

defined by

$$\mathsf{I}(U) \overset{\text{def}}{=} [\![x \mapsto [U, \{x\}]_X]\!]$$

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

Remark 4.4.8.1.2 ▶ Motivation for the Isbell Function

Recall from Remark 4.4.1.1.2 that we may view the powerset $\mathcal{P}(X)$ of a set X as the decategorification of the category of presheaves $\mathsf{PSh}(C)$ of a category C. Building upon this analogy, we want to mimic the definition of the Isbell Spec functor, which is given on objects by

$$\mathsf{Spec}(\mathcal{F}) \overset{\text{def}}{=} \mathrm{Nat}(\mathcal{F}, h_{(-)})$$

for each $\mathcal{F} \in \mathrm{Obj}(\mathsf{PSh}(\mathcal{C}))$. To this end, we could define

$$\mathsf{I}(U) \stackrel{\text{def}}{=} [U, \chi_{(-)}]_X,$$

replacing:

- The Yoneda embedding $X \mapsto h_X$ of $\mathcal{C}$ into $\mathsf{PSh}(\mathcal{C})$ with the characteristic embedding $x \mapsto \chi_x$ of X into $\mathcal{P}(X)$ of Definition 4.5.4.1.1.
- The internal Hom Nat of $\mathsf{PSh}(\mathcal{C})$ with the internal Hom $[-,-]_X$ of $\mathcal{P}(X)$ of Proposition 4.4.7.1.1.

However, since $[U, \chi_x]_X$ is a subset of U instead of a truth value, we get a function

$$\mathsf{I}\colon \mathcal{P}(X) \to \mathsf{Sets}(X, \mathcal{P}(X))$$

instead of a function

$$\mathsf{I}\colon \mathcal{P}(X) \to \mathcal{P}(X).$$

This makes some of the properties involving I a bit more cumbersome to state, although we still have an analogue of Isbell duality in that $\mathsf{I}_! \circ \mathsf{I}$ evaluates to $\mathrm{id}_{\mathcal{P}(X)}$ in the sense of Proposition 4.4.8.1.3.

Proposition 4.4.8.1.3 ▶ Isbell Duality for Sets

The diagram

$$\begin{tikzcd} \mathcal{P}(X) \arrow[r, "\mathsf{I}"] \arrow[dr, "\Delta_{\Delta_{\mathrm{id}_{\mathcal{P}(X)}}}"'] & \mathsf{Sets}(X, \mathcal{P}(X)) \arrow[d, "\mathsf{I}_!"] \\ & \mathsf{Sets}(X, \mathsf{Sets}(X, \mathcal{P}(X))) \end{tikzcd}$$

commutes, i.e. we have

$$\mathsf{I}_!(\mathsf{I}(U)) = [\![x \mapsto [\![y \mapsto U]\!]]\!]$$

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

Proof 4.4.8.1.4 ► Proof of Proposition 4.4.8.1.3

We have

$$\begin{aligned} \mathsf{I}_!(\mathsf{I}(U)) &\overset{\text{def}}{=} \mathsf{I}_!([\![x \mapsto U^{\mathsf{c}} \cup \{x\}]\!]) \\ &\overset{\text{def}}{=} [\![x \mapsto \mathsf{I}(U^{\mathsf{c}} \cup \{x\})]\!] \\ &\overset{\text{def}}{=} [\![x \mapsto [\![y \mapsto (U^{\mathsf{c}} \cup \{x\})^{\mathsf{c}} \cup \{x\}]\!]]\!] \\ &= [\![x \mapsto [\![y \mapsto (U \cap (X \setminus \{x\})) \cup \{x\}]\!]]\!] \\ &= [\![x \mapsto [\![y \mapsto (U \setminus \{x\}) \cup \{x\}]\!]]\!] \\ &= [\![x \mapsto [\![y \mapsto U]\!]]\!], \end{aligned}$$

where we have used Item 2 of Proposition 4.3.11.1.2 for the fourth equality above.

4.5 Characteristic Functions

4.5.1 The Characteristic Function of a Subset

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

Definition 4.5.1.1.1 ► The Characteristic Function of a Subset

The **characteristic function of** U[1] is the function $\chi_U \colon X \to \{\mathsf{t}, \mathsf{f}\}$[2] defined by

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

for each $x \in X$.

[1] *Further Terminology:* Also called the **indicator function of** U.
[2] *Further Notation:* Also written $\chi_X(U, -)$ or $\chi_X(-, U)$.

Remark 4.5.1.1.2 ► Characteristic Functions of Subsets as Decategorifications of Presheaves

Under the analogy that $\{\mathsf{t}, \mathsf{f}\}$ should be the (-1)-categorical analogue of Sets, we may view a function

$$f \colon X \to \{\mathsf{t}, \mathsf{f}\}$$

as a decategorification of presheaves and copresheaves

$$\mathcal{F} \colon \mathcal{C}^{\mathsf{op}} \to \mathsf{Sets},$$
$$F \colon \mathcal{C} \to \mathsf{Sets}.$$

The characteristic functions χ_U of the subsets of X are then the primordial examples of such functions (and, in fact, all of them).

Notation 4.5.1.1.3 ► Further Notation for Characteristic Functions

We will often employ the bijection $\{\mathsf{t}, \mathsf{f}\} \cong \{0, 1\}$ to make use of the arithmetical operations defined on $\{0, 1\}$ when disucssing characteristic functions.

Examples of this include Items 4 to 11 of Proposition 4.5.1.1.4 below.

Proposition 4.5.1.1.4 ► Properties of Characteristic Functions of Subsets

Let X be a set.

1. *Functionality.* The assignment $U \mapsto \chi_U$ defines a function
$$\chi_{(-)} \colon \mathcal{P}(X) \to \mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\}).$$
2. *Bijectivity.* The function $\chi_{(-)}$ from Item 1 is bijective.
3. *Naturality.* The collection
$$\left\{\chi_{(-)} \colon \mathcal{P}(X) \to \mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})\right\}_{X \in \mathrm{Obj}(\mathsf{Sets})}$$
defines a natural isomorphism between $\mathcal{P}^{-1}$ and $\mathsf{Sets}(-, \{\mathsf{t}, \mathsf{f}\})$. In particular, given a function $f \colon X \to Y$, the diagram
$$\begin{tikzcd}
\mathcal{P}(Y) \arrow[r, "f^{-1}"] \arrow[d, dashed, "\chi_{(-)}"', "\wr"] & \mathcal{P}(X) \arrow[d, dashed, "\chi_{(-)}", "\wr"'] \\
\mathsf{Sets}(Y, \{\mathsf{t}, \mathsf{f}\}) \arrow[r, "f^*"'] & \mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})
\end{tikzcd}$$

commutes, i.e. we have

$$\chi_V \circ f = \chi_{f^{-1}(V)}$$

for each $V \in \mathcal{P}(Y)$.

4. *Interaction With Unions I.* We have

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

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

5. *Interaction With Unions II.* We have

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

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

6. *Interaction With Intersections I.* We have

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

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

7. *Interaction With Intersections II.* We have

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

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

8. *Interaction With Differences.* We have

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

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

9. *Interaction With Complements.* We have

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

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

10. *Interaction With Symmetric Differences.* We have

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

and thus, in particular, we have

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

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

11. *Interaction With Internal Homs.* We have

$$\chi_{[U,V]_{\mathcal{P}(X)}} = \max(1 - \chi_U \pmod 2, \chi_V)$$

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

PROOF 4.5.1.1.5 ▶ PROOF OF PROPOSITION 4.5.1.1.4

Item 1: Functionality

There is nothing to prove.

Item 2: Bijectivity

We proceed in three steps:

1. *The Inverse of $\chi_{(-)}$.* The inverse of $\chi_{(-)}$ is the map

$$\Phi \colon \mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\}) \overset{\sim}{\dashrightarrow} \mathcal{P}(X),$$

defined by

$$\begin{aligned} \Phi(f) &\overset{\text{def}}{=} U_f \\ &\overset{\text{def}}{=} f^{-1}(\mathsf{true}) \\ &\overset{\text{def}}{=} \{x \in X \mid f(x) = \mathsf{true}\} \end{aligned}$$

for each $f \in \mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})$.

2. *Invertibility I.* We have

$$[\Phi \circ \chi_{(-)}](U) \overset{\text{def}}{=} \Phi(\chi_U)$$

$$
\begin{aligned}
&\stackrel{\text{def}}{=} \chi_U^{-1}(\mathsf{true}) \\
&\stackrel{\text{def}}{=} \{x \in X \mid \chi_U(x) = \mathsf{true}\} \\
&\stackrel{\text{def}}{=} \{x \in X \mid x \in U\} \\
&= U \\
&\stackrel{\text{def}}{=} [\mathrm{id}_{\mathcal{P}(X)}](U)
\end{aligned}
$$

for each $U \in \mathcal{P}(X)$. Thus, we have

$$\Phi \circ \chi_{(-)} = \mathrm{id}_{\mathcal{P}(X)}.$$

3. *Invertibility II.* We have

$$
\begin{aligned}
[\chi_{(-)} \circ \Phi](U) &\stackrel{\text{def}}{=} \chi_{\Phi(f)} \\
&\stackrel{\text{def}}{=} \chi_{f^{-1}(\mathsf{true})} \\
&\stackrel{\text{def}}{=} \left[\!\left[x \mapsto \begin{cases} \mathsf{true} & \text{if } x \in f^{-1}(\mathsf{true}) \\ \mathsf{false} & \text{otherwise} \end{cases} \right]\!\right] \\
&= [\![x \mapsto f(x)]\!] \\
&= f \\
&\stackrel{\text{def}}{=} [\mathrm{id}_{\mathsf{Sets}(X,\{\mathsf{t},\mathsf{f}\})}](f)
\end{aligned}
$$

for each $f \in \mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})$. Thus, we have

$$\chi_{(-)} \circ \Phi = \mathrm{id}_{\mathsf{Sets}(X,\{\mathsf{t},\mathsf{f}\})}.$$

This finishes the proof.

Item 3: Naturality

We proceed in two steps:

1. *Naturality of $\chi_{(-)}$.* We have

$$
\begin{aligned}
[\chi_V \circ f](v) &\stackrel{\text{def}}{=} \chi_V(f(v)) \\
&= \begin{cases} \mathsf{true} & \text{if } f(v) \in V, \\ \mathsf{false} & \text{otherwise} \end{cases}
\end{aligned}
$$

$$\begin{aligned} &= \begin{cases} \text{true} & \text{if } v \in f^{-1}(V), \\ \text{false} & \text{otherwise} \end{cases} \\ &\stackrel{\text{def}}{=} \chi_{f^{-1}(V)}(v) \end{aligned}$$

for each $v \in V$.

2. *Naturality of* Φ. Since $\chi_{(-)}$ is natural and a componentwise inverse to Φ, it follows from Categories, Item 2 of Proposition 11.9.7.1.2 that Φ is also natural in each argument.

This finishes the proof.

Item 4: Interaction With Unions I

This is a repetition of Item 10 of Proposition 4.3.8.1.2 and is proved there.

Item 5: Interaction With Unions II

This is a repetition of Item 11 of Proposition 4.3.8.1.2 and is proved there.

Item 6: Interaction With Intersections I

This is a repetition of Item 10 of Proposition 4.3.9.1.2 and is proved there.

Item 7: Interaction With Intersections II

This is a repetition of Item 11 of Proposition 4.3.9.1.2 and is proved there.

Item 8: Interaction With Differences

This is a repetition of Item 16 of Proposition 4.3.10.1.2 and is proved there.

Item 9: Interaction With Complements

This is a repetition of Item 4 of Proposition 4.3.11.1.2 and is proved there.

Item 10: Interaction With Symmetric Differences

This is a repetition of Item 15 of Proposition 4.3.12.1.2 and is proved there.

Item 11: Interaction With Internal Homs

This is a repetition of Item 17 of Proposition 4.4.7.1.4 and is proved there.

Remark 4.5.1.1.6 ▶ Powersets as Sets of Functions and Un/Straightening

The bijection

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

of Item 2 of Proposition 4.5.1.1.4, which

- Takes a subset $U \hookrightarrow X$ of X and *straightens* it to a function $\chi_U \colon X \to \{\mathsf{true}, \mathsf{false}\}$;
- Takes a function $f \colon X \to \{\mathsf{true}, \mathsf{false}\}$ and *unstraightens* it to a subset $f^{-1}(\mathsf{true}) \hookrightarrow X$ of X;

may be viewed as the (-1)-categorical version of the 0-categorical un/straightening isomorphism between indexed and fibred sets

$$\underbrace{\mathsf{FibSets}_X}_{\stackrel{\text{def}}{=}\mathsf{Sets}_{/X}} \cong \underbrace{\mathsf{ISets}_X}_{\stackrel{\text{def}}{=}\mathsf{Fun}(X_{\mathsf{disc}},\mathsf{Sets})}$$

of Un/Straightening for Indexed and Fibred Sets, **??**. Here we view:

- Subsets $U \hookrightarrow X$ as being analogous to X-fibred sets $\phi_X \colon A \to X$.
- Functions $f \colon X \to \{\mathsf{t}, \mathsf{f}\}$ as being analogous to X-indexed sets $A \colon X_{\mathsf{disc}} \to \mathsf{Sets}$.

4.5.2 The Characteristic Function of a Point

Let X be a set and let $x \in X$.

Definition 4.5.2.1.1 ▶ The Characteristic Function of a Point

The **characteristic function of** x is the function[1]

$$\chi_x \colon X \to \{\mathsf{t}, \mathsf{f}\}$$

defined by

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

i.e. by

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

for each $y \in X$.

[1] *Further Notation:* Also written χ^x, $\chi_X(x, -)$, or $\chi_X(-, x)$.

Remark 4.5.2.1.2 ▶ Characteristic Functions of Points as Decategorifications of Representable Presheaves

Expanding upon Remark 4.5.1.1.2, we may think of the characteristic function

$$\chi_x \colon X \to \{\mathsf{t}, \mathsf{f}\}$$

of an *element* x of X as a decategorification of the representable presheaf and of the representable copresheaf

$$h_X \colon \mathcal{C}^{\mathsf{op}} \to \mathsf{Sets},$$
$$h^X \colon \mathcal{C} \to \mathsf{Sets}$$

associated of an *object* X of a category $\mathcal{C}$.

4.5.3 The Characteristic Relation of a Set

Let X be a set.

Definition 4.5.3.1.1 ▶ The Characteristic Relation of a Set

The **characteristic relation on** X[1] is the relation[2]

$$\chi_X(-_1, -_2) \colon X \times X \to \{\mathsf{t}, \mathsf{f}\}$$

on X defined by[3]

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

for each $x, y \in X$.

[1] *Further Terminology:* Also called the **identity relation on** X.

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

[3] Under the bijection $\mathsf{Sets}(X \times X, \{\mathsf{t}, \mathsf{f}\}) \cong \mathcal{P}(X \times X)$ of Item 2 of Proposition 4.5.1.1.4, the relation χ_X corresponds to the diagonal $\Delta_X \subset X \times X$ of X.

Remark 4.5.3.1.2 ► The Characteristic Relation of a Set as a Decategorification of the Hom Profunctor

Expanding upon Remarks 4.5.1.1.2 and 4.5.2.1.2, we may view the characteristic relation

$$\chi_X(-_1, -_2) \colon X \times X \to \{\mathsf{t}, \mathsf{f}\}$$

of X as a decategorification of the Hom profunctor

$$\mathrm{Hom}_{\mathcal{C}}(-_1, -_2) \colon \mathcal{C}^{\mathsf{op}} \times \mathcal{C} \to \mathsf{Sets}$$

of a category $\mathcal{C}$.

Proposition 4.5.3.1.3 ► Properties of Characteristic Relations

Let $f \colon X \to Y$ be a function.

1. *The Inclusion of Characteristic Relations Associated to a Function.* Let $f \colon A \to B$ be a function. We have an inclusion[1]

$$\chi_B \circ (f \times f) \subset \chi_A, \qquad \begin{tikzcd} A \times A \arrow[rr, "f \times f"] \arrow[dr, "\chi_A"'] & \arrow[d, phantom, "\supset"] & B \times B \arrow[dl, "\chi_B"] \\ & \{\mathsf{t}, \mathsf{f}\}. & \end{tikzcd}$$

[1] *Note:* This is the 0-categorical version of Categories, Definition 11.5.4.1.1.

Proof 4.5.3.1.4 ► Proof of Proposition 4.5.3.1.3

Item 1: The Inclusion of Characteristic Relations Associated to a Functi

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. ∎

4.5.4 The Characteristic Embedding of a Set

Let X be a set.

Definition 4.5.4.1.1 ▶ The Characteristic Embedding of a Set

The **characteristic embedding**[1] **of** X **into** $\mathcal{P}(X)$ is the function

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

defined by[2]

$$\begin{aligned}\chi_{(-)}(x) &\overset{\text{def}}{=} \chi_x \\ &= \{x\}\end{aligned}$$

for each $x \in X$.

[1]The name "characteristic *embedding*" is justified by Corollary 4.5.5.1.3, which gives an analogue of fully faithfulness for $\chi_{(-)}$.

[2]Here we are identifying $\mathcal{P}(X)$ with $\mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})$ as per Item 2 of Proposition 4.5.1.1.4.

Remark 4.5.4.1.2 ▶ The Characteristic Embedding of a Set as a Decategorification of the Yoneda Embedding

Expanding upon Remarks 4.5.1.1.2, 4.5.2.1.2 and 4.5.3.1.2, we may view the characteristic embedding

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

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

$$\text{よ} \colon C^{\mathsf{op}} \hookrightarrow \mathsf{PSh}(C)$$

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

Proposition 4.5.4.1.3 ▶ Properties of Characteristic Embeddings

Let $f \colon X \to Y$ be a map of sets.

1. *Interaction With Functions.* We have

$$
f_! \circ \chi_X = \chi_Y \circ f, \qquad
\begin{tikzcd}
X \arrow[r, "f"] \arrow[d, "\chi_X"'] & Y \arrow[d, "\chi_Y"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y).
\end{tikzcd}
$$

Proof 4.5.4.1.4 ▶ Proof of Proposition 4.5.4.1.3

Item 1: Interaction With Functions

Indeed, we have

$$
\begin{aligned}
[f_! \circ \chi_X](x) &\overset{\text{def}}{=} f_!(\chi_X(x)) \\
&\overset{\text{def}}{=} f_!(\{x\}) \\
&= \{f(x)\} \\
&\overset{\text{def}}{=} \chi_{X'}(f(x)) \\
&\overset{\text{def}}{=} [\chi_{X'} \circ f](x),
\end{aligned}
$$

for each $x \in X$, showing the desired equality. □

4.5.5 The Yoneda Lemma for Sets

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

Proposition 4.5.5.1.1 ▶ The Yoneda Lemma for Sets

We have

$$\chi_{\mathcal{P}(X)}(\chi_x, \chi_U) = \chi_U(x)$$

for each $x \in X$, giving an equality of functions

$$\chi_{\mathcal{P}(X)}(\chi_{(-)}, \chi_U) = \chi_U,$$

where

$$\chi_{\mathcal{P}(X)}(U, V) \overset{\text{def}}{=} \begin{cases} \text{true} & \text{if } U \subset V, \\ \text{false} & \text{otherwise.} \end{cases}$$

Proof 4.5.5.1.2 ▶ Proof of Proposition 4.5.5.1.1

We have

$$\begin{aligned}\chi_{\mathcal{P}(X)}(\chi_x, \chi_U) &\stackrel{\text{def}}{=} \begin{cases}\text{true} & \text{if } \{x\} \subset U, \\ \text{false} & \text{otherwise}\end{cases} \\ &= \begin{cases}\text{true} & \text{if } x \in U \\ \text{false} & \text{otherwise}\end{cases} \\ &\stackrel{\text{def}}{=} \chi_U(x).\end{aligned}$$

This finishes the proof.

Corollary 4.5.5.1.3 ▶ The Characteristic Embedding Is Fully Faithful

The characteristic embedding is fully faithful, i.e., we have

$$\chi_{\mathcal{P}(X)}(\chi_x, \chi_y) \cong \chi_X(x, y)$$

for each $x, y \in X$.

Proof 4.5.5.1.4 ▶ Proof of Corollary 4.5.5.1.3

We have

$$\begin{aligned}\chi_{\mathcal{P}(X)}(\chi_x, \chi_y) &= \chi_y(x) \\ &\stackrel{\text{def}}{=} \begin{cases}\text{true} & \text{if } x \in \{y\} \\ \text{false} & \text{otherwise}\end{cases} \\ &= \begin{cases}\text{true} & \text{if } x = y \\ \text{false} & \text{otherwise}\end{cases} \\ &\stackrel{\text{def}}{=} \chi_X(x, y).\end{aligned}$$

where we have used Proposition 4.5.5.1.1 for the first equality.

4.6 The Adjoint Triple $f_! \dashv f^{-1} \dashv f_*$

4.6.1 Direct Images

Let $f\colon X \to Y$ be a function.

Definition 4.6.1.1.1 ► Direct Images

The **direct image function associated to** f is the function[1]

$$f_!\colon \mathcal{P}(X) \to \mathcal{P}(Y)$$

defined by[2]

$$\begin{aligned} f_!(U) &\overset{\text{def}}{=} \left\{ y \in Y \;\middle|\; \begin{array}{l} \text{there exists some } x \in U \\ \text{such that } y = f(x) \end{array} \right\} \\ &= \{ f(x) \in Y \mid x \in U \} \end{aligned}$$

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

[1] *Further Notation:* Also written simply $f\colon \mathcal{P}(X) \to \mathcal{P}(Y)$.
[2] *Further Terminology:* The set $f(U)$ is called the **direct image of** U **by** f.

Notation 4.6.1.1.2 ► Further Notation for Direct Images

Sometimes one finds the notation

$$\exists_f\colon \mathcal{P}(X) \to \mathcal{P}(Y)$$

for $f_!$. This notation comes from the fact that the following statements are equivalent, where $y \in Y$ and $U \in \mathcal{P}(X)$:

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

We will not make use of this notation elsewhere in Clowder.

Warning 4.6.1.1.3 ► Notation for Direct Images Is Confusing

Notation for direct images between powersets is tricky:

1. Direct images for powersets and presheaves are both adjoint to their corresponding inverse image functors. However, the direct image functor for powersets is a *left* adjoint, while the direct image functor for presheaves is a *right* adjoint:

   (a) *Powersets.* Given a function $f \colon X \to Y$, we have an inverse image functor
   $$f^{-1} \colon \mathcal{P}(Y) \to \mathcal{P}(X).$$
   The *left* adjoint of this functor is the usual direct image, defined above in Definition 4.6.1.1.1.

   (b) *Presheaves.* Given a morphism of topological spaces $f \colon X \to Y$, we have an inverse image functor
   $$f^{-1} \colon \mathsf{PSh}(Y) \to \mathsf{PSh}(X).$$
   The *right* adjoint of this functor is the direct image functor of presheaves, defined in **??**.

2. The presheaf direct image functor is denoted f_*, but the direct image functor for powersets is denoted $f_!$ (as it's a left adjoint).

3. Adding to the confusion, it's somewhat common for $f_! \colon \mathcal{P}(X) \to \mathcal{P}(Y)$ to be denoted f_*.

We chose to write $f_!$ for the direct image to keep the notation aligned with the following similar adjoint situations:

Situation	**Adjoint String**
Functoriality of Powersets	$(f_! \dashv f^{-1} \dashv f_*) \colon \mathcal{P}(X) \overset{\rightleftarrows}{\to} \mathcal{P}(Y)$
Functoriality of Presheaf Categories	$(f_! \dashv f^{-1} \dashv f_*) \colon \mathsf{PSh}(X) \overset{\rightleftarrows}{\to} \mathsf{PSh}(Y)$
Base Change	$(f_! \dashv f^* \dashv f_*) \colon \mathcal{C}_{/X} \overset{\rightleftarrows}{\to} \mathcal{C}_{/Y}$
Kan Extensions	$(F_! \dashv F^* \dashv F_*) \colon \mathsf{Fun}(\mathcal{C}, \mathcal{E}) \overset{\rightleftarrows}{\to} \mathsf{Fun}(\mathcal{D}, \mathcal{E})$

Remark 4.6.1.1.4 ▶ Unwinding Definition 4.6.1.1.1

Identifying $\mathcal{P}(X)$ with $\mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})$ via Item 2 of Proposition 4.5.1.1.4, we see that the direct image function associated to f is equivalently the function

$$f_! \colon \mathcal{P}(X) \to \mathcal{P}(Y)$$

defined by

$$\begin{aligned} f_!(\chi_U) &\overset{\text{def}}{=} \mathrm{Lan}_f(\chi_U) \\ &= \operatorname{colim}\big((f \overset{\rightarrow}{\times} \underline{(-_1)}) \overset{\mathrm{pr}}{\twoheadrightarrow} A \xrightarrow{\chi_U} \{\mathsf{t}, \mathsf{f}\}\big) \\ &= \operatorname*{colim}_{\substack{x \in X \\ f(x) = -_1}} (\chi_U(x)) \\ &= \bigvee_{\substack{x \in X \\ f(x) = -_1}} (\chi_U(x)), \end{aligned}$$

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

$$\begin{aligned} [f_!(\chi_U)](y) &= \bigvee_{\substack{x \in X \\ f(x) = y}} (\chi_U(x)) \\ &= \begin{cases} \mathsf{true} & \text{if there exists some } x \in X \text{ such} \\ & \text{that } f(x) = y \text{ and } x \in U, \\ \mathsf{false} & \text{otherwise} \end{cases} \\ &= \begin{cases} \mathsf{true} & \text{if there exists some } x \in U \\ & \text{such that } f(x) = y, \\ \mathsf{false} & \text{otherwise} \end{cases} \end{aligned}$$

for each $y \in Y$.

Proposition 4.6.1.1.5 ▶ Properties of Direct Images I

Let $f \colon X \to Y$ be a function.

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

$$f_! \colon (\mathcal{P}(X), \subset) \to (\mathcal{P}(Y), \subset).$$

In particular, for each $U, V \in \mathcal{P}(X)$, the following condition is satisfied:

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

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

$$
(f_! \dashv f^{-1} \dashv f_*)\colon\quad
\begin{tikzcd}
\mathcal{P}(X) \arrow[r, bend left, "f_!"] \arrow[r, bend right, "f_*"'] \arrow[r, phantom, shift left=3, "\perp"] \arrow[r, phantom, shift right=3, "\perp"] & \mathcal{P}(Y) \arrow[l, "f^{-1}" description]
\end{tikzcd},
$$

witnessed by:

(a) Units and counits of the form

$$
\begin{aligned}
\mathrm{id}_{\mathcal{P}(X)} &\hookrightarrow f^{-1} \circ f_!, & \mathrm{id}_{\mathcal{P}(Y)} &\hookrightarrow f_* \circ f^{-1},\\
f_! \circ f^{-1} &\hookrightarrow \mathrm{id}_{\mathcal{P}(Y)}, & f^{-1} \circ f_* &\hookrightarrow \mathrm{id}_{\mathcal{P}(X)},
\end{aligned}
$$

having components of the form

$$
\begin{aligned}
U &\subset f^{-1}(f_!(U)), & V &\subset f_*(f^{-1}(V)),\\
f_!(f^{-1}(V)) &\subset V, & f^{-1}(f_*(U)) &\subset U
\end{aligned}
$$

indexed by $U \in \mathcal{P}(X)$ and $V \in \mathcal{P}(Y)$.

(b) Bijections of sets

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

natural in $U \in \mathcal{P}(X)$ and $V \in \mathcal{P}(Y)$ and (respectively) $V \in \mathcal{P}(X)$ and $U \in \mathcal{P}(Y)$. In particular:

i. The following conditions are equivalent:
   A. We have $f_!(U) \subset V$.
   B. We have $U \subset f^{-1}(V)$.

ii. The following conditions are equivalent:
   A. We have $f^{-1}(U) \subset V$.

B. We have $U \subset f_*(V)$.

3. *Interaction With Unions of Families of Subsets.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_!)_!"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\bigcup"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{U\in\mathcal{U}} f_!(U) = \bigcup_{V\in f_!(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_!(\mathcal{U}) \stackrel{\text{def}}{=} (f_!)_!(\mathcal{U})$.

4. *Interaction With Intersections of Families of Subsets.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_!)_!"] \arrow[d, "\bigcap"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{U\in\mathcal{U}} f_!(U) = \bigcap_{V\in f_!(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_!(\mathcal{U}) \stackrel{\text{def}}{=} (f_!)_!(\mathcal{U})$.

5. *Interaction With Binary Unions.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_! \times f_!"] \arrow[d, "\cup"'] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cup"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_!(U \cup V) = f_!(U) \cup f_!(V)$$

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

6. *Interaction With Binary Intersections.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_! \times f_!"] \arrow[d, "\cap"'] \arrow[dr, phantom, "\subset"] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cap"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_!(U \cap V) \subset f_!(U) \cap f_!(V)$$

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

7. *Interaction With Differences.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_!^{\mathsf{op}} \times f_!"] \arrow[d, "\setminus"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "\setminus"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_!(U) \setminus f_!(V) \subset f_!(U \setminus V)$$

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

8. *Interaction With Complements.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_*^{\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}}"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_!(U^{\mathsf{c}}) = f_*(U)^{\mathsf{c}}$$

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

9. *Interaction With Symmetric Differences.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_!^{\mathsf{op}} \times f_!"] \arrow[d, "\triangle"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "\triangle"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_!(U) \triangle f_!(V) \subset f_!(U \triangle V)$$

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

10. *Interaction With Internal Homs of Powersets.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_*^{\mathsf{op}} \times f_!"] \arrow[d, "{[-_1,-_2]_X}"'] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "{[-_1,-_2]_Y}"] \\
\mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have an equality of sets

$$f_!([U, V]_X) = [f_*(U), f_!(V)]_Y,$$

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

11. *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 $\{U_i\}_{i\in I} \in \mathcal{P}(X)^{\times I}$. In particular, we have equalities

$$\begin{aligned} f_!(U) \cup f_!(V) &= f_!(U \cup V), \\ f_!(\emptyset) &= \emptyset, \end{aligned}$$

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

12. *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 $\{U_i\}_{i\in I} \in \mathcal{P}(X)^{\times I}$. In particular, we have inclusions

$$\begin{aligned} f_!(U \cap V) &\subset f_!(U) \cap f_!(V), \\ f_!(X) &\subset Y, \end{aligned}$$

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

13. *Symmetric Strict Monoidality With Respect to Unions.* The direct image function of Item 1 has a symmetric strict monoidal structure

$$(f_!, f_!^{\otimes}, f_{!|\mathbb{1}}^{\otimes}) \colon (\mathcal{P}(X), \cup, \emptyset) \longrightarrow (\mathcal{P}(Y), \cup, \emptyset),$$

being equipped with equalities

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

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

14. *Symmetric Oplax Monoidality With Respect to Intersections.* The direct image function of Item 1 has a symmetric oplax monoidal structure

$$(f_!, f_!^{\otimes}, f_{!|\mathbb{1}}^{\otimes}) \colon (\mathcal{P}(X), \cap, X) \longrightarrow (\mathcal{P}(Y), \cap, Y),$$

being equipped with inclusions

$$\begin{aligned} f_{!|U,V}^{\otimes} &\colon f_!(U \cap V) \hookrightarrow f_!(U) \cap f_!(V), \\ f_{!|\mathbb{1}}^{\otimes} &\colon f_!(X) \hookrightarrow Y, \end{aligned}$$

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

15. *Interaction With Coproducts.* Let $f\colon X \to X'$ and $g\colon Y \to Y'$ be maps of sets. We have

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

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

16. *Interaction With Products.* Let $f\colon X \to X'$ and $g\colon Y \to Y'$ be maps of sets. We have

$$(f \boxtimes_{X\times Y} g)_!(U \boxtimes_{X\times Y} V) = f_!(U) \boxtimes_{X'\times Y'} g_!(V)$$

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

17. *Relation to Codirect Images.* We have

$$\begin{aligned} f_!(U) &= f_*(U^{\mathsf{c}})^{\mathsf{c}} \\ &\stackrel{\text{def}}{=} Y \setminus f_*(X \setminus U) \end{aligned}$$

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

Proof 4.6.1.1.6 ▶ **Proof of Proposition 4.6.1.1.5**

Item 1: Functoriality

Omitted.

Item 2: Triple Adjointness

This follows from Remark 4.6.1.1.4, Remark 4.6.2.1.2, Remark 4.6.3.1.4, and Kan Extensions, **??** of **??**.

Item 3: Interaction With Unions of Families of Subsets

We have

$$\begin{aligned} \bigcup_{V \in f_!(\mathcal{U})} V &= \bigcup_{V \in \{f_!(U) \in \mathcal{P}(X) \mid U \in \mathcal{U}\}} V \\ &= \bigcup_{U \in \mathcal{U}} f_!(U). \end{aligned}$$

This finishes the proof.

Item 4: Interaction With Intersections of Families of Subsets

We have

$$\begin{aligned}\bigcap_{V\in f_!(\mathcal{U})} V &= \bigcap_{V\in\{f_!(U)\in\mathcal{P}(X)\mid U\in\mathcal{U}\}} V\\ &= \bigcap_{U\in\mathcal{U}} f_!(U).\end{aligned}$$

This finishes the proof.

Item 5: Interaction With Binary Unions

See [Pro25p].

Item 6: Interaction With Binary Intersections

See [Pro25n].

Item 7: Interaction With Differences

See [Pro25o].

Item 8: Interaction With Complements

Applying Item 17 to $X \setminus U$, we have

$$\begin{aligned}f_!(U^{\mathsf{c}}) &= f_!(X \setminus U)\\ &= Y \setminus f_*(X \setminus (X \setminus U))\\ &= Y \setminus f_*(U)\\ &= f_*(U)^{\mathsf{c}}.\end{aligned}$$

This finishes the proof.

Item 9: Interaction With Symmetric Differences

We have

$$\begin{aligned}f_!(U) \bigtriangleup f_!(V) &= (f_!(U) \cup f_!(V)) \setminus (f_!(U) \cap f_!(V))\\ &\subset (f_!(U) \cup f_!(V)) \setminus (f_!(U \cap V))\\ &= (f_!(U \cup V)) \setminus (f_!(U \cap V))\end{aligned}$$

$$\begin{aligned} &\subset f_!((U \cup V) \setminus (U \cap V)) \\ &= f_!(U \triangle V), \end{aligned}$$

where we have used:

1. Item 2 of Proposition 4.3.12.1.2 for the first equality.
2. Item 6 of this proposition together with Item 1 of Proposition 4.3.10.1.2 for the first inclusion.
3. Item 5 for the second equality.
4. Item 7 for the second inclusion.
5. Item 2 of Proposition 4.3.12.1.2 for the tchird equality.

Since $\mathcal{P}(Y)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2). This finishes the proof.

Item 10: Interaction With Internal Homs of Powersets

We have

$$\begin{aligned} f_!([U,V]_X) &\stackrel{\text{def}}{=} f_!(U^{\mathsf{c}} \cup V) \\ &= f_!(U^{\mathsf{c}}) \cup f_!(V) \\ &= f_*(U)^{\mathsf{c}} \cup f_!(V) \\ &\stackrel{\text{def}}{=} [f_*(U), f_!(V)]_Y, \end{aligned}$$

where we have used:

1. Item 5 for the second equality.
2. Item 17 for the third equality.

Since $\mathcal{P}(Y)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2). This finishes the proof.

Item 11: Preservation of Colimits

This follows from Item 2 and **??**, **??** of **??**.[1]

Item 12: Oplax Preservation of Limits

The inclusion $f_!(X) \subset Y$ is automatic. See [Pro25n] for the other inclusions.

Item 13: Symmetric Strict Monoidality With Respect to Unions

This follows from Item 11.

Item 14: Symmetric Oplax Monoidality With Respect to Intersections

The inclusions in the statement follow from Item 12. Since $\mathcal{P}(Y)$ is posetal, the commutativity of the diagrams in the definition of a symmetric oplax monoidal functor is automatic (Categories, Item 4 of Proposition 11.2.7.1.2).

Item 15: Interaction With Coproducts

Omitted.

Item 16: Interaction With Products

Omitted.

Item 17: Relation to Codirect Images

Applying Item 16 of Proposition 4.6.3.1.7 to $X \setminus U$, we have

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

Taking complements, we then obtain

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

which finishes the proof.

[1] *Reference:* [Pro25p].

Proposition 4.6.1.1.7 ► Properties of Direct Images II

Let $f : X \to Y$ be a function.

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

$$(-)_{*|X,Y} : \mathsf{Sets}(X, Y) \to \mathsf{Sets}(\mathcal{P}(X), \mathcal{P}(Y)).$$

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

$$(-)_{*|X,Y} \colon \mathsf{Sets}(X,Y) \to \mathsf{Pos}((\mathcal{P}(X),\subset),(\mathcal{P}(Y),\subset)).$$

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

$$(\mathrm{id}_X)_! = \mathrm{id}_{\mathcal{P}(X)}\,.$$

4. *Interaction With Composition.* For each pair of composable functions $f\colon X \to Y$ and $g\colon Y \to Z$, we have

$$(g \circ f)_! = g_! \circ f_!, \qquad \begin{tikzcd} \mathcal{P}(X) \arrow[r, "f_!"] \arrow[dr, "(g\circ f)_!"'] & \mathcal{P}(Y) \arrow[d, "g_!"] \\ & \mathcal{P}(Z). \end{tikzcd}$$

Proof 4.6.1.1.8 ▶ Proof of Proposition 4.6.1.1.7

Item 1: Functionality I

There is nothing to prove.

Item 2: Functionality II

This follows from Item 1 of Proposition 4.6.1.1.5.

Item 3: Interaction With Identities

This follows from Remark 4.6.1.1.4 and Kan Extensions, **??** of **??**.

Item 4: Interaction With Composition

This follows from Remark 4.6.1.1.4 and Kan Extensions, **??** of **??**. □

4.6.2 Inverse Images

Let $f\colon X \to Y$ be a function.

Definition 4.6.2.1.1 ▶ Inverse Images

The **inverse image function associated to** f is the function[1]

$$f^{-1}\colon \mathcal{P}(Y) \to \mathcal{P}(X)$$

defined by[2]

$$f^{-1}(V) \overset{\text{def}}{=} \{x \in X \mid \text{we have } f(x) \in V\}$$

for each $V \in \mathcal{P}(Y)$.

[1] *Further Notation:* Also written $f^*\colon \mathcal{P}(Y) \to \mathcal{P}(X)$.
[2] *Further Terminology:* The set $f^{-1}(V)$ is called the **inverse image of** V **by** f.

Remark 4.6.2.1.2 ▶ Unwinding Definition 4.6.2.1.1

Identifying $\mathcal{P}(Y)$ with $\mathsf{Sets}(Y, \{\mathsf{t}, \mathsf{f}\})$ via Item 2 of Proposition 4.5.1.1.4, we see that the inverse image function associated to f is equivalently the function

$$f^*\colon \mathcal{P}(Y) \to \mathcal{P}(X)$$

defined by

$$f^*(\chi_V) \overset{\text{def}}{=} \chi_V \circ f$$

for each $\chi_V \in \mathcal{P}(Y)$, where $\chi_V \circ f$ is the composition

$$X \xrightarrow{f} Y \xrightarrow{\chi_V} \{\mathsf{true}, \mathsf{false}\}$$

in Sets.

Proposition 4.6.2.1.3 ▶ Properties of Inverse Images I

Let $f\colon X \to Y$ be a function.

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

$$f^{-1}\colon (\mathcal{P}(Y), \subset) \to (\mathcal{P}(X), \subset).$$

In particular, for each $U, V \in \mathcal{P}(Y)$, the following condition is satisfied:

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

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

$$(f_! \dashv f^{-1} \dashv f_*)\colon \quad \begin{tikzcd} \mathcal{P}(X) \arrow[r, bend left, "f_!"] \arrow[r, bend right, "f_*"'] & \mathcal{P}(Y), \arrow[l, "f^{-1}"'] \end{tikzcd}$$

witnessed by:

(a) Units and counits of the form

$$\begin{aligned} \mathrm{id}_{\mathcal{P}(X)} &\hookrightarrow f^{-1} \circ f_!, & \mathrm{id}_{\mathcal{P}(Y)} &\hookrightarrow f_* \circ f^{-1}, \\ f_! \circ f^{-1} &\hookrightarrow \mathrm{id}_{\mathcal{P}(Y)}, & f^{-1} \circ f_* &\hookrightarrow \mathrm{id}_{\mathcal{P}(X)}, \end{aligned}$$

having components of the form

$$\begin{aligned} U &\subset f^{-1}(f_!(U)), & V &\subset f_*(f^{-1}(V)), \\ f_!(f^{-1}(V)) &\subset V, & f^{-1}(f_*(U)) &\subset U \end{aligned}$$

indexed by $U \in \mathcal{P}(X)$ and $V \in \mathcal{P}(Y)$.

(b) Bijections of sets

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

natural in $U \in \mathcal{P}(X)$ and $V \in \mathcal{P}(Y)$ and (respectively) $V \in \mathcal{P}(X)$ and $U \in \mathcal{P}(Y)$. In particular:

i. The following conditions are equivalent:
   A. We have $f_!(U) \subset V$.
   B. We have $U \subset f^{-1}(V)$.

ii. The following conditions are equivalent:
   A. We have $f^{-1}(U) \subset V$.
   B. We have $U \subset f_*(V)$.

3. *Interaction With Unions of Families of Subsets.* The diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(Y)) \arrow[r, "(f^{-1})^{-1}"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcup"] \\ \mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{V \in \mathcal{V}} f^{-1}(V) = \bigcup_{U \in f^{-1}(\mathcal{U})} U$$

for each $\mathcal{V} \in \mathcal{P}(Y)$, where $f^{-1}(\mathcal{V}) \stackrel{\text{def}}{=} (f^{-1})^{-1}(\mathcal{V})$.

4. *Interaction With Intersections of Families of Subsets.* The diagram

$$\begin{tikzcd} \mathcal{P}(\mathcal{P}(Y)) \arrow[r, "(f^{-1})^{-1}"] \arrow[d, "\bigcap"'] & \mathcal{P}(\mathcal{P}(X)) \arrow[d, "\bigcap"] \\ \mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{V \in \mathcal{V}} f^{-1}(V) = \bigcap_{U \in f^{-1}(\mathcal{U})} U$$

for each $\mathcal{V} \in \mathcal{P}(Y)$, where $f^{-1}(\mathcal{V}) \stackrel{\text{def}}{=} (f^{-1})^{-1}(\mathcal{V})$.

5. *Interaction With Binary Unions.* The diagram

$$\begin{tikzcd} \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[r, "f^{-1} \times f^{-1}"] \arrow[d, "\cup"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cup"] \\ \mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U \cup V) = f^{-1}(U) \cup f^{-1}(V)$$

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

6. *Interaction With Binary Intersections.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[r, "f^{-1} \times f^{-1}"] \arrow[d, "\cap"'] & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[d, "\cap"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U \cap V) = f^{-1}(U) \cap f^{-1}(V)$$

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

7. *Interaction With Differences.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[r, "f^{\mathsf{op},-1} \times f^{-1}"] \arrow[d, "\setminus"'] & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[d, "\setminus"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U \setminus V) = f^{-1}(U) \setminus f^{-1}(V)$$

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

8. *Interaction With Complements.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \arrow[r, "f^{-1,\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}}"'] & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(U^{\mathsf{c}}) = f^{-1}(U)^{\mathsf{c}}$$

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

9. *Interaction With Symmetric Differences.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[r, "f^{\mathsf{op},-1} \times f^{-1}"] \arrow[d, "\triangle"'] & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[d, "\triangle"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

i.e. we have

$$f^{-1}(U) \triangle f^{-1}(V) = f^{-1}(U \triangle V)$$

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

10. *Interaction With Internal Homs of Powersets.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[r, "f^{-1,\mathsf{op}} \times f^{-1}"] \arrow[d, "{[-_1,-_2]_Y}"'] & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[d, "{[-_1,-_2]_X}"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have an equality of sets

$$f^{-1}([U, V]_Y) = [f^{-1}(U), f^{-1}(V)]_X,$$

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

11. *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 $\{U_i\}_{i\in I} \in \mathcal{P}(Y)^{\times I}$. 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 $U, V \in \mathcal{P}(Y)$.

12. *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 $\{U_i\}_{i\in I} \in \mathcal{P}(Y)^{\times I}$. In particular, we have equalities

$$\begin{aligned} f^{-1}(U) \cap f^{-1}(V) &= f^{-1}(U \cap V), \\ f^{-1}(Y) &= X, \end{aligned}$$

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

13. *Symmetric Strict Monoidality With Respect to Unions.* The inverse image function of Item 1 has a symmetric strict monoidal structure

$$(f^{-1}, f^{-1,\otimes}, f^{-1,\otimes}_{\mathbb{1}})\colon (\mathcal{P}(Y), \cup, \emptyset) \to (\mathcal{P}(X), \cup, \emptyset),$$

being equipped with equalities

$$\begin{aligned} f^{-1,\otimes}_{U,V}\colon f^{-1}(U) \cup f^{-1}(V) &\xrightarrow{=} f^{-1}(U \cup V), \\ f^{-1,\otimes}_{\mathbb{1}}\colon \emptyset &\xrightarrow{=} f^{-1}(\emptyset), \end{aligned}$$

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

14. *Symmetric Strict Monoidality With Respect to Intersections.* The inverse image function of Item 1 has a symmetric strict monoidal structure

$$(f^{-1}, f^{-1,\otimes}, f^{-1,\otimes}_{\mathbb{1}})\colon (\mathcal{P}(Y), \cap, Y) \to (\mathcal{P}(X), \cap, X),$$

being equipped with equalities

$$\begin{aligned} f^{-1,\otimes}_{U,V}\colon f^{-1}(U) \cap f^{-1}(V) &\xrightarrow{=} f^{-1}(U \cap V), \\ f^{-1,\otimes}_{\mathbb{1}}\colon X &\xrightarrow{=} f^{-1}(Y), \end{aligned}$$

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

15. *Interaction With Coproducts.* Let $f\colon X \to X'$ and $g\colon Y \to Y'$ be maps of sets. We have

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

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

16. *Interaction With Products.* Let $f\colon X \to X'$ and $g\colon Y \to Y'$ be maps of sets. We have

$$(f \boxtimes_{X' \times Y'} g)^{-1}(U' \boxtimes_{X' \times Y'} V') = f^{-1}(U') \boxtimes_{X \times Y} g^{-1}(V')$$

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

Proof 4.6.2.1.4 ► Proof of Proposition 4.6.2.1.3

Item 1: Functoriality

Omitted.

Item 2: Triple Adjointness

This follows from Remark 4.6.1.1.4, Remark 4.6.2.1.2, Remark 4.6.3.1.4, and Kan Extensions, **??** of **??**.

Item 3: Interaction With Unions of Families of Subsets

We have

$$\begin{aligned}\bigcup_{U \in f^{-1}(\mathcal{V})} U &= \bigcup_{U \in \{f^{-1}(V) \in \mathcal{P}(X) \mid V \in \mathcal{V}\}} U \\ &= \bigcup_{V \in \mathcal{V}} f^{-1}(V).\end{aligned}$$

This finishes the proof.

Item 4: Interaction With Intersections of Families of Subsets

We have

$$\bigcap_{U \in f^{-1}(\mathcal{V})} U = \bigcap_{U \in \{f^{-1}(V) \in \mathcal{P}(X) \mid V \in \mathcal{V}\}} U$$

$$= \bigcap_{V \in \mathcal{V}} f^{-1}(V).$$

This finishes the proof.

Item 5: Interaction With Binary Unions

See [Pro25y].

Item 6: Interaction With Binary Intersections

See [Pro25w].

Item 7: Interaction With Differences

See [Pro25x].

Item 8: Interaction With Complements

See [Pro25j].

Item 9: Interaction With Symmetric Differences

We have

$$\begin{aligned} f^{-1}(U \triangle V) &= f^{-1}((U \cup V) \setminus (U \cap V)) \\ &= f^{-1}(U \cup V) \setminus f^{-1}(U \cap V) \\ &= f^{-1}(U) \cup f^{-1}(V) \setminus f^{-1}(U \cap V) \\ &= f^{-1}(U) \cup f^{-1}(V) \setminus f^{-1}(U) \cap f^{-1}(V) \\ &= f^{-1}(U) \triangle f^{-1}(V), \end{aligned}$$

where we have used:

1. Item 2 of Proposition 4.3.12.1.2 for the first equality.
2. Item 7 for the second equality.
3. Item 5 for the third equality.
4. Item 6 for the fourth equality.
5. Item 2 of Proposition 4.3.12.1.2 for the fifth equality.

This finishes the proof.

Item 10: Interaction With Internal Homs of Powersets

We have

$$\begin{aligned} f^{-1}([U,V]_Y) &\overset{\text{def}}{=} f^{-1}(U^{\mathsf{c}} \cup V) \\ &= f^{-1}(U^{\mathsf{c}}) \cup f^{-1}(V) \\ &= f^{-1}(U)^{\mathsf{c}} \cup f^{-1}(V) \\ &\overset{\text{def}}{=} [f^{-1}(U), f^{-1}(V)]_X, \end{aligned}$$

where we have used:

1. Item 8 for the second equality.
2. Item 5 for the third equality.

Since $\mathcal{P}(Y)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2). This finishes the proof.

Item 11: Preservation of Colimits

This follows from Item 2 and **??**, **??** of **??**.[1]

Item 12: Preservation of Limits

This follows from Item 2 and **??**, **??** of **??**.[2]

Item 13: Symmetric Strict Monoidality With Respect to Unions

This follows from Item 11.

Item 14: Symmetric Strict Monoidality With Respect to Intersections

This follows from Item 12.

Item 15: Interaction With Coproducts

Omitted.

Item 16: Interaction With Products

Omitted.

[1] *Reference:* [Pro25y].
[2] *Reference:* [Pro25w].

Proposition 4.6.2.1.5 ► Properties of Inverse Images II

Let $f : X \to Y$ be a function.

1. *Functionality I.* The assignment $f \mapsto f^{-1}$ defines a function
$$(-)^{-1}_{X,Y} : \mathsf{Sets}(X, Y) \to \mathsf{Sets}(\mathcal{P}(Y), \mathcal{P}(X)).$$
2. *Functionality II.* The assignment $f \mapsto f^{-1}$ defines a function
$$(-)^{-1}_{X,Y} : \mathsf{Sets}(X, Y) \to \mathsf{Pos}((\mathcal{P}(Y), \subset), (\mathcal{P}(X), \subset)).$$
3. *Interaction With Identities.* For each $X \in \mathrm{Obj}(\mathsf{Sets})$, we have
$$\mathrm{id}_X^{-1} = \mathrm{id}_{\mathcal{P}(X)}.$$
4. *Interaction With Composition.* For each pair of composable functions $f : X \to Y$ and $g : Y \to Z$, we have
$$(g \circ f)^{-1} = f^{-1} \circ g^{-1}, \qquad \begin{tikzcd} \mathcal{P}(Z) \arrow[r, "g^{-1}"] \arrow[dr, "(g\circ f)^{-1}"'] & \mathcal{P}(Y) \arrow[d, "f^{-1}"] \\ & \mathcal{P}(X). \end{tikzcd}$$

Proof 4.6.2.1.6 ► Proof of Proposition 4.6.2.1.5

Item 1: Functionality I

There is nothing to prove.

Item 2: Functionality II

This follows from Item 1 of Proposition 4.6.2.1.3.

Item 3: Interaction With Identities

This follows from Remark 4.6.2.1.2 and Categories, Item 5 of Proposition 11.1.4.1.2.

Item 4: Interaction With Composition

This follows from Remark 4.6.2.1.2 and Categories, Item 2 of Proposition 11.1.4.1.2.

4.6.3 Codirect Images

Let $f : X \to Y$ be a function.

Definition 4.6.3.1.1 ▶ Codirect Images

The **codirect image function associated to** f is the function

$$f_* : \mathcal{P}(X) \to \mathcal{P}(Y)$$

defined by[1,2]

$$\begin{aligned} f_*(U) &\stackrel{\text{def}}{=} \left\{ y \in Y \;\middle|\; \begin{array}{l} \text{for each } x \in X, \text{ if we have} \\ f(x) = y, \text{ then } x \in U \end{array} \right\} \\ &= \left\{ y \in Y \;\middle|\; \text{we have } f^{-1}(y) \subset U \right\} \end{aligned}$$

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

[1] *Further Terminology:* The set $f_*(U)$ is called the **codirect image of** U **by** f.

[2] We also have

$$\begin{aligned} f_*(U) &= f_!(U^{\mathsf{c}})^{\mathsf{c}} \\ &\stackrel{\text{def}}{=} Y \setminus f_!(X \setminus U); \end{aligned}$$

see Item 16 of Proposition 4.6.3.1.7.

Notation 4.6.3.1.2 ▶ Further Notation for Codirect Images

Sometimes one finds the notation

$$\forall_f : \mathcal{P}(X) \to \mathcal{P}(Y)$$

for $f_!$. This notation comes from the fact that the following statements are equivalent, where $y \in Y$ and $U \in \mathcal{P}(X)$:

- We have $y \in \forall_f(U)$.

- For each $x \in X$, if $y = f(x)$, then $x \in U$.

We will not make use of this notation elsewhere in Clowder.

WARNING 4.6.3.1.3 ► NOTATION FOR CODIRECT IMAGES IS CONFUSING

See Warning 4.6.1.1.3.

REMARK 4.6.3.1.4 ► UNWINDING DEFINITION 4.6.3.1.1

Identifying $\mathcal{P}(X)$ with $\mathsf{Sets}(X, \{\mathsf{t}, \mathsf{f}\})$ via Item 2 of Proposition 4.5.1.1.4, we see that the codirect image function associated to f is equivalently the function

$$f_* \colon \mathcal{P}(X) \to \mathcal{P}(Y)$$

defined by

$$\begin{aligned}
f_*(\chi_U) &\overset{\text{def}}{=} \mathrm{Ran}_f(\chi_U) \\
&= \lim\left(\left(\underline{(-_1)} \overrightarrow{\times} f\right) \overset{\text{pr}}{\twoheadrightarrow} X \xrightarrow{\chi_U} \{\mathsf{true}, \mathsf{false}\}\right) \\
&= \lim_{\substack{x \in X \\ f(x) = -_1}} (\chi_U(x)) \\
&= \bigwedge_{\substack{x \in X \\ f(x) = -_1}} (\chi_U(x)).
\end{aligned}$$

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

$$\begin{aligned}
[f_*(\chi_U)](y) &= \bigwedge_{\substack{x \in X \\ f(x) = y}} (\chi_U(x)) \\
&= \begin{cases} \mathsf{true} & \text{if, for each } x \in X \text{ such that} \\ & f(x) = y\text{, we have } x \in U, \\ \mathsf{false} & \text{otherwise} \end{cases}
\end{aligned}$$

$$= \begin{cases} \text{true} & \text{if } f^{-1}(y) \subset U \\ \text{false} & \text{otherwise} \end{cases}$$

for each $y \in Y$.

Definition 4.6.3.1.5 ► The Image and Complement Parts of f_*

Let U be a subset of X.[1,2]

1. The **image part of the codirect image** $f_*(U)$ **of** U is the set $f_{*,\mathrm{im}}(U)$ defined by

$$\begin{aligned} f_{*,\mathrm{im}}(U) &\overset{\mathrm{def}}{=} f_*(U) \cap \mathrm{Im}(f) \\ &= \left\{ y \in Y \,\middle|\, \begin{array}{l} \text{we have } f^{-1}(y) \subset U \\ \text{and } f^{-1}(y) \neq \emptyset. \end{array} \right\}. \end{aligned}$$

2. The **complement part of the codirect image** $f_*(U)$ **of** U is the set $f_{*,\mathrm{cp}}(U)$ defined by

$$\begin{aligned} f_{*,\mathrm{cp}}(U) &\overset{\mathrm{def}}{=} f_*(U) \cap (Y \setminus \mathrm{Im}(f)) \\ &= Y \setminus \mathrm{Im}(f) \\ &= \left\{ y \in Y \,\middle|\, \begin{array}{l} \text{we have } f^{-1}(y) \subset U \\ \text{and } f^{-1}(y) = \emptyset. \end{array} \right\} \\ &= \left\{ y \in Y \,\middle|\, f^{-1}(y) = \emptyset \right\}. \end{aligned}$$

[1] Note that we have

$$f_*(U) = f_{*,\mathrm{im}}(U) \cup f_{*,\mathrm{cp}}(U),$$

as

$$\begin{aligned} f_*(U) &= f_*(U) \cap Y \\ &= f_*(U) \cap (\mathrm{Im}(f) \cup (Y \setminus \mathrm{Im}(f))) \\ &= (f_*(U) \cap \mathrm{Im}(f)) \cup (f_*(U) \cap (Y \setminus \mathrm{Im}(f))) \\ &\overset{\mathrm{def}}{=} f_{*,\mathrm{im}}(U) \cup f_{*,\mathrm{cp}}(U). \end{aligned}$$

[2]In terms of the meet computation of $f_*(U)$ of Remark 4.6.3.1.4, namely

$$f_*(\chi_U) = \bigwedge_{\substack{x\in X\\ f(x)=-_1}} (\chi_U(x)),$$

we see that $f_{*,\mathrm{im}}$ corresponds to meets indexed over nonempty sets, while $f_{*,\mathrm{cp}}$ corresponds to meets indexed over the empty set.

Example 4.6.3.1.6 ► Examples of Codirect Images

Here are some examples of codirect images.

1. *Multiplication by Two.* Consider the function $f\colon \mathbb{N} \longrightarrow \mathbb{N}$ given by

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

   for each $n \in \mathbb{N}$. Since f is injective, we have

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

   for any $U \subset \mathbb{N}$. In particular, we have

   $$f_*(\{\text{even natural numbers}\}) = \mathbb{N}.$$

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

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

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

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

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

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

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

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

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

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

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.:

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

Proposition 4.6.3.1.7 ▶ Properties of Codirect Images I

Let $f \colon X \to Y$ be a function.

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

$$f_* \colon (\mathcal{P}(X), \subset) \to (\mathcal{P}(Y), \subset).$$

   In particular, for each $U, V \in \mathcal{P}(X)$, the following condition is satisfied:

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

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

$$(f_! \dashv f^{-1} \dashv f_*) \colon \quad \begin{tikzcd} \mathcal{P}(X) \arrow[r, bend left=45, "f_!"] \arrow[r, bend right=45, "f_*"'] & \mathcal{P}(Y), \arrow[l, "f^{-1}"'] \end{tikzcd}$$

   witnessed by:

(a) Units and counits of the form

$$\mathrm{id}_{\mathcal{P}(X)} \hookrightarrow f^{-1} \circ f_!, \qquad \mathrm{id}_{\mathcal{P}(Y)} \hookrightarrow f_* \circ f^{-1},$$
$$f_! \circ f^{-1} \hookrightarrow \mathrm{id}_{\mathcal{P}(Y)}, \qquad f^{-1} \circ f_* \hookrightarrow \mathrm{id}_{\mathcal{P}(X)},$$

having components of the form

$$U \subset f^{-1}(f_!(U)), \qquad V \subset f_*(f^{-1}(V)),$$
$$f_!(f^{-1}(V)) \subset V, \qquad f^{-1}(f_*(U)) \subset U$$

indexed by $U \in \mathcal{P}(X)$ and $V \in \mathcal{P}(Y)$.

(b) Bijections of sets

$$\mathrm{Hom}_{\mathcal{P}(Y)}(f_!(U), V) \cong \mathrm{Hom}_{\mathcal{P}(X)}(U, f^{-1}(V)),$$
$$\mathrm{Hom}_{\mathcal{P}(X)}(f^{-1}(U), V) \cong \mathrm{Hom}_{\mathcal{P}(X)}(U, f_*(V)),$$

natural in $U \in \mathcal{P}(X)$ and $V \in \mathcal{P}(Y)$ and (respectively) $V \in \mathcal{P}(X)$ and $U \in \mathcal{P}(Y)$. In particular:

i. The following conditions are equivalent:
   A. We have $f_!(U) \subset V$.
   B. We have $U \subset f^{-1}(V)$.

ii. The following conditions are equivalent:
   A. We have $f^{-1}(U) \subset V$.
   B. We have $U \subset f_*(V)$.

3. *Interaction With Unions of Families of Subsets.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_*)_*"] \arrow[d, "\bigcup"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\bigcup"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcup_{U \in \mathcal{U}} f_*(U) = \bigcup_{V \in f_*(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_*(\mathcal{U}) \stackrel{\mathrm{def}}{=} (f_*)_*(\mathcal{U})$.

4. *Interaction With Intersections of Families of Subsets.* The diagram

$$\begin{tikzcd}
\mathcal{P}(\mathcal{P}(X)) \arrow[r, "(f_*)_*"] \arrow[d, "\bigcap"'] & \mathcal{P}(\mathcal{P}(Y)) \arrow[d, "\bigcap"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$\bigcap_{U\in\mathcal{U}} f_*(U) = \bigcap_{V\in f_*(\mathcal{U})} V$$

for each $\mathcal{U} \in \mathcal{P}(X)$, where $f_*(\mathcal{U}) \overset{\text{def}}{=} (f_*)_*(\mathcal{U})$.

5. *Interaction With Binary Unions.* Let $f : X \to Y$ be a function. We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_* \times f_*"] \arrow[d, "\cup"'] \arrow[dr, phantom, "\subset"] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cup"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_*(U) \cup f_*(V) \subset f_*(U \cup V)$$

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

6. *Interaction With Binary Intersections.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "f_* \times f_*"] \arrow[d, "\cap"'] & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[d, "\cap"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_*(U) \cap f_*(V) = f_*(U \cap V)$$

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

7. *Interaction With Complements.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_!^{\mathsf{op}}"] \arrow[d, "(-)^{\mathsf{c}}"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "(-)^{\mathsf{c}}"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_*(U^{\mathsf{c}}) = f_!(U)^{\mathsf{c}}$$

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

8. *Interaction With Symmetric Differences.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_*^{\mathsf{op}} \times f_*"] \arrow[d, "\triangle"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "\triangle"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$f_*(U \triangle V) \subset f_*(U) \triangle f_*(V)$$

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

9. *Interaction With Internal Homs of Powersets.* We have a natural transformation

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[r, "f_!^{\mathsf{op}} \times f_*"] \arrow[d, "{[-_1,-_2]_X}"'] \arrow[dr, phantom, "\supset"] & \mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[d, "{[-_1,-_2]_Y}"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

with components

$$[f_!(U), f_*(V)]_Y \subset f_*([U,V]_X)$$

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

10. *Lax Preservation of Colimits.* We have an inclusion of sets

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

natural in $\{U_i\}_{i \in I} \in \mathcal{P}(X)^{\times I}$. 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 $U, V \in \mathcal{P}(X)$.

11. *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 $\{U_i\}_{i \in I} \in \mathcal{P}(X)^{\times I}$. In particular, we have equalities

$$\begin{aligned} f^{-1}(U \cap V) &= f_*(U) \cap f^{-1}(V), \\ f_*(X) &= Y, \end{aligned}$$

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

12. *Symmetric Lax Monoidality With Respect to Unions.* The codirect image function of Item 1 has a symmetric lax monoidal structure

$$(f_*, f_*^{\otimes}, f_{*|\mathbb{1}}^{\otimes}) \colon (\mathcal{P}(X), \cup, \emptyset) \to (\mathcal{P}(Y), \cup, \emptyset),$$

being equipped with inclusions

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

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

13. *Symmetric Strict Monoidality With Respect to Intersections.* The direct image function of Item 1 has a symmetric strict monoidal structure

$$(f_*, f_*^{\otimes}, f_{*|\mathbb{1}}^{\otimes}) \colon (\mathcal{P}(X), \cap, X) \to (\mathcal{P}(Y), \cap, Y),$$

being equipped with equalities

$$\begin{aligned} f_{*|U,V}^{\otimes} \colon f_*(U \cap V) &\xrightarrow{=} f_*(U) \cap f_*(V), \\ f_{*|\mathbb{1}}^{\otimes} \colon f_*(X) &\xrightarrow{=} Y, \end{aligned}$$

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

14. *Interaction With Coproducts.* Let $f \colon X \to X'$ and $g \colon Y \to Y'$ be maps of sets. We have

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

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

15. *Interaction With Products.* Let $f \colon X \to X'$ and $g \colon Y \to Y'$ be maps of sets. We have

$$(f \boxtimes_{X \times Y} g)_*(U \boxtimes_{X \times Y} V) = f_*(U) \boxtimes_{X' \times Y'} g_*(V)$$

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

16. *Relation to Direct Images.* We have

$$\begin{aligned} f_*(U) &= f_!(U^{\mathsf{c}})^{\mathsf{c}} \\ &= Y \setminus f_!(X \setminus U) \end{aligned}$$

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

17. *Interaction With Injections.* If f is injective, then we have

$$\begin{aligned} f_{*,\mathrm{im}}(U) &= f_!(U), \\ f_{*,\mathrm{cp}}(U) &= Y \setminus \mathrm{Im}(f), \end{aligned}$$

and so

$$\begin{aligned} f_*(U) &= f_{*,\mathrm{im}}(U) \cup f_{*,\mathrm{cp}}(U) \\ &= f_!(U) \cup (Y \setminus \mathrm{Im}(f)) \end{aligned}$$

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

18. *Interaction With Surjections.* If f is surjective, then we have

$$\begin{aligned} f_{*,\mathrm{im}}(U) &\subset f_!(U), \\ f_{*,\mathrm{cp}}(U) &= \emptyset, \end{aligned}$$

and so

$$f_*(U) \subset f_!(U)$$

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

PROOF 4.6.3.1.8 ► PROOF OF PROPOSITION 4.6.3.1.7

Item 1: Functoriality

Omitted.

Item 2: Triple Adjointness

This follows from Remark 4.6.1.1.4, Remark 4.6.2.1.2, Remark 4.6.3.1.4, and Kan Extensions, **??** of **??**.

Item 3: Interaction With Unions of Families of Subsets

We have

$$\begin{aligned} \bigcup_{V \in f_*(\mathcal{U})} V &= \bigcup_{V \in \{f_*(U) \in \mathcal{P}(X) \mid U \in \mathcal{U}\}} V \\ &= \bigcup_{U \in \mathcal{U}} f_*(U). \end{aligned}$$

This finishes the proof.

Item 4: Interaction With Intersections of Families of Subsets

We have

$$\begin{aligned}\bigcap_{V\in f_*(\mathcal{U})} V &= \bigcap_{V\in\{f_*(U)\in\mathcal{P}(X)\mid U\in\mathcal{U}\}} V\\ &= \bigcap_{U\in\mathcal{U}} f_*(U).\end{aligned}$$

This finishes the proof.

Item 5: Interaction With Binary Unions

We have

$$\begin{aligned}f_*(U)\cup f_*(V) &= f_!(U^{\mathsf{c}})^{\mathsf{c}}\cup f_!(V^{\mathsf{c}})^{\mathsf{c}}\\ &= (f_!(U^{\mathsf{c}})\cap f_!(V^{\mathsf{c}}))^{\mathsf{c}}\\ &\subset (f_!(U^{\mathsf{c}}\cap V^{\mathsf{c}}))^{\mathsf{c}}\\ &= f_!((U\cup V)^{\mathsf{c}})^{\mathsf{c}}\\ &= f_*(U\cup V),\end{aligned}$$

where:

1. We have used Item 16 for the first equality.
2. We have used Item 2 of Proposition 4.3.11.1.2 for the second equality.
3. We have used Item 6 of Proposition 4.6.1.1.5 for the third equality.
4. We have used Item 2 of Proposition 4.3.11.1.2 for the fourth equality.
5. We have used Item 16 for the last equality.

This finishes the proof.

Item 6: Interaction With Binary Intersections

This follows from Item 11.

Item 7: Interaction With Complements

Omitted.

Item 8: Interaction With Symmetric Differences

Omitted.

Item 9: Interaction With Internal Homs of Powersets

We have

$$\begin{aligned}
\left[f_!(U), f^!(V)\right]_X &\stackrel{\text{def}}{=} f_!(U)^{\mathsf{c}} \cup f_*(V) \\
&= f_*(U^{\mathsf{c}}) \cup f_*(V) \\
&\subset f_*(U^{\mathsf{c}} \cup V) \\
&\stackrel{\text{def}}{=} f_*([U, V]_X),
\end{aligned}$$

where we have used:

1. Item 7 of Proposition 4.6.3.1.7 for the second equality.

2. Item 5 of Proposition 4.6.3.1.7 for the inclusion.

Since $\mathcal{P}(X)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2). This finishes the proof.

Item 10: Lax Preservation of Colimits

Omitted.

Item 11: Preservation of Limits

This follows from Item 2 and **??**, **??** of **??**.

Item 12: Symmetric Lax Monoidality With Respect to Unions

This follows from Item 10.

Item 13: Symmetric Strict Monoidality With Respect to Intersections

This follows from Item 11.

Item 14: Interaction With Coproducts

Omitted.

Item 15: Interaction With Products

Omitted.

Item 16: Relation to Direct Images

We claim that $f_*(U) = Y \setminus f_!(X \setminus U)$.

- *The First Implication*. We claim that

$$f_*(U) \subset Y \setminus f_!(X \setminus U).$$

Let $y \in f_*(U)$. We need to show that $y \notin f_!(X \setminus U)$, i.e. that there is no $x \in X \setminus U$ such that $f(x) = y$.

This is indeed the case, as otherwise we would have $x \in f^{-1}(y)$ and $x \notin U$, contradicting $f^{-1}(y) \subset U$ (which holds since $y \in f_*(U)$).

Thus $y \in Y \setminus f_!(X \setminus U)$.

- *The Second Implication*. We claim that

$$Y \setminus f_!(X \setminus U) \subset f_*(U).$$

Let $y \in Y \setminus f_!(X \setminus U)$. We need to show that $y \in f_*(U)$, i.e. that $f^{-1}(y) \subset U$.

Since $y \notin f_!(X \setminus U)$, there exists no $x \in X \setminus U$ such that $y = f(x)$, and hence $f^{-1}(y) \subset U$.

Thus $y \in f_*(U)$.

This finishes the proof of Item 16.

Item 17: Interaction With Injections

Omitted.

Item 18: Interaction With Surjections

Omitted.

PROPOSITION 4.6.3.1.9 ► PROPERTIES OF CODIRECT IMAGES II

Let $f : X \to B$ be a function.

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

$$(-)_{!|X,Y} : \mathsf{Sets}(X, Y) \to \mathsf{Sets}(\mathcal{P}(X), \mathcal{P}(Y)).$$

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

$$(-)_{!|X,Y} : \mathsf{Sets}(X, Y) \to \mathsf{Pos}((\mathcal{P}(X), \subset), (\mathcal{P}(Y), \subset)).$$

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

$$(\mathrm{id}_X)_* = \mathrm{id}_{\mathcal{P}(X)}.$$

4. *Interaction With Composition.* For each pair of composable functions $f: X \to Y$ and $g: Y \to Z$, we have

$$(g \circ f)_* = g_* \circ f_*, \qquad \begin{tikzcd} \mathcal{P}(X) \arrow[r, "f_*"] \arrow[dr, "(g\circ f)_*"'] & \mathcal{P}(Y) \arrow[d, "g_*"] \\ & \mathcal{P}(Z). \end{tikzcd}$$

Proof 4.6.3.1.10 ► Proof of Proposition 4.6.3.1.9

Item 1: Functionality I

There is nothing to prove.

Item 2: Functionality II

This follows from Item 1 of Proposition 4.6.3.1.7.

Item 3: Interaction With Identities

This follows from Remark 4.6.3.1.4 and Kan Extensions, **??** of **??**.

Item 4: Interaction With Composition

This follows from Remark 4.6.3.1.4 and Kan Extensions, **??** of **??**. ∎

4.6.4 A Six-Functor Formalism for Sets

Remark 4.6.4.1.1 ► A Six-Functor Formalism for Sets

The assignment $X \mapsto \mathcal{P}(X)$ together with the functors f_*, f^{-1}, and $f_!$ of Item 1 of Proposition 4.6.1.1.5, Item 1 of Proposition 4.6.2.1.3, and Item 1 of Proposition 4.6.3.1.7, and the functors

$$-_1 \cap -_2 : \mathcal{P}(X) \times \mathcal{P}(X) \to \mathcal{P}(X),$$
$$[-_1, -_2]_X : \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \to \mathcal{P}(X)$$

of Item 1 of Proposition 4.3.9.1.2 and Item 1 of Proposition 4.4.7.1.4 satisfy several properties reminiscent of a six functor formalism in the sense of **??**.
We collect these properties in Proposition 4.6.4.1.2 below.[1]

[1] See also [nLa25].

Proposition 4.6.4.1.2 ► A Six-Functor Formalism for Sets

Let X be a set.

1. *The Beck–Chevalley Condition.* Let

$$\begin{tikzcd} X \times_Z Y \arrow[r, "\mathrm{pr}_2"] \arrow[d, "\mathrm{pr}_1"'] \arrow[dr, phantom, "\lrcorner", very near start] & Y \arrow[d, "g"] \\ X \arrow[r, "f"'] & Z \end{tikzcd}$$

be a pullback diagram in Sets. We have

$$\begin{tikzcd} \mathcal{P}(X) \arrow[r, "\mathrm{pr}_1^{-1}"] \arrow[d, "f_!"'] & \mathcal{P}(X \times_Z Y) \arrow[d, "(\mathrm{pr}_2)_!"] \\ \mathcal{P}(Z) \arrow[r, "g^{-1}"'] & \mathcal{P}(Y), \end{tikzcd} \qquad \begin{aligned} g^{-1} \circ f_! &= (\mathrm{pr}_2)_! \circ \mathrm{pr}_1^{-1}, \\ f^{-1} \circ g_! &= (\mathrm{pr}_1)_! \circ \mathrm{pr}_2^{-1}, \end{aligned} \qquad \begin{tikzcd} \mathcal{P}(X) \arrow[r, "\mathrm{pr}_2^{-1}"] \arrow[d, "g_!"'] & \mathcal{P}(X \times_Z Y) \arrow[d, "(\mathrm{pr}_1)_!"] \\ \mathcal{P}(Z) \arrow[r, "f^{-1}"'] & \mathcal{P}(Y). \end{tikzcd}$$

2. *The Projection Formula I.* The diagram

$$\begin{tikzcd} & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[dr, "\cap"] & \\ \mathcal{P}(X) \times \mathcal{P}(Y) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)} \times f^{-1}"] \arrow[d, "f_! \times \mathrm{id}_{\mathcal{P}(Y)}"'] & & \mathcal{P}(X) \arrow[d, "f_!"] \\ \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[rr, "\cap"'] & & \mathcal{P}(Y), \end{tikzcd}$$

commutes, i.e. we have

$$f_!(U \cap f^{-1}(V)) = f_!(U) \cap V$$

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

3. *The Projection Formula II.* We have a natural transformation

$$\begin{tikzcd}
 & & \mathcal{P}(X) \times \mathcal{P}(X) \arrow[drr, "\cap"] & & \\
\mathcal{P}(X) \times \mathcal{P}(Y) \arrow[urr, "\mathrm{id}_{\mathcal{P}(X)} \times f^{-1}"] \arrow[dr, "f_* \times \mathrm{id}_{\mathcal{P}(Y)}"'] & & & & \mathcal{P}(X) \arrow[dl, "f_*"] \\
 & \mathcal{P}(Y) \times \mathcal{P}(Y) \arrow[rr, "\cap"'] & & \mathcal{P}(Y), &
\end{tikzcd}$$

with components

$$f_*(U) \cap V \subset f_*(U \cap f^{-1}(V))$$

indexed by $U \in \mathcal{P}(X)$ and $V \in \mathcal{P}(Y)$.

4. *Strong Closed Monoidality.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \times \mathcal{P}(Y) \arrow[r, "f^{-1,\mathsf{op}} \times f^{-1}"] \arrow[d, "{[-_1,-_2]_Y}"'] & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[d, "{[-_1,-_2]_X}"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have an equality of sets

$$f^{-1}([U, V]_Y) = [f^{-1}(U), f^{-1}(V)]_X,$$

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

5. *The External Tensor Product.* We have an external tensor product

$$-_1 \boxtimes_{X\times Y} -_2 \colon \mathcal{P}(X) \times \mathcal{P}(Y) \to \mathcal{P}(X \times Y)$$

given by

$$\begin{aligned} U \boxtimes_{X\times Y} V &\overset{\text{def}}{=} \mathrm{pr}_1^{-1}(U) \cap \mathrm{pr}_2^{-1}(V) \\ &= \{(u,v) \in X \times Y \mid u \in U \text{ and } v \in V\}. \end{aligned}$$

This is the same map as the one in Item 5 of Proposition 4.4.1.1.4. Moreover, the following conditions are satisfied:

(a) *Interaction With Direct Images.* Let $f \colon X \to X'$ and $g \colon Y \to Y'$ be functions. The diagram

$$\begin{tikzcd} \mathcal{P}(X) \times \mathcal{P}(Y) \arrow[r, "f_! \times g_!"] \arrow[d, "\boxtimes_{X\times Y}"'] & \mathcal{P}(X') \times \mathcal{P}(Y') \arrow[d, "\boxtimes_{X'\times Y'}"] \\ \mathcal{P}(X \times Y) \arrow[r, "f_! \times g_!"'] & \mathcal{P}(X' \times Y') \end{tikzcd}$$

commutes, i.e. we have

$$[f_! \times g_!](U \boxtimes_{X\times Y} V) = f_!(U) \boxtimes_{X'\times Y'} g_!(V)$$

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

(b) *Interaction With Inverse Images.* Let $f \colon X \to X'$ and $g \colon Y \to Y'$ be functions. The diagram

$$\begin{tikzcd} \mathcal{P}(X') \times \mathcal{P}(Y') \arrow[r, "f^{-1} \times g^{-1}"] \arrow[d, "\boxtimes_{X'\times Y'}"'] & \mathcal{P}(X) \times \mathcal{P}(Y) \arrow[d, "\boxtimes_{X\times Y}"] \\ \mathcal{P}(X' \times Y') \arrow[r, "f^{-1} \times g^{-1}"'] & \mathcal{P}(X \times Y) \end{tikzcd}$$

commutes, i.e. we have

$$[f^{-1} \times g^{-1}](U \boxtimes_{X'\times Y'} V) = f^{-1}(U) \boxtimes_{X\times Y} g^{-1}(V)$$

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

(c) *Interaction With Codirect Images.* Let $f\colon X \to X'$ and $g\colon Y \to Y'$ be functions. The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(Y) \arrow[r, "f_* \times g_*"] \arrow[d, "\boxtimes_{X\times Y}"'] & \mathcal{P}(X') \times \mathcal{P}(Y') \arrow[d, "\boxtimes_{X'\times Y'}"] \\
\mathcal{P}(X \times Y) \arrow[r, "f_* \times g_*"'] & \mathcal{P}(X' \times Y')
\end{tikzcd}$$

commutes, i.e. we have

$$[f_* \times g_*](U \boxtimes_{X\times Y} V) = f_*(U) \boxtimes_{X'\times Y'} g_*(V)$$

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

(d) *Interaction With Diagonals.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X) \times \mathcal{P}(X) \arrow[r, "\boxtimes_{X\times X}"] \arrow[dr, "\cap"'] & \mathcal{P}(X \times X) \arrow[d, "\Delta_X^{-1}"] \\
& \mathcal{P}(X),
\end{tikzcd}$$

i.e. we have

$$U \cap V = \Delta_X^{-1}(U \boxtimes_{X\times X} V)$$

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

6. *The Dualisation Functor.* We have a functor

$$D_X\colon \mathcal{P}(X)^{\mathsf{op}} \to \mathcal{P}(X)$$

given by

$$\begin{aligned} D_X(U) &\overset{\text{def}}{=} [U, \emptyset]_X \\ &\overset{\text{def}}{=} U^{\mathsf{c}} \end{aligned}$$

for each $U \in \mathcal{P}(X)$, as in Item 5 of Proposition 4.4.7.1.4, satisfying the following conditions:

(a) *Duality.* We have

$$D_X(D_X(U)) = U, \qquad \begin{tikzcd} \mathcal{P}(X) \arrow[r, "D_X"] \arrow[dr, "\mathrm{id}_{\mathcal{P}(X)}"'] & \mathcal{P}(X) \arrow[d, "D_X"] \\ & \mathcal{P}(X). \end{tikzcd}$$

(b) *Duality.* The diagram

$$\begin{tikzcd} & \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X)^{\mathsf{op}} \arrow[r, "\cap^{\mathsf{op}}"] & \mathcal{P}(X)^{\mathsf{op}} \arrow[dr, "D_X"] & \\ \mathcal{P}(X)^{\mathsf{op}} \times \mathcal{P}(X) \arrow[ur, "\mathrm{id}_{\mathcal{P}(X)^{\mathsf{op}}} \times D_X"] \arrow[rrr, "{[-_1,-_2]_X}"'] & & & \mathcal{P}(X) \end{tikzcd}$$

commutes, i.e. we have

$$\underbrace{D_X(U \cap D_X(V))}_{\stackrel{\text{def}}{=}[U\cap[V,\emptyset]_X,\emptyset]_X} = [U, V]_X$$

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

(c) *Interaction With Direct Images.* The diagram

$$\begin{tikzcd} \mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_*^{\mathsf{op}}"] \arrow[d, "D_X"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "D_Y"] \\ \mathcal{P}(X) \arrow[r, "f_!"'] & \mathcal{P}(Y) \end{tikzcd}$$

commutes, i.e. we have

$$f_!(D_X(U)) = D_Y(f_*(U))$$

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

(d) *Interaction With Inverse Images.* The diagram

$$\begin{tikzcd}
\mathcal{P}(Y)^{\mathsf{op}} \arrow[r, "f^{-1,\mathsf{op}}"] \arrow[d, "D_Y"'] & \mathcal{P}(X)^{\mathsf{op}} \arrow[d, "D_X"] \\
\mathcal{P}(Y) \arrow[r, "f^{-1}"'] & \mathcal{P}(X)
\end{tikzcd}$$

commutes, i.e. we have

$$f^{-1}(D_Y(U)) = D_X(f^{-1}(U))$$

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

(e) *Interaction With Codirect Images.* The diagram

$$\begin{tikzcd}
\mathcal{P}(X)^{\mathsf{op}} \arrow[r, "f_!^{\mathsf{op}}"] \arrow[d, "D_X"'] & \mathcal{P}(Y)^{\mathsf{op}} \arrow[d, "D_Y"] \\
\mathcal{P}(X) \arrow[r, "f_*"'] & \mathcal{P}(Y)
\end{tikzcd}$$

commutes, i.e. we have

$$f_*(D_X(U)) = D_Y(f_!(U))$$

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

Proof 4.6.4.1.3 ► Proof of Proposition 4.6.4.1.2

Item 1: The Beck–Chevalley Condition

We have

$$\begin{aligned}
[g^{-1} \circ f_!](U) &\overset{\text{def}}{=} g^{-1}(f_!(U)) \\
&\overset{\text{def}}{=} \{y \in Y \mid g(y) \in f_!(U)\}
\end{aligned}$$

$$
\begin{aligned}
&= \left\{ y \in Y \,\middle|\, \begin{array}{l} \text{there exists some } x \in U \\ \text{such that } f(x) = g(y) \end{array} \right\} \\
&= \left\{ y \in Y \,\middle|\, \begin{array}{l} \text{there exists some} \\ (x, y) \in \{(x, y) \in X \times_Z Y \mid x \in U\} \end{array} \right\} \\
&= \left\{ y \in Y \,\middle|\, \begin{array}{l} \text{there exists some} \\ (x, y) \in \{(x, y) \in X \times_Z Y \mid x \in U\} \\ \text{such that } y = y \end{array} \right\} \\
&= \left\{ y \in Y \,\middle|\, \begin{array}{l} \text{there exists some} \\ (x, y) \in \{(x, y) \in X \times_Z Y \mid x \in U\} \\ \text{such that } \mathrm{pr}_2(x, y) = y \end{array} \right\} \\
&\stackrel{\text{def}}{=} (\mathrm{pr}_2)_!(\{(x, y) \in X \times_Z Y \mid x \in U\}) \\
&= (\mathrm{pr}_2)_!\left(\left\{(x, y) \in X \times_Z Y \,\middle|\, \mathrm{pr}_1(x, y) \in U\right\}\right) \\
&\stackrel{\text{def}}{=} (\mathrm{pr}_2)_!(\mathrm{pr}_1^{-1}(U)) \\
&\stackrel{\text{def}}{=} [(\mathrm{pr}_2)_! \circ \mathrm{pr}_1^{-1}](U)
\end{aligned}
$$

for each $U \in \mathcal{P}(X)$. Therefore, we have

$$
g^{-1} \circ f_! = (\mathrm{pr}_2)_! \circ \mathrm{pr}_1^{-1} .
$$

For the second equality, we have

$$
\begin{aligned}
[f^{-1} \circ g_!](U) &\stackrel{\text{def}}{=} f^{-1}(g_!(U)) \\
&\stackrel{\text{def}}{=} \{x \in X \mid f(x) \in g_!(V)\} \\
&= \left\{ x \in X \,\middle|\, \begin{array}{l} \text{there exists some } y \in V \\ \text{such that } f(x) = g(y) \end{array} \right\} \\
&= \left\{ x \in X \,\middle|\, \begin{array}{l} \text{there exists some} \\ (x, y) \in \{(x, y) \in X \times_Z Y \mid y \in V\} \end{array} \right\} \\
&= \left\{ x \in X \,\middle|\, \begin{array}{l} \text{there exists some} \\ (x, y) \in \{(x, y) \in X \times_Z Y \mid y \in V\} \\ \text{such that } x = x \end{array} \right\}
\end{aligned}
$$

$$
\begin{aligned}
&= \left\{ x \in X \;\middle|\; \begin{array}{l} \text{there exists some} \\ (x, y) \in \{(x, y) \in X \times_Z Y \mid y \in V\} \\ \text{such that } \mathrm{pr}_1(x, y) = x \end{array} \right\} \\
&\overset{\text{def}}{=} (\mathrm{pr}_1)_!(\{(x, y) \in X \times_Z Y \mid y \in V\}) \\
&= (\mathrm{pr}_1)_!\left(\left\{(x, y) \in X \times_Z Y \;\middle|\; \mathrm{pr}_2(x, y) \in V\right\}\right) \\
&\overset{\text{def}}{=} (\mathrm{pr}_1)_!(\mathrm{pr}_2^{-1}(V)) \\
&\overset{\text{def}}{=} [(\mathrm{pr}_1)_! \circ \mathrm{pr}_2^{-1}](V)
\end{aligned}
$$

for each $V \in \mathcal{P}(Y)$. Therefore, we have

$$f^{-1} \circ g_! = (\mathrm{pr}_1)_! \circ \mathrm{pr}_2^{-1}.$$

This finishes the proof.

Item 2: The Projection Formula I

We claim that

$$f_!(U) \cap V \subset f_!(U \cap f^{-1}(V)).$$

Indeed, we have

$$
\begin{aligned}
f_!(U) \cap V &\subset f_!(U) \cap f_!(f^{-1}(V)) \\
&= f_!(U \cap f^{-1}(V)),
\end{aligned}
$$

where we have used:

1. Item 2 of Proposition 4.6.1.1.5 for the inclusion.
2. Item 6 of Proposition 4.6.1.1.5 for the equality.

Conversely, we claim that

$$f_!(U \cap f^{-1}(V)) \subset f_!(U) \cap V.$$

Indeed:

1. Let $y \in f_!(U \cap f^{-1}(V))$.

2. Since $y \in f_!(U \cap f^{-1}(V))$, there exists some $x \in U \cap f^{-1}(V)$ such that $f(x) = y$.

3. Since $x \in U \cap f^{-1}(V)$, we have $x \in U$, and thus $f(x) \in f_!(U)$.

4. Since $x \in U \cap f^{-1}(V)$, we have $x \in f^{-1}(V)$, and thus $f(x) \in V$.

5. Since $f(x) \in f_!(U)$ and $f(x) \in V$, we have $f(x) \in f_!(U) \cap V$.

6. But $y = f(x)$, so $y \in f_!(U) \cap V$.

7. Thus $f_!(U \cap f^{-1}(V)) \subset f_!(U) \cap V$.

This finishes the proof.

Item 3: The Projection Formula II

We have

$$\begin{aligned} f_*(U) \cap V &\subset f_*(U) \cap f_*(f^{-1}(V)) \\ &= f_*(U \cap f^{-1}(V)), \end{aligned}$$

where we have used:

1. Item 2 of Proposition 4.6.3.1.7 for the inclusion.

2. Item 6 of Proposition 4.6.3.1.7 for the equality.

Since $\mathcal{P}(Y)$ is posetal, naturality is automatic (Categories, Item 4 of Proposition 11.2.7.1.2).

Item 4: Strong Closed Monoidality

This is a repetition of Item 19 of Proposition 4.4.7.1.4 and is proved there.

Item 5: The External Tensor Product

We have

$$\begin{aligned} U \boxtimes_{X \times Y} V &\overset{\text{def}}{=} \mathrm{pr}_1^{-1}(U) \cap \mathrm{pr}_2^{-1}(V) \\ &\overset{\text{def}}{=} \left\{(x, y) \in X \times Y \,\middle|\, \mathrm{pr}_1(x, y) \in U\right\} \\ &\quad \cup \left\{(x, y) \in X \times Y \,\middle|\, \mathrm{pr}_2(x, y) \in V\right\} \end{aligned}$$

$$
\begin{aligned}
&= \{(x,y) \in X \times Y \mid x \in U\} \\
&\quad \cup \{(x,y) \in X \times Y \mid y \in V\} \\
&= \{(x,y) \in X \times Y \mid x \in U \text{ and } y \in V\} \\
&\stackrel{\text{def}}{=} U \times V.
\end{aligned}
$$

Next, we claim that Items 5a to 5d are indeed true:

1. *Proof of Item 5a:* This is a repetition of Item 16 of Proposition 4.6.1.1.5 and is proved there.

2. *Proof of Item 5b:* This is a repetition of Item 16 of Proposition 4.6.2.1.3 and is proved there.

3. *Proof of Item 5c:* This is a repetition of Item 15 of Proposition 4.6.3.1.7 and is proved there.

4. *Proof of Item 5d:* We have

$$
\begin{aligned}
\Delta_X^{-1}(U \boxtimes_{X\times X} V) &\stackrel{\text{def}}{=} \{x \in X \mid (x,x) \in U \boxtimes_{X\times X} V\} \\
&= \{x \in X \mid (x,x) \in \{(u,v) \in X \times X \mid u \in U \text{ and } v \in V\}\} \\
&= U \cap V.
\end{aligned}
$$

This finishes the proof.

Item 6: The Dualisation Functor

This is a repetition of Items 5 and 6 of Proposition 4.4.7.1.4 and is proved there. □

4.7 Miscellany

4.7.1 Injective Functions

Let A and B be sets.

Definition 4.7.1.1.1 ▶ Injective Functions

A function $f\colon A \to B$ is **injective** if it satisfies the following condition:

($\star$) For each $a, a' \in A$, if $f(a) = f(a')$, then $a = a'$.

Proposition 4.7.1.1.2 ▶ Properties of Injective Functions

Let $f\colon A \to B$ be a function.

1. *Characterisations.* The following conditions are equivalent:[1]

   (a) The function f is injective.

   (b) The function f is a monomorphism in Sets.

   (c) The direct image function

   $$f_!\colon \mathcal{P}(A) \to \mathcal{P}(B)$$

   associated to f is injective.

   (d) The codirect image function

   $$f_*\colon \mathcal{P}(A) \to \mathcal{P}(B)$$

   associated to f is injective.

   (e) The direct image functor

   $$f_!\colon (\mathcal{P}(A), \subset) \to (\mathcal{P}(B), \subset)$$

   associated to f is full.

   (f) The codirect image function

   $$f_*\colon \mathcal{P}(A) \to \mathcal{P}(B)$$

   associated to f is full.

   (g) The diagram

   $$\begin{tikzcd} A \arrow[r, "f"] \arrow[dr, hook, "\chi_A"'] & B \arrow[d, "f^{-1}"] \\ & \mathcal{P}(A) \end{tikzcd}$$

commutes. That is, we have

$$f^{-1}(f(a)) = \{a\}$$

for each $a \in A$.

(h) We have

$$f^{-1} \circ f_! = \mathrm{id}_{\mathcal{P}(A)} \qquad \begin{tikzcd} \mathcal{P}(A) \arrow[r, "f_!"] \arrow[dr, equal] & \mathcal{P}(B) \arrow[d, "f^{-1}"] \\ & \mathcal{P}(A). \end{tikzcd}$$

In other words, we have

$$\{a \in A \mid f(a) \in f(U)\} = U$$

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

(i) We have

$$f^{-1} \circ f_* = \mathrm{id}_{\mathcal{P}(A)} \qquad \begin{tikzcd} \mathcal{P}(A) \arrow[r, "f_*"] \arrow[dr, equal] & \mathcal{P}(B) \arrow[d, "f^{-1}"] \\ & \mathcal{P}(A). \end{tikzcd}$$

In other words, we have

$$\left\{a \in A \,\middle|\, f^{-1}(f(a)) \subset U\right\} = U$$

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

[1] Items 1c to 1f unwind respectively to the following statements:

- For each $U, V \in \mathcal{P}(A)$, if $f_!(U) = f_!(V)$, then $U = V$.
- For each $U, V \in \mathcal{P}(A)$, if $f_*(U) = f_*(V)$, then $U = V$.
- For each $U, V \in \mathcal{P}(A)$, if $f_!(U) \subset f_!(V)$, then $U \subset V$.
- For each $U, V \in \mathcal{P}(A)$, if $f_*(U) \subset f_*(V)$, then $U \subset V$.

Item 1: Characterisations

We will proceed by showing:

- Step 1: Item 1a $\iff$ Item 1b.
- Step 2: Item 1a $\iff$ Item 1c.
- Step 3: Item 1a $\iff$ Item 1d.
- Step 4: Item 1c $\iff$ Item 1e.
- Step 5: Item 1e $\iff$ Item 1f.
- Step 6: Item 1a $\iff$ Item 1g.
- Step 7: Item 1g $\iff$ Item 1h.
- Step 8: Item 1a $\iff$ Item 1i.

Step 1: Item 1a $\iff$ Item 1b

We claim that Items 1a and 1b are equivalent:

- *Item 1a* $\implies$ *Item 1b*: We proceed in a few steps:
  - Proceeding by contrapositive, we claim that given a pair of maps $g, h \colon C \rightrightarrows A$ such that $g \neq h$, we have $f \circ g \neq f \circ h$.
  - Indeed, as g and h are different maps, there must exist at least one element $x \in C$ such that $g(x) \neq h(x)$.
  - But then we have $f(g(x)) \neq f(h(x))$, as f is injective.
  - Thus $f \circ g \neq f \circ h$, and we are done.
- *Item 1b* $\implies$ *Item 1a*: We proceed in a few steps:
  - Consider the diagram

$$\mathrm{pt} \underset{[y]}{\overset{[x]}{\rightrightarrows}} A \xrightarrow{f} B,$$

where $[x]$ and $[y]$ are the morphisms picking the elements x and y of A.

- Note that we have $f(x) = f(y)$ iff $f \circ [x] = f \circ [y]$.
- Since f is assumed to be a monomorphism, if $f(x) = f(y)$, then $f \circ [x] = f \circ [y]$ and therefore $[x] = [y]$.
- This shows that if $f(x) = f(y)$, then $x = y$, so f is injective.

Step 2: Item 1a $\Longleftrightarrow$ Item 1c

We claim that Items 1a and 1c are indeed equivalent:

- *Item 1a* $\Longrightarrow$ *Item 1c*: We proceed in a few steps:
  - Assume that f is injective and let $U, V \in \mathcal{P}(A)$ such that $f_!(U) = f_!(V)$. We wish to show that $U = V$.
  - To show that $U \subset V$, let $u \in U$.
  - By the definition of the direct image, we have $f(u) \in f_!(U)$.
  - Since $f_!(U) = f_!(V)$, it follows that $f(u) \in f_!(V)$.
  - Thus, there exists some $v \in V$ such that $f(v) = f(u)$.
  - Since f is injective, the equality $f(v) = f(u)$ implies that $v = u$.
  - Thus $u \in V$ and $U \subset V$.
  - A symmetric argument shows that $V \subset U$.
  - Therefore $U = V$, showing $f_!$ to be injective.
- *Item 1c* $\Longrightarrow$ *Item 1a*: We proceed in a few steps:
  - Assume that the direct image function $f_!$ is injective and let $a, a' \in A$ such that $f(a) = f(a')$. We wish to show that $a = a'$.
  - Since

$$f_!(\{a\}) = \{f(a)\}$$

$$\begin{aligned} &= \{f(a')\} \\ &= f_!(\{a'\}), \end{aligned}$$

we must have $\{a\} = \{a'\}$, as $f_!$ is injective, so $a = a'$, showing f to be injective.

Step 3: Item 1c $\iff$ Item 1d

This follows from Item 17 of Proposition 4.6.1.1.5.

Step 4: Item 1c $\iff$ Item 1e

We claim that Items 1c and 1e are equivalent:

- *Item 1c* $\implies$ *Item 1e*: We proceed in a few steps:
  - Let $U, V \in \mathcal{P}(A)$ such that $f_!(U) \subset f_!(V)$, assume $f_!$ to be injective, and consider the set $U \cup V$.
  - Since $f_!(U) \subset f_!(V)$, we have

    $$\begin{aligned} f_!(U \cup V) &= f_!(U) \cup f_!(V) \\ &= f_!(V), \end{aligned}$$

    where we have used Item 5 of Proposition 4.6.1.1.5 for the first equality.
  - Since $f_!$ is injective, this implies $U \cup V = V$.
  - Thus $U \subset V$, as we wished to show.
- *Item 1c* $\implies$ *Item 1e*: We proceed in a few steps:
  - Suppose Item 1e holds, and let $U, V \in \mathcal{P}(A)$ such that $f_!(U) = f_!(V)$.
  - Since $f_!(U) = f_!(V)$, we have $f_!(U) \subset f_!(V)$ and $f_!(V) \subset f_!(U)$.
  - By assumption, this implies $U \subset V$ and $V \subset U$.

– Thus $U = V$, showing $f_!$ to be injective.

Step 5: Item 1e $\iff$ Item 1f

This follows from Item 17 of Proposition 4.6.1.1.5.

Step 6: Item 1a $\iff$ Item 1g

We have

$$f^{-1}(f(a)) = \{a' \in A \mid f(a') = f(a)\}$$

so the condition $f^{-1}(f(a)) = \{a\}$ states precisely that if $f(a') = f(a)$, then $a' = a$.

Step 7: Item 1g $\iff$ Item 1h

We claim that Items 1g and 1h are indeed equivalent:

- *Item 1g* $\implies$ *Item 1h*: We have

$$\begin{aligned}
[f^{-1} \circ f_!](U) &\stackrel{\text{def}}{=} f^{-1}(f_!(U)) \\
&= f^{-1}\left(f_!\left(\bigcup_{u \in U} \{u\}\right)\right) \\
&= f^{-1}\left(\bigcup_{u \in U} f_!(\{u\})\right) \\
&= \bigcup_{u \in U} f^{-1}(f_!(\{u\})) \\
&= \bigcup_{u \in U} f^{-1}(f_!(u)) \\
&= \bigcup_{u \in U} \{u\} \\
&= U
\end{aligned}$$

for each $U \in \mathcal{P}(A)$, where we have used Item 5 of Proposition 4.6.1.1.5 for the third equality and Item 5 of Proposition 4.6.2.1.3 for the fourth equality.

- *Item 1h* $\implies$ *Item 1g*: Applying the condition $f^{-1} \circ f_! = \mathrm{id}_{\mathcal{P}(A)}$ to $U = \{a\}$ gives
$$f^{-1}(f_!(\{a\})) = \{a\}.$$

Step 8: Item 1a $\iff$ Item 1i

We claim that Items 1a and 1i are equivalent:

- *Item 1a* $\implies$ *Item 1i*: If f is injective, then $f^{-1}(f(a)) = \{a\}$, so we have
$$\begin{aligned} f^{-1}(f_*(a)) &= \{a \in A \mid \{a\} \subset U\} \\ &= U. \end{aligned}$$

- *Item 1i* $\implies$ *Item 1a*: For $U = \{a\}$, the condition $f^{-1}(f_*(U)) = U$ becomes
$$\left\{a' \in A \,\middle|\, f^{-1}(f(a')) \subset \{a\}\right\} = \{a\}.$$
Since the set $f^{-1}(f(a'))$ is given by
$$\{a \in A \mid f(a) = f(a')\},$$
it follows that f is injective.

This finishes the proof. □

4.7.2 Surjective Functions

Let A and B be sets.

Definition 4.7.2.1.1 ▶ Surjective Functions

A function $f\colon A \to B$ is **surjective** if it satisfies the following condition:

($\star$) For each $b \in B$, there exists some $a \in A$ such that $f(a) = b$.

Proposition 4.7.2.1.2 ▶ Properties of Surjective Functions

Let $f\colon A \to B$ be a function.

1. *Characterisations.* The following conditions are equivalent:

   (a) The function f is surjective.

   (b) The function f is an epimorphism in Sets.

   (c) The inverse image function

   $$f^{-1}\colon \mathcal{P}(B) \to \mathcal{P}(A)$$

   associated to f is injective.

   (d) The inverse image functor

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

   associated to f is full.

   (e) The diagram

   $$\begin{tikzcd} B \arrow[r, "f^{-1}"] \arrow[dr, hook, "\chi_B"'] & \mathcal{P}(A) \arrow[d, "f_!"] \\ & \mathcal{P}(B) \end{tikzcd}$$

   commutes. That is, we have

   $$f_!(f^{-1}(b)) = \{b\}$$

   for each $b \in B$.

(f) We have

$$f_! \circ f^{-1} = \mathrm{id}_{\mathcal{P}(B)} \qquad \begin{tikzcd} \mathcal{P}(B) \arrow[r, "f^{-1}"] \arrow[dr, equal] & \mathcal{P}(A) \arrow[d, "f_!"] \\ & \mathcal{P}(B). \end{tikzcd}$$

In other words, we have

$$\left\{ b \in B \,\middle|\, \begin{array}{l} \text{there exists some } a \in f^{-1}(U) \\ \text{such that } f(a) = b \end{array} \right\} = U$$

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

(g) We have

$$f_* \circ f^{-1} = \mathrm{id}_{\mathcal{P}(B)} \qquad \begin{tikzcd} \mathcal{P}(B) \arrow[r, "f^{-1}"] \arrow[dr, equal] & \mathcal{P}(A) \arrow[d, "f_*"] \\ & \mathcal{P}(B). \end{tikzcd}$$

In other words, we have

$$\left\{ b \in B \,\middle|\, f^{-1}(b) \subset f^{-1}(U) \right\} = U$$

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

Proof 4.7.2.1.3 ▶ Proof of Proposition 4.7.2.1.2

Item 1: Characterisations

We will proceed by showing:

- Step 1: Item 1a $\iff$ Item 1b.

- Step 2: Item 1a $\iff$ Item 1c.
- Step 3: Item 1c $\iff$ Item 1d.
- Step 4: Item 1a $\iff$ Item 1e.
- Step 5: Item 1e $\iff$ Item 1f.
- Step 6: Item 1a $\iff$ Item 1g.

Step 1: Item 1a $\iff$ Item 1b

We claim Items 1a and 1b are indeed equivalent:

- *Item 1a* $\implies$ *Item 1b*: We proceed in a few steps:
  - Let $g, h \colon B \rightrightarrows C$ be morphisms such that $g \circ f = h \circ f$.
  - For each $a \in A$, we have
  $$g(f(a)) = h(f(a)).$$
  - However, this implies that
  $$g(b) = h(b)$$
  for each $b \in B$, as f is surjective.
  - Thus $g = h$ and f is an epimorphism.
- *Item 1b* $\implies$ *Item 1a*: We proceed by contrapositive. Consider the diagram
  $$A \xrightarrow{f} B \underset{h}{\overset{g}{\rightrightarrows}} C,$$
  where h is the map defined by $h(b) = 0$ for each $b \in B$ and g is the map defined by
  $$g(b) = \begin{cases} 1 & \text{if } b \in \mathrm{Im}(f), \\ 0 & \text{otherwise.} \end{cases}$$

Then $h \circ f = g \circ f$, as $h(f(a)) = 1 = g(f(a))$ for each $a \in A$. However, for any $b \in B \setminus \mathrm{Im}(f)$, we have

$$g(b) = 0 \neq 1 = h(b).$$

Therefore $g \neq h$ and f is not an epimorphism.

Step 2: Item 1a $\Longleftrightarrow$ Item 1c

We claim Items 1a and 1c are indeed equivalent:

- *Item 1a* $\Longrightarrow$ *Item 1c*: We proceed in a few steps:
  - Assume that f is surjective. Let $U, V \in \mathcal{P}(B)$ such that $f^{-1}(U) = f^{-1}(V)$. We wish to show that $U = V$.
  - To show that $U \subset V$, let $b \in U$.
  - Since f is surjective, there must exist some $a \in A$ such that $f(a) = b$.
  - By the definition of the inverse image, since $f(a) = b$ and $b \in U$, we have $a \in f^{-1}(U)$.
  - By our initial assumption, $f^{-1}(U) = f^{-1}(V)$, so it follows that $a \in f^{-1}(V)$.
  - Again, by the definition of the inverse image, $a \in f^{-1}(V)$ means that $f(a) \in V$.
  - Since $f(a) = b$, we have shown that $b \in V$.
  - This establishes that $U \subset V$. A symmetric argument shows that $V \subset U$.
  - Thus $U = V$, proving that f^{-1} is injective.
- *Item 1c* $\Longrightarrow$ *Item 1a*: We proceed in a few steps:
  - Assume that the inverse image function f^{-1} is injective. Suppose, for the sake of contradiction, that f is not surjective.

- The assumption that f is not surjective means there exists some $b_0 \in B$ such that for all $a \in A$, we have $f(a) \neq b_0$.
- By the definition of the inverse image, this is equivalent to stating that $f^{-1}(\{b_0\}) = \emptyset$.
- Since $f^{-1}(\emptyset) = \emptyset$, we have $f^{-1}(\{b_0\}) = f^{-1}(\emptyset)$.
- Since f^{-1} is injective, this implies that $\{b_0\} = \emptyset$.
- This is a contradiction, as the singleton set $\{b_0\}$ is non-empty.
- Therefore, f is surjective.

Step 3: Item 1c $\iff$ Item 1d

We claim that Items 1c and 1d are equivalent:

- *Item 1c* $\implies$ *Item 1d*: We proceed in a few steps:
  - Let $U, V \in \mathcal{P}(B)$ such that $f^{-1}(U) \subset f^{-1}(V)$, assume f^{-1} to be injective, and consider the set $U \cup V$.
  - Since $f^{-1}(U) \subset f^{-1}(V)$, we have

    $$\begin{aligned} f^{-1}(U \cup V) &= f^{-1}(U) \cup f^{-1}(V) \\ &= f^{-1}(V), \end{aligned}$$

    where we have used Item 5 of Proposition 4.6.2.1.3 for the first equality.
  - Since f^{-1} is injective, this implies $U \cup V = V$.
  - Thus $U \subset V$, as we wished to show.
- *Item 1d* $\implies$ *Item 1c*: We proceed in a few steps:
  - Suppose Item 1d holds, and let $U, V \in \mathcal{P}(B)$ such that $f^{-1}(U) = f^{-1}(V)$.
  - Since $f^{-1}(U) = f^{-1}(V)$, we have $f^{-1}(U) \subset f^{-1}(V)$ and $f^{-1}(V) \subset f^{-1}(U)$.

- By assumption, this implies $U \subset V$ and $V \subset U$.
- Thus $U = V$, showing f^{-1} to be injective.

Step 4: Item 1a $\iff$ Item 1e

We have

$$f_!(f^{-1}(b)) = \left\{ b \in B \,\middle|\, \begin{array}{l} \text{there exists some } a \in f^{-1}(b) \\ \text{such that } f(a) = b \end{array} \right\},$$

so the condition $f_!(f^{-1}(b)) = \{b\}$ holds iff f is surjective.

Step 5: Item 1e $\iff$ Item 1f

We claim that Items 1e and 1f are indeed equivalent:

- *Item 1e* $\implies$ *Item 1f*: We have

$$\begin{aligned} [f_! \circ f^{-1}](U) &\stackrel{\text{def}}{=} f_!(f^{-1}(U)) \\ &= f_!\left(f^{-1}\left(\bigcup_{u \in U}\{u\}\right)\right) \\ &= f_!\left(\bigcup_{u \in U} f^{-1}(\{u\})\right) \\ &= \bigcup_{u \in U} f_!(f^{-1}(\{u\})) \\ &= \bigcup_{u \in U} f_!(f^{-1}(u)) \\ &= \bigcup_{u \in U} \{u\} \\ &= U \end{aligned}$$

for each $U \in \mathcal{P}(B)$, where we have used Item 5 of Proposition 4.6.1.1.5 for the third equality and Item 5 of Proposition 4.6.2.1.3 for the fourth equality.

- *Item 1f* $\implies$ *Item 1e*: Applying the condition $f_! \circ f^{-1} = \mathrm{id}_{\mathcal{P}(B)}$ to $U = \{b\}$ gives
$$f_!(f^{-1}(\{b\})) = \{b\}.$$

Step 6: Item 1a $\iff$ Item 1g

First, note that for the condition $f^{-1}(b) \subset f^{-1}(U)$ to hold, we must have $b \in U$ or $f^{-1}(b) = \emptyset$. Thus
$$f_*(f^{-1}(U)) = (U \cap \mathrm{Im}(f)) \cup (B \setminus \mathrm{Im}(f)).$$

We now claim that Items 1a and 1g are indeed equivalent:

- *Item 1a* $\implies$ *Item 1g*: If f is surjective, we have
$$\begin{aligned}(U \cap \mathrm{Im}(f)) \cup (B \setminus \mathrm{Im}(f)) &= U \cup \emptyset \\ &= U,\end{aligned}$$
so $f_* \circ f^{-1} = \mathrm{id}_{\mathcal{P}(B)}$.
- *Item 1g* $\implies$ *Item 1a*: Taking $U = \emptyset$ gives
$$\begin{aligned}f_*(f^{-1}(\emptyset)) &= (\emptyset \cap \mathrm{Im}(f)) \cup (B \setminus \mathrm{Im}(f)) \\ &= B \setminus \mathrm{Im}(f),\end{aligned}$$
so the condition $f_*(f^{-1}(\emptyset)) = \emptyset$ implies $B \setminus \mathrm{Im}(f) = \emptyset$. Thus $\mathrm{Im}(f) = B$ and f is surjective.

This finishes the proof. $\square$

Appendices

A Other Chapters

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