

Monoidal Structures on the Category of Sets

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July 22, 2025

01NK This chapter contains some material on monoidal structures on Sets.

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01NL 5.1 The Monoidal Category of Sets and Products

01NM 5.1.1 Products of Sets

See [Constructions With Sets, Section 4.1.3](#).

01NN 5.1.2 The Internal Hom of Sets

See [Constructions With Sets, Section 4.3.5](#).

01NP 5.1.3 The Monoidal Unit

01NQ DEFINITION 5.1.3.1.1 ► THE MONOIDAL UNIT OF \times

The **monoidal unit of the product of sets** is the functor

$$\mathbb{1}^{\text{Sets}} : \text{pt} \rightarrow \text{Sets}$$

defined by

$$\mathbb{1}_{\text{Sets}} \stackrel{\text{def}}{=} \text{pt},$$

where pt is the terminal set of [Constructions With Sets, Definition 4.1.1.1.1](#).

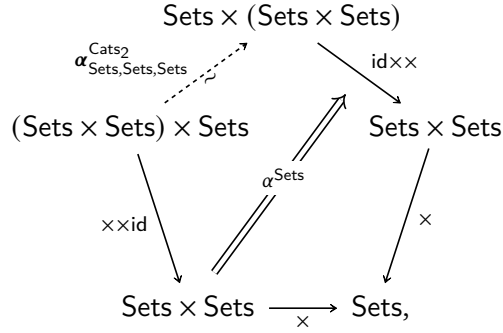
01NR 5.1.4 The Associator

01NS DEFINITION 5.1.4.1.1 ► THE ASSOCIATOR OF \times

The **associator of the product of sets** is the natural isomorphism

$$\alpha^{\text{Sets}} : \times \circ (\times \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \times \circ (\text{id}_{\text{Sets}} \times \times) \circ \alpha_{\text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2},$$

as in the diagram



whose component

$$\alpha_{X,Y,Z}^{\text{Sets}}: (X \times Y) \times Z \xrightarrow{\sim} X \times (Y \times Z)$$

at (X, Y, Z) is given by

$$\alpha_{X,Y,Z}^{\text{Sets}}((x, y), z) \stackrel{\text{def}}{=} (x, (y, z))$$

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

PROOF 5.1.4.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.1.4.1.1

Invertibility

The inverse of $\alpha_{X,Y,Z}^{\text{Sets}}$ is the morphism

$$\alpha_{X,Y,Z}^{\text{Sets}, -1}: X \times (Y \times Z) \xrightarrow{\sim} (X \times Y) \times Z$$

defined by

$$\alpha_{X,Y,Z}^{\text{Sets}, -1}(x, (y, z)) \stackrel{\text{def}}{=} ((x, y), z)$$

for each $(x, (y, z)) \in X \times (Y \times Z)$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned} \left[\alpha_{X,Y,Z}^{\text{Sets}, -1} \circ \alpha_{X,Y,Z}^{\text{Sets}} \right]((x, y), z) &\stackrel{\text{def}}{=} \alpha_{X,Y,Z}^{\text{Sets}, -1} \left(\alpha_{X,Y,Z}^{\text{Sets}}((x, y), z) \right) \\ &\stackrel{\text{def}}{=} \alpha_{X,Y,Z}^{\text{Sets}, -1}(x, (y, z)) \end{aligned}$$

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

$$\stackrel{\text{def}}{=} [\text{id}_{(X \times Y) \times Z}]((x, y), z)$$

for each $((x, y), z) \in (X \times Y) \times Z$, and therefore we have

$$\alpha_{X,Y,Z}^{\text{Sets}, -1} \circ \alpha_{X,Y,Z}^{\text{Sets}} = \text{id}_{(X \times Y) \times Z}.$$

- *Invertibility II.* We have

$$\left[\alpha_{X,Y,Z}^{\text{Sets}} \circ \alpha_{X,Y,Z}^{\text{Sets}, -1} \right](x, (y, z)) \stackrel{\text{def}}{=} \alpha_{X,Y,Z}^{\text{Sets}} \left(\alpha_{X,Y,Z}^{\text{Sets}, -1}(x, (y, z)) \right)$$

$$\stackrel{\text{def}}{=} \alpha_{X,Y,Z}^{\text{Sets}}((x, y), z)$$

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

$$\stackrel{\text{def}}{=} [\text{id}_{(X \times Y) \times Z}](x, (y, z))$$

for each $(x, (y, z)) \in X \times (Y \times Z)$, and therefore we have

$$\alpha_{X,Y,Z}^{\text{Sets}, -1} \circ \alpha_{X,Y,Z}^{\text{Sets}} = \text{id}_{X \times (Y \times Z)}.$$

Therefore $\alpha_{X,Y,Z}^{\text{Sets}}$ is indeed an isomorphism.

Naturality

We need to show that, given functions

$$f: X \rightarrow X',$$

$$g: Y \rightarrow Y',$$

$$h: Z \rightarrow Z'$$

the diagram


$$\begin{array}{ccc} (X \times Y) \times Z & \xrightarrow{(f \times g) \times h} & (X' \times Y') \times Z' \\ \alpha_{X,Y,Z}^{\text{Sets}} \downarrow & & \downarrow \alpha_{X',Y',Z'}^{\text{Sets}} \\ X \times (Y \times Z) & \xrightarrow{f \times (g \times h)} & X' \times (Y' \times Z') \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} ((x, y), z) & \longmapsto & ((f(x), g(y)), h(z)) \\ \downarrow & & \downarrow \\ (x, (y, z)) \longmapsto (f(x), (g(y), h(z))) & & (f(x), (g(y), h(z))) \end{array}$$

and hence indeed commutes, showing α^{Sets} to be a natural transformation.

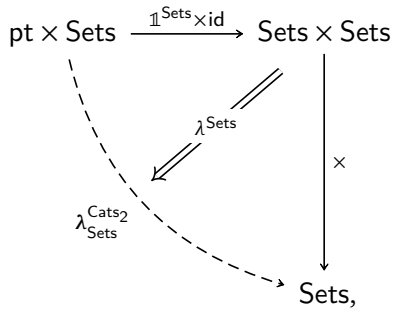
Being a Natural Isomorphism

Since α^{Sets} is natural and $\alpha^{\text{Sets}, -1}$ is a componentwise inverse to α^{Sets} , it follows from **Categories, Item 2** of **Proposition 11.9.7.1.2** that $\alpha^{\text{Sets}, -1}$ is also natural. Thus α^{Sets} is a natural isomorphism. 

01NT 5.1.5 The Left Unitor

01NU DEFINITION 5.1.5.1.1 ► THE LEFT UNITOR OF \times

The left unitor of the product of sets is the natural isomorphism

$$\lambda^{\text{Sets}} : \times \circ (\mathbb{1}^{\text{Sets}} \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \lambda_{\text{Sets}}^{\text{Cats}_2}$$


whose component

$$\lambda_X^{\text{Sets}} : \text{pt} \times X \xrightarrow{\sim} X$$

at $X \in \text{Obj}(\text{Sets})$ is given by

$$\lambda_X^{\text{Sets}}(\star, x) \stackrel{\text{def}}{=} x$$

for each $(\star, x) \in \text{pt} \times X$.

PROOF 5.1.5.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.1.5.1.1

Invertibility

The inverse of λ_X^{Sets} is the morphism

$$\lambda_X^{\text{Sets}, -1} : X \xrightarrow{\sim} \text{pt} \times X$$

defined by

$$\lambda_X^{\text{Sets}, -1}(x) \stackrel{\text{def}}{=} (\star, x)$$

for each $x \in X$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned} \left[\lambda_X^{\text{Sets}, -1} \circ \lambda_X^{\text{Sets}} \right](\text{pt}, x) &= \lambda_X^{\text{Sets}, -1} \left(\lambda_X^{\text{Sets}}(\text{pt}, x) \right) \\ &= \lambda_X^{\text{Sets}, -1}(x) \\ &= (\text{pt}, x) \\ &= [\text{id}_{\text{pt} \times X}](\text{pt}, x) \end{aligned}$$

for each $(\text{pt}, x) \in \text{pt} \times X$, and therefore we have

$$\lambda_X^{\text{Sets}, -1} \circ \lambda_X^{\text{Sets}} = \text{id}_{\text{pt} \times X}.$$

- *Invertibility II.* We have

$$\begin{aligned} \left[\lambda_X^{\text{Sets}} \circ \lambda_X^{\text{Sets}, -1} \right](x) &= \lambda_X^{\text{Sets}} \left(\lambda_X^{\text{Sets}, -1}(x) \right) \\ &= \lambda_X^{\text{Sets}, -1}(\text{pt}, x) \\ &= x \\ &= [\text{id}_X](x) \end{aligned}$$

for each $x \in X$, and therefore we have

$$\lambda_X^{\text{Sets}} \circ \lambda_X^{\text{Sets}, -1} = \text{id}_X.$$

Therefore λ_X^{Sets} is indeed an isomorphism.

Naturality

We need to show that, given a function $f: X \rightarrow Y$, the diagram


$$\begin{array}{ccc} \text{pt} \times X & \xrightarrow{\text{id}_{\text{pt}} \times f} & \text{pt} \times Y \\ \lambda_X^{\text{Sets}} \downarrow & & \downarrow \lambda_Y^{\text{Sets}} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 (\star, x) & & (\star, x) \mapsto (\star, f(x)) \\
 \downarrow & & \downarrow \\
 x & \xrightarrow{\quad} & f(x)
 \end{array}$$

and hence indeed commutes. Therefore $\lambda^{\mathbf{Sets}}$ is a natural transformation.

Being a Natural Isomorphism

Since $\lambda^{\mathbf{Sets}}$ is natural and $\lambda^{\mathbf{Sets}, -1}$ is a componentwise inverse to $\lambda^{\mathbf{Sets}}$, it follows from **Categories, Item 2** of **Proposition 11.9.7.1.2** that $\lambda^{\mathbf{Sets}, -1}$ is also natural. Thus $\lambda^{\mathbf{Sets}}$ is a natural isomorphism. 

01NV 5.1.6 The Right Unitor

01NW DEFINITION 5.1.6.1.1 ► THE RIGHT UNITOR OF \times

The **right unitor of the product of sets** is the natural isomorphism

$$\rho^{\mathbf{Sets}} : \times \circ (\text{id} \times \mathbb{1}^{\mathbf{Sets}}) \xrightarrow{\sim} \rho_{\mathbf{Sets}}^{\mathbf{Cats}_2},$$

whose component

$$\rho_X^{\mathbf{Sets}} : X \times \text{pt} \xrightarrow{\sim} X$$

at $X \in \text{Obj}(\mathbf{Sets})$ is given by

$$\rho_X^{\mathbf{Sets}}(x, \star) \stackrel{\text{def}}{=} x$$

for each $(x, \star) \in X \times \text{pt}$.

PROOF 5.1.6.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.1.6.1.1

Invertibility

The inverse of ρ_X^{Sets} is the morphism

$$\rho_X^{\text{Sets}, -1} : X \dashrightarrow X \times \text{pt}$$

defined by

$$\rho_X^{\text{Sets}, -1}(x) \stackrel{\text{def}}{=} (x, \star)$$

for each $x \in X$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned} \left[\rho_X^{\text{Sets}, -1} \circ \rho_X^{\text{Sets}} \right](x, \star) &= \rho_X^{\text{Sets}, -1} \left(\rho_X^{\text{Sets}}(x, \star) \right) \\ &= \rho_X^{\text{Sets}, -1}(x) \\ &= (x, \star) \\ &= [\text{id}_{X \times \text{pt}}](x, \star) \end{aligned}$$

for each $(x, \star) \in X \times \text{pt}$, and therefore we have

$$\rho_X^{\text{Sets}, -1} \circ \rho_X^{\text{Sets}} = \text{id}_{X \times \text{pt}}.$$

- *Invertibility II.* We have

$$\begin{aligned} \left[\rho_X^{\text{Sets}} \circ \rho_X^{\text{Sets}, -1} \right](x) &= \rho_X^{\text{Sets}} \left(\rho_X^{\text{Sets}, -1}(x) \right) \\ &= \rho_X^{\text{Sets}, -1}(x, \star) \\ &= x \\ &= [\text{id}_X](x) \end{aligned}$$

for each $x \in X$, and therefore we have

$$\rho_X^{\text{Sets}} \circ \rho_X^{\text{Sets}, -1} = \text{id}_X.$$

Therefore ρ_X^{Sets} is indeed an isomorphism.

Naturality

We need to show that, given a function $f: X \rightarrow Y$, the diagram


$$\begin{array}{ccc} X \times \text{pt} & \xrightarrow{f \times \text{id}_{\text{pt}}} & Y \times \text{pt} \\ \rho_X^{\text{Sets}} \downarrow & & \downarrow \rho_Y^{\text{Sets}} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} (x, \star) & & (x, \star) \mapsto (f(x), \star) \\ \downarrow & & \downarrow \\ x & \xrightarrow{\quad} & f(x) \end{array}$$

and hence indeed commutes. Therefore ρ^{Sets} is a natural transformation.

Being a Natural Isomorphism

Since ρ^{Sets} is natural and $\rho^{\text{Sets}, -1}$ is a componentwise inverse to ρ^{Sets} , it follows from **Categories, Item 2** of **Proposition 11.9.7.1.2** that $\rho^{\text{Sets}, -1}$ is also natural. Thus ρ^{Sets} is a natural isomorphism. 

01NY

DEFINITION 5.1.7.1.1 ► THE SYMMETRY OF \times

The **symmetry of the product of sets** is the natural isomorphism

$$\sigma^{\text{Sets}} : \times \xRightarrow{\sim} \times \circ \sigma_{\text{Sets}, \text{Sets}}^{\text{Cats}_2},$$

whose component

$$\sigma_{X,Y}^{\text{Sets}} : X \times Y \xrightarrow{\sim} Y \times X$$

at $X, Y \in \text{Obj}(\text{Sets})$ is defined by

$$\sigma_{X,Y}^{\text{Sets}}(x, y) \stackrel{\text{def}}{=} (y, x)$$

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

PROOF 5.1.7.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.1.7.1.1

Invertibility

The inverse of $\sigma_{X,Y}^{\text{Sets}}$ is the morphism

$$\sigma_{X,Y}^{\text{Sets}, -1} : Y \times X \xrightarrow{\sim} X \times Y$$

defined by

$$\sigma_{X,Y}^{\text{Sets}, -1}(y, x) \stackrel{\text{def}}{=} (x, y)$$

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

- *Invertibility I.* We have

$$\begin{aligned} \left[\sigma_{X,Y}^{\text{Sets}, -1} \circ \sigma_{X,Y}^{\text{Sets}} \right](x, y) &\stackrel{\text{def}}{=} \sigma_{X,Y}^{\text{Sets}, -1} \left(\sigma_{X,Y}^{\text{Sets}}(x, y) \right) \\ &\stackrel{\text{def}}{=} \sigma_{X,Y}^{\text{Sets}, -1}(y, x) \\ &\stackrel{\text{def}}{=} (x, y) \\ &\stackrel{\text{def}}{=} [\text{id}_{X \times Y}](x, y) \end{aligned}$$

for each $(x, y) \in X \times Y$, and therefore we have

$$\sigma_{X,Y}^{\text{Sets}, -1} \circ \sigma_{X,Y}^{\text{Sets}} = \text{id}_{X \times Y}.$$

- *Invertibility II.* We have

$$\begin{aligned}
 \left[\sigma_{X,Y}^{\text{Sets}} \circ \sigma_{X,Y}^{\text{Sets},-1} \right] (y, x) &\stackrel{\text{def}}{=} \sigma_{X,Y}^{\text{Sets},-1} \left(\sigma_{X,Y}^{\text{Sets}} (y, x) \right) \\
 &\stackrel{\text{def}}{=} \sigma_{X,Y}^{\text{Sets},-1} (x, y) \\
 &\stackrel{\text{def}}{=} (y, x) \\
 &\stackrel{\text{def}}{=} [\text{id}_{Y \times X}] (y, x)
 \end{aligned}$$

for each $(y, x) \in Y \times X$, and therefore we have

$$\sigma_{X,Y}^{\text{Sets}} \circ \sigma_{X,Y}^{\text{Sets},-1} = \text{id}_{Y \times X}.$$

Therefore $\sigma_{X,Y}^{\text{Sets}}$ is indeed an isomorphism.

Naturality

We need to show that, given functions

$$\begin{aligned}
 f &: X \rightarrow A, \\
 g &: Y \rightarrow B
 \end{aligned}$$

the diagram


$$\begin{array}{ccc}
 X \times Y & \xrightarrow{f \times g} & A \times B \\
 \sigma_{X,Y}^{\text{Sets}} \downarrow & & \downarrow \sigma_{A,B}^{\text{Sets}} \\
 Y \times X & \xrightarrow{g \times f} & B \times A
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 (x, y) & & (x, y) \mapsto (f(x), g(y)) \\
 \downarrow & & \downarrow \\
 (y, x) \mapsto (g(y), f(x)) & & (g(y), f(x))
 \end{array}$$

and hence indeed commutes, showing σ^{Sets} to be a natural transformation.

Being a Natural Isomorphism

Since σ^{Sets} is natural and $\sigma^{\text{Sets},-1}$ is a componentwise inverse to σ^{Sets} , it follows from **Categories, Item 2** of **Proposition 11.9.7.1.2** that $\sigma^{\text{Sets},-1}$ is also natural. Thus σ^{Sets} is a natural isomorphism. 

01NZ 5.1.8 The Diagonal

01P0 DEFINITION 5.1.8.1.1 ► THE DIAGONAL OF \times

The **diagonal of the product of sets** is the natural transformation

$$\Delta: \text{id}_{\text{Sets}} \Rightarrow \times \circ \Delta_{\text{Sets}}^{\text{Cats}_2},$$

whose component

$$\Delta_X: X \rightarrow X \times X$$

at $X \in \text{Obj}(\text{Sets})$ is given by

$$\Delta_X(x) \stackrel{\text{def}}{=} (x, x)$$

for each $x \in X$.

PROOF 5.1.8.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.1.8.1.1

We need to show that, given a function $f: X \rightarrow Y$, the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \Delta_X \downarrow & & \downarrow \Delta_Y \\ X \times X & \xrightarrow{f \times f} & Y \times Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} x & \xrightarrow{\quad} & f(x) \\ \downarrow & & \downarrow \\ (x, x) & \xrightarrow{\quad} & (f(x), f(x)) \end{array}$$

and hence indeed commutes, showing Δ to be natural. 

01P1 **PROPOSITION 5.1.8.1.3 ► PROPERTIES OF THE DIAGONAL MAP**

Let X be a set.

01P2 1. *Monoidality.* The diagonal map

$$\Delta: \text{id}_{\text{Sets}} \Rightarrow \times \circ \Delta_{\text{Sets}}^{\text{Cats}_2},$$

is a monoidal natural transformation:

01P3 (a) *Compatibility With Strong Monoidality Constraints.* For each $X, Y \in \text{Obj}(\text{Sets})$, the diagram

$$\begin{array}{ccc} X \times Y & \xrightarrow{\Delta_X \times \Delta_Y} & (X \times X) \times (Y \times Y) \\ & \searrow \Delta_{X \times Y} & \downarrow \wr \\ & & (X \times Y) \times (X \times Y) \end{array}$$

commutes.

01P4 (b) *Compatibility With Strong Unitality Constraints.* The diagrams

$$\begin{array}{ccc} \text{pt} & \xrightarrow{\Delta_{\text{pt}}} & \text{pt} \times \text{pt} \\ & \searrow & \downarrow \lambda_{\text{pt}}^{\text{Sets}} \\ & & \text{pt} \end{array} \quad \begin{array}{ccc} \text{pt} & \xrightarrow{\Delta_{\text{pt}}} & \text{pt} \times \text{pt} \\ & \searrow & \downarrow \rho_{\text{pt}}^{\text{Sets}} \\ & & \text{pt} \end{array}$$

commute, i.e. we have

$$\begin{aligned} \Delta_{\text{pt}} &= \lambda_{\text{pt}}^{\text{Sets}, -1} \\ &= \rho_{\text{pt}}^{\text{Sets}, -1}, \end{aligned}$$

where we recall that the equalities

$$\begin{aligned} \lambda_{\text{pt}}^{\text{Sets}} &= \rho_{\text{pt}}^{\text{Sets}}, \\ \lambda_{\text{pt}}^{\text{Sets}, -1} &= \rho_{\text{pt}}^{\text{Sets}, -1} \end{aligned}$$

are always true in any monoidal category by Monoidal Categories, ?? of ??.

01P5 2. *The Diagonal of the Unit.* The component

$$\Delta_{\text{pt}}: \text{pt} \xrightarrow{\sim} \text{pt} \times \text{pt}$$

of Δ at pt is an isomorphism.

PROOF 5.1.8.1.4 ► PROOF OF PROPOSITION 5.1.8.1.3

Item 1: Monoidality

We claim that Δ is indeed monoidal:

024S

1. *Item 1a: Compatibility With Strong Monoidality Constraints:* We need to show that the diagram

$$\begin{array}{ccc} X \times Y & \xrightarrow{\Delta_X \times \Delta_Y} & (X \times X) \times (Y \times Y) \\ & \searrow \Delta_{X \times Y} & \downarrow \wr \\ & & (X \times Y) \times (X \times Y) \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc} (x, y) & \longmapsto & ((x, x), (y, y)) & & (x, y) \\ & & \downarrow & & \searrow \\ & & ((x, y), (x, y)) & & ((x, y), (x, y)) \end{array}$$

and hence indeed commutes.

024T

2. *Item 1b: Compatibility With Strong Unitality Constraints:* As shown in the proof of [Definition 5.1.5.1.1](#), the inverse of the left unitor of Sets with respect to the product at $X \in \text{Obj}(\text{Sets})$ is given by

$$\lambda_X^{\text{Sets}, -1}(x) \stackrel{\text{def}}{=} (\star, x)$$

for each $x \in X$, so when $X = \text{pt}$, we have

$$\lambda_{\text{pt}}^{\text{Sets}, -1}(\star) \stackrel{\text{def}}{=} (\star, \star),$$


and also

$$\Delta_{\text{pt}}^{\text{Sets}}(\star) \stackrel{\text{def}}{=} (\star, \star),$$

so we have $\Delta_{\text{pt}} = \lambda_{\text{pt}}^{\text{Sets}, -1}$.

This finishes the proof.

Item 2: The Diagonal of the Unit

This follows from [Item 1](#) and the invertibility of the left/right unitor of Sets with respect to \times , proved in the proof of [Definition 5.1.5.1.1](#) for the left unitor or the proof of [Definition 5.1.6.1.1](#) for the right unitor. 

01P6 **5.1.9 The Monoidal Category of Sets and Products**

01P7

PROPOSITION 5.1.9.1.1 ► THE MONOIDAL STRUCTURE ON SETS ASSOCIATED TO THE PRODUCT

The category **Sets** admits a closed symmetric monoidal category with diagonals structure consisting of:

- *The Underlying Category.* The category **Sets** of pointed sets.
- *The Monoidal Product.* The product functor

$$\times: \mathbf{Sets} \times \mathbf{Sets} \rightarrow \mathbf{Sets}$$

of **Constructions With Sets**, Item 1 of **Proposition 4.1.3.1.4**.

- *The Internal Hom.* The internal Hom functor

$$\mathbf{Sets}: \mathbf{Sets}^{\text{op}} \times \mathbf{Sets} \rightarrow \mathbf{Sets}$$

of **Constructions With Sets**, Item 1 of **Proposition 4.3.5.1.2**.

- *The Monoidal Unit.* The functor

$$\mathbb{1}^{\mathbf{Sets}}: \text{pt} \rightarrow \mathbf{Sets}$$

of **Definition 5.1.3.1.1**.

- *The Associators.* The natural isomorphism

$$\alpha^{\mathbf{Sets}}: \times \circ (\times \times \text{id}_{\mathbf{Sets}}) \xrightarrow{\sim} \times \circ (\text{id}_{\mathbf{Sets}} \times \times) \circ \alpha_{\mathbf{Sets}, \mathbf{Sets}, \mathbf{Sets}}^{\mathbf{Cats}}$$

of **Definition 5.1.4.1.1**.

- *The Left Unitors.* The natural isomorphism

$$\lambda^{\mathbf{Sets}}: \times \circ (\mathbb{1}^{\mathbf{Sets}} \times \text{id}_{\mathbf{Sets}}) \xrightarrow{\sim} \lambda_{\mathbf{Sets}}^{\mathbf{Cats}_2}$$

of **Definition 5.1.5.1.1**.

- *The Right Unitors.* The natural isomorphism

$$\rho^{\mathbf{Sets}}: \times \circ (\text{id} \times \mathbb{1}^{\mathbf{Sets}}) \xrightarrow{\sim} \rho_{\mathbf{Sets}}^{\mathbf{Cats}_2}$$

of **Definition 5.1.6.1.1**.

- *The Symmetry.* The natural isomorphism

$$\sigma^{\text{Sets}}: \times \xrightarrow{\sim} \times \circ \sigma_{\text{Sets}, \text{Sets}}^{\text{Cats}_2}$$

of Definition 5.1.7.1.1.

- *The Diagonals.* The monoidal natural transformation

$$\Delta: \text{id}_{\text{Sets}} \Rightarrow \times \circ \Delta_{\text{Sets}}^{\text{Cats}_2}$$

of Definition 5.1.8.1.1.

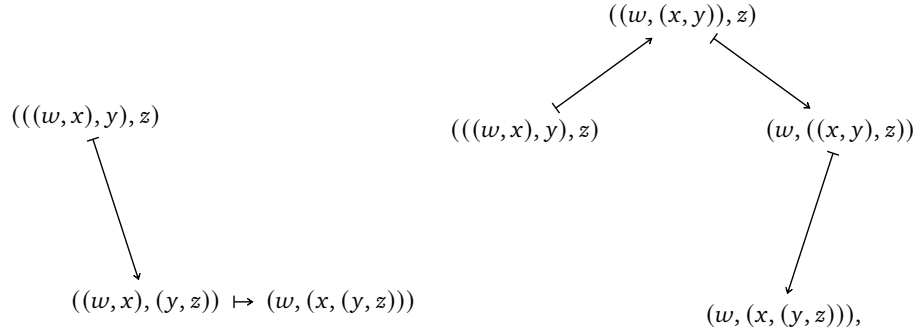
PROOF 5.1.9.1.2 ► PROOF OF PROPOSITION 5.1.9.1.1

The Pentagon Identity

Let W, X, Y and Z be sets. We have to show that the diagram

$$\begin{array}{ccccc}
 & & (W \times (X \times Y)) \times Z & & \\
 & \nearrow \alpha_{W,X,Y}^{\text{Sets}} \times \text{id}_Z & & \searrow \alpha_{W,X \times Y,Z}^{\text{Sets}} & \\
 ((W \times X) \times Y) \times Z & & & & W \times ((X \times Y) \times Z) \\
 \downarrow \alpha_{W \times X,Y,Z}^{\text{Sets}} & & & & \downarrow \text{id}_W \times \alpha_{X,Y,Z}^{\text{Sets}} \\
 (W \times X) \times (Y \times Z) & \xrightarrow{\alpha_{W,X,Y \times Z}^{\text{Sets}}} & & & W \times (X \times (Y \times Z))
 \end{array}$$

commutes. Indeed, this diagram acts on elements as



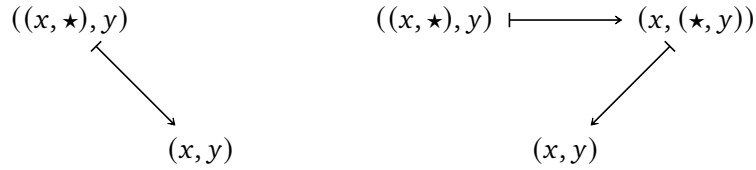
and thus the pentagon identity is satisfied.

The Triangle Identity

Let X and Y be sets. We have to show that the diagram

$$\begin{array}{ccc}
 (X \times \text{pt}) \times Y & \xrightarrow{\alpha_{X, \text{pt}, Y}^{\text{Sets}}} & X \times (\text{pt} \times Y) \\
 \searrow \rho_X^{\text{Sets}} \times \text{id}_Y & & \swarrow \text{id}_X \times \lambda_Y^{\text{Sets}} \\
 & X \times Y &
 \end{array}$$

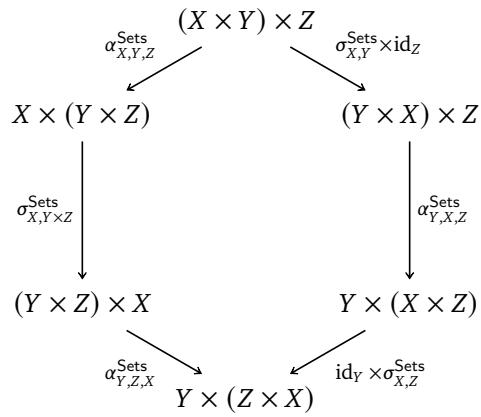
commutes. Indeed, this diagram acts on elements as



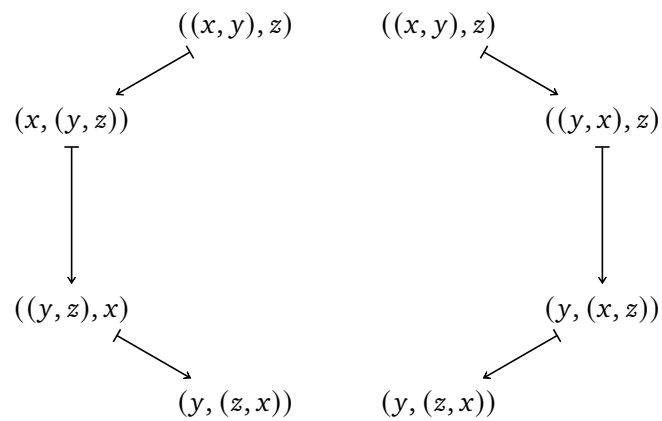
and thus the triangle identity is satisfied.

The Left Hexagon Identity

Let X , Y , and Z be sets. We have to show that the diagram



commutes. Indeed, this diagram acts on elements as



and thus the left hexagon identity is satisfied.

The Right Hexagon Identity

Let $X, Y,$ and Z be sets. We have to show that the diagram

$$\begin{array}{ccc}
 & X \times (Y \times Z) & \\
 (\alpha_{X,Y,Z}^{\text{Sets}})^{-1} \swarrow & & \searrow \text{id}_X \times \sigma_{Y,Z}^{\text{Sets}} \\
 (X \times Y) \times Z & & X \times (Z \times Y) \\
 \downarrow \sigma_{X \times Y, Z}^{\text{Sets}} & & \downarrow (\alpha_{X,Z,Y}^{\text{Sets}})^{-1} \\
 Z \times (X \times Y) & & (X \times Z) \times Y \\
 & \searrow (\alpha_{Z,X,Y}^{\text{Sets}})^{-1} \quad \swarrow \sigma_{X,Z}^{\text{Sets}} \times \text{id}_Y & \\
 & (Z \times X) \times Y &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc}
 & (x, (y, z)) & & (x, (y, z)) & \\
 & \swarrow & & \searrow & \\
 ((x, y), z) & & & & (x, (z, y)) \\
 \downarrow & & & & \downarrow \\
 (z, (x, y)) & & & & ((x, z), y) \\
 & \swarrow & & \swarrow & \\
 & ((z, x), y) & & ((z, x), y) &
 \end{array}$$

and thus the right hexagon identity is satisfied.

Monoidal Closedness

This follows from **Constructions With Sets, Item 2** of **Proposition 4.3.5.1.2**

Existence of Monoidal Diagonals

This follows from **Items 1** and **2** of **Proposition 5.1.8.1.3**. 

01P8 5.1.10 The Universal Property of $(\mathbf{Sets}, \times, \mathbf{pt})$ 01P9 THEOREM 5.1.10.1.1 ► THE UNIVERSAL PROPERTY OF $(\mathbf{Sets}, \times, \mathbf{pt})$

The symmetric monoidal structure on the category \mathbf{Sets} of **Proposition 5.1.9.1.1** is uniquely determined by the following requirements:

01PA 1. *Existence of an Internal Hom.* The tensor product

$$\otimes_{\mathbf{Sets}} : \mathbf{Sets} \times \mathbf{Sets} \rightarrow \mathbf{Sets}$$

of \mathbf{Sets} admits an internal Hom $[-1, -2]_{\mathbf{Sets}}$.

01PB 2. *The Unit Object Is pt.* We have $\mathbb{1}_{\mathbf{Sets}} \cong \mathbf{pt}$.

More precisely, the full subcategory of the category $\mathcal{M}_{\mathbf{E}_{\infty}}^{\text{cld}}(\mathbf{Sets})$ of ?? spanned by the closed symmetric monoidal categories $(\mathbf{Sets}, \otimes_{\mathbf{Sets}}, [-1, -2]_{\mathbf{Sets}}, \mathbb{1}_{\mathbf{Sets}}, \lambda^{\mathbf{Sets}}, \rho^{\mathbf{Sets}}, \sigma^{\mathbf{Sets}})$ satisfying **Items 1** and **2** is contractible (i.e. equivalent to the punctual category).

PROOF 5.1.10.1.2 ► PROOF OF THEOREM 5.1.10.1.1

Unwinding the Statement

Let $(\mathbf{Sets}, \otimes_{\mathbf{Sets}}, [-1, -2]_{\mathbf{Sets}}, \mathbb{1}_{\mathbf{Sets}}, \lambda', \rho', \sigma')$ be a closed symmetric monoidal category satisfying **Items 1** and **2**. We need to show that the identity functor

$$\text{id}_{\mathbf{Sets}} : \mathbf{Sets} \rightarrow \mathbf{Sets}$$

admits a *unique* closed symmetric monoidal functor structure

$$\begin{aligned} \text{id}_{\mathbf{Sets}}^{\otimes} : A \otimes_{\mathbf{Sets}} B &\xrightarrow{\sim} A \times B, \\ \text{id}_{\mathbf{Sets}}^{\text{Hom}} : [A, B]_{\mathbf{Sets}} &\xrightarrow{\sim} \mathbf{Sets}(A, B), \\ \text{id}_{\mathbb{1}_{\mathbf{Sets}}}^{\otimes} : \mathbb{1}_{\mathbf{Sets}} &\xrightarrow{\sim} \mathbf{pt}, \end{aligned}$$

making it into a symmetric monoidal strongly closed isomorphism of categories from $(\mathbf{Sets}, \otimes_{\mathbf{Sets}}, [-1, -2]_{\mathbf{Sets}}, \mathbb{1}_{\mathbf{Sets}}, \lambda', \rho', \sigma')$ to the closed symmetric monoidal category $(\mathbf{Sets}, \times, \mathbf{Sets}(-1, -2), \mathbb{1}_{\mathbf{Sets}}, \lambda^{\mathbf{Sets}}, \rho^{\mathbf{Sets}}, \sigma^{\mathbf{Sets}})$ of **Proposition 5.1.9.1.1**.

Constructing an Isomorphism $[-1, -2]_{\mathbf{Sets}} \cong \mathbf{Sets}(-1, -2)$

By ??, we have a natural isomorphism

$$\text{Sets}(\text{pt}, [-_1, -_2]_{\text{Sets}}) \cong \text{Sets}(-_1, -_2).$$

By **Constructions With Sets, Item 3** of **Proposition 4.3.5.1.2**, we also have a natural isomorphism

$$\text{Sets}(\text{pt}, [-_1, -_2]_{\text{Sets}}) \cong [-_1, -_2]_{\text{Sets}}.$$

Composing both natural isomorphisms, we obtain a natural isomorphism

$$\text{Sets}(-_1, -_2) \cong [-_1, -_2]_{\text{Sets}}.$$

Given $A, B \in \text{Obj}(\text{Sets})$, we will write

$$\text{id}_{A,B}^{\text{Hom}} : \text{Sets}(A, B) \xrightarrow{\sim} [A, B]_{\text{Sets}}$$

for the component of this isomorphism at (A, B) .

Constructing an Isomorphism $\otimes_{\text{Sets}} \cong \times$

Since \otimes_{Sets} is adjoint in each variable to $[-_1, -_2]_{\text{Sets}}$ by assumption and \times is adjoint in each variable to $\text{Sets}(-_1, -_2)$ by **Constructions With Sets, Item 2** of **Proposition 4.3.5.1.2**, uniqueness of adjoints (??) gives us natural isomorphisms

$$\begin{aligned} A \otimes_{\text{Sets}} - &\cong A \times -, \\ - \otimes_{\text{Sets}} B &\cong B \times -. \end{aligned}$$

By ??, we then have $\otimes_{\text{Sets}} \cong \times$. We will write

$$\text{id}_{\text{Sets}|A,B}^{\otimes} : A \otimes_{\text{Sets}} B \xrightarrow{\sim} A \times B$$

for the component of this isomorphism at (A, B) .

Alternative Construction of an Isomorphism $\otimes_{\text{Sets}} \cong \times$

Alternatively, we may construct a natural isomorphism $\otimes_{\text{Sets}} \cong \times$ as follows:

01PC

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

01PD

2. Since \otimes_{Sets} is part of a closed monoidal structure, it preserves colimits in each variable by ??.

01PE

3. Since $A \cong \coprod_{a \in A} \text{pt}$ and \otimes_{Sets} preserves colimits in each variable, we have

$$\begin{aligned} A \otimes_{\text{Sets}} B &\cong \left(\coprod_{a \in A} \text{pt} \right) \otimes_{\text{Sets}} B \\ &\cong \coprod_{a \in A} (\text{pt} \otimes_{\text{Sets}} B) \\ &\cong \coprod_{a \in A} B \\ &\cong A \times B, \end{aligned}$$

naturally in $B \in \text{Obj}(\text{Sets})$, where we have used that pt is the monoidal unit for \otimes_{Sets} . Thus $A \otimes_{\text{Sets}} - \cong A \times -$ for each $A \in \text{Obj}(\text{Sets})$.

01PF

4. Similarly, $- \otimes_{\text{Sets}} B \cong - \times B$ for each $B \in \text{Obj}(\text{Sets})$.

01PG

5. By ??, we then have $\otimes_{\text{Sets}} \cong \times$.

Below, we'll show that if a natural isomorphism $\otimes_{\text{Sets}} \cong \times$ exists, then it must be unique. This will show that the isomorphism constructed above is equal to the isomorphism $\text{id}_{\text{Sets}|A,B}^{\otimes} : A \otimes_{\text{Sets}} B \rightarrow A \times B$ from before.

Constructing an Isomorphism $\text{id}_{\mathbb{1}}^{\otimes} : \mathbb{1}_{\text{Sets}} \rightarrow \text{pt}$

We define an isomorphism $\text{id}_{\mathbb{1}}^{\otimes} : \mathbb{1}_{\text{Sets}} \rightarrow \text{pt}$ as the composition

$$\mathbb{1}_{\text{Sets}} \xrightarrow[\sim]{\rho_{\mathbb{1}_{\text{Sets}}}^{\text{Sets}, -1}} \mathbb{1}_{\text{Sets}} \times \text{pt} \xrightarrow[\sim]{\text{id}_{\text{Sets}|\mathbb{1}_{\text{Sets}}}^{\otimes}} \mathbb{1}_{\text{Sets}} \otimes_{\text{Sets}} \text{pt} \xrightarrow[\sim]{\lambda'_{\text{pt}}} \text{pt}$$

in Sets .

Monoidal Left Unity of the Isomorphism $\otimes_{\text{Sets}} \cong \times$

We have to show that the diagram

$$\begin{array}{ccc} & \text{pt} \otimes_{\text{Sets}} A & \xrightarrow{\text{id}_{\text{Sets}|\text{pt},A}^{\otimes}} \text{pt} \times A \\ \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes} \otimes_{\text{Sets}} \text{id}_A \nearrow & & \searrow \lambda_A^{\text{Sets}} \\ \mathbb{1}_{\text{Sets}} \otimes_{\text{Sets}} A & \xrightarrow{\lambda'_A} & A \end{array}$$

commutes. First, note that the diagram

$$\begin{array}{ccc}
 & \text{pt} \otimes_{\mathbf{Sets}} \text{pt} & \xrightarrow{\text{id}_{\mathbf{Sets}|\text{pt},\text{pt}}^{\otimes}} \text{pt} \times \text{pt} \\
 \text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes} \otimes_{\mathbf{Sets}} \text{id}_{\text{pt}} \nearrow & & \searrow \lambda_{\text{pt}}^{\mathbf{Sets}} \\
 \mathbb{1}_{\mathbf{Sets}} \otimes_{\mathbf{Sets}} \text{pt} & \xrightarrow{\lambda'_{\text{pt}}} & \text{pt},
 \end{array}$$

corresponding to the case $A = \text{pt}$, commutes by the terminality of pt (**Constructions With Sets, Construction 4.1.1.1.2**). Since this diagram commutes, so does the diagram

$$\begin{array}{ccc}
 & \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\mathbf{Sets}|\text{pt},\text{pt}}^{\otimes, -1}} \text{pt} \otimes_{\mathbf{Sets}} \text{pt} \\
 \lambda_{\text{pt}}^{\mathbf{Sets}, -1} \nearrow & & \searrow \text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \otimes_{\mathbf{Sets}} \text{id}_{\text{pt}} \\
 \text{pt} & \xrightarrow{\lambda'^{-1}_{\text{pt}}} & \mathbb{1}_{\mathbf{Sets}} \otimes_{\mathbf{Sets}} \text{pt}.
 \end{array}
 \quad (\dagger)$$

Now, let $A \in \text{Obj}(\mathbf{Sets})$, let $a \in A$, and consider the diagram

$$\begin{array}{ccccc}
 & \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\mathbf{Sets}|\text{pt},\text{pt}}^{\otimes, -1}} & \text{pt} \otimes_{\mathbf{Sets}} \text{pt} & \xrightarrow{\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \times \text{id}_{\text{pt}}} \mathbb{1}_{\mathbf{Sets}} \otimes_{\mathbf{Sets}} \text{pt} \\
 \lambda_{\text{pt}}^{\mathbf{Sets}, -1} \nearrow & & \text{(\dagger)} & & \searrow \\
 \text{pt} & \xrightarrow{\lambda'^{-1}_{\text{pt}}} & & & \\
 \downarrow [a] & \downarrow \text{id}_{\text{pt}} \times [a] & (1) & \downarrow \text{id}_{\text{pt}} \otimes_{\mathbf{Sets}} [a] & \downarrow \text{id}_{\mathbb{1}_{\mathbf{Sets}}} \times [a] \\
 & \text{pt} \times A & \xrightarrow{\text{id}_{\mathbf{Sets}|\text{pt}, A}^{\otimes, -1}} & \text{pt} \otimes_{\mathbf{Sets}} A & \\
 \downarrow \lambda_A^{\mathbf{Sets}, -1} & & (2) & & \downarrow \text{id}_{\mathbb{1}_{\mathbf{Sets}}} \times [a] \\
 A & \xrightarrow{\lambda'^{-1}_A} & & & \mathbb{1}_{\mathbf{Sets}} \otimes_{\mathbf{Sets}} A.
 \end{array}$$

(3) (4) (5)

Since:

- Subdiagram (5) commutes by the naturality of λ'^{-1} .

- Subdiagram (\dagger) commutes, as proved above.
- Subdiagram (4) commutes by the naturality of $\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1}$.
- Subdiagram (1) commutes by the naturality of $\text{id}_{\mathbf{Sets}}^{\otimes, -1}$.
- Subdiagram (3) commutes by the naturality of $\lambda^{\mathbf{Sets}, -1}$.

it follows that the diagram

$$\begin{array}{ccccc}
 & & \text{pt} \times A & \xrightarrow{\text{id}_{\mathbf{Sets}|\text{pt}, A}^{\otimes, -1}} & \text{pt} \otimes_{\mathbf{Sets}} A \\
 & \nearrow \lambda_A^{\mathbf{Sets}, -1} & & & \searrow \text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \otimes_{\mathbf{Sets}} \text{id}_A \\
 \text{pt} & \xrightarrow{[a]} & A & \xrightarrow{\lambda_A'^{-1}} & \mathbb{1}_{\mathbf{Sets}} \otimes_{\mathbf{Sets}} A
 \end{array}$$

Here's a step-by-step showcase of this argument: [\[Link\]](#). We then have

$$\begin{aligned}
 \lambda_A'^{-1}(a) &= [\lambda_A'^{-1} \circ [a]](\star) \\
 &= \left[\left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \times \text{id}_A \right) \circ \text{id}_{\mathbf{Sets}|\text{pt}, A}^{\otimes, -1} \circ \lambda_A^{\mathbf{Sets}, -1} \circ [a] \right](\star) \\
 &= \left[\left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \times \text{id}_A \right) \circ \text{id}_{\mathbf{Sets}|\text{pt}, A}^{\otimes, -1} \circ \lambda_A^{\mathbf{Sets}, -1} \right](a)
 \end{aligned}$$

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

$$\lambda_A'^{-1} = \left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \times \text{id}_A \right) \circ \text{id}_{\mathbf{Sets}|\text{pt}, A}^{\otimes, -1} \circ \lambda_A^{\mathbf{Sets}, -1}.$$

Taking inverses then gives

$$\lambda_A' = \lambda_A^{\mathbf{Sets}} \circ \text{id}_{\mathbf{Sets}|\text{pt}, A}^{\otimes} \circ \left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes} \times \text{id}_A \right),$$

showing that the diagram

$$\begin{array}{ccccc}
 & & \text{pt} \otimes_{\mathbf{Sets}} A & \xrightarrow{\text{id}_{\mathbf{Sets}|\text{pt}, A}^{\otimes}} & \text{pt} \times A \\
 & \nearrow \text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes} \otimes_{\mathbf{Sets}} \text{id}_A & & & \searrow \lambda_A^{\mathbf{Sets}} \\
 \mathbb{1}_{\mathbf{Sets}} \otimes_{\mathbf{Sets}} A & \xrightarrow{\lambda_A'} & & & A
 \end{array}$$

indeed commutes.

Monoidal Right Unity of the Isomorphism $\otimes_{\text{Sets}} \cong \times$

We can use the same argument we used to prove the monoidal left unity of the isomorphism $\otimes_{\text{Sets}} \cong \times$ above. For completeness, we repeat it below. We have to show that the diagram

$$\begin{array}{ccc}
 & A \otimes_{\text{Sets}} \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|A,\text{pt}}^{\otimes}} A \times \text{pt} \\
 \text{id}_A \otimes_{\text{Sets}} \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes} \nearrow & & \searrow \rho_A^{\text{Sets}} \\
 A \otimes_{\text{Sets}} \mathbb{1}_{\text{Sets}} & \xrightarrow{\rho'_A} & A
 \end{array}$$

commutes. First, note that the diagram

$$\begin{array}{ccc}
 & \text{pt} \otimes_{\text{Sets}} \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|\text{pt},\text{pt}}^{\otimes}} \text{pt} \times \text{pt} \\
 \text{id}_{\text{pt}} \otimes_{\text{Sets}} \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes} \nearrow & & \searrow \rho_{\text{pt}}^{\text{Sets}} \\
 \text{pt} \otimes_{\text{Sets}} \mathbb{1}_{\text{Sets}} & \xrightarrow{\rho'_{\text{pt}}} & \text{pt},
 \end{array}$$

corresponding to the case $A = \text{pt}$, commutes by the terminality of pt (**Constructions With Sets, Construction 4.1.1.1.2**). Since this diagram commutes, so does the diagram

$$\begin{array}{ccc}
 & \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|\text{pt},\text{pt}}^{\otimes,-1}} \text{pt} \otimes_{\text{Sets}} \text{pt} \\
 \rho_{\text{pt}}^{\text{Sets},-1} \nearrow & & \searrow \text{id}_{\text{pt}} \otimes_{\text{Sets}} \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes,-1} \\
 \text{pt} & \xrightarrow{\rho_{\text{pt}}'^{-1}} & \text{pt} \otimes_{\text{Sets}} \mathbb{1}_{\text{Sets}}.
 \end{array}
 \quad (\dagger)$$

Now, let $A \in \text{Obj}(\text{Sets})$, let $a \in A$, and consider the diagram

$$\begin{array}{ccccc}
 & & \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|\text{pt},\text{pt}}^{\otimes,-1}} & \text{pt} \otimes_{\text{Sets}} \text{pt} \\
 & \nearrow \rho_{\text{pt}}^{\text{Sets},-1} & \downarrow & \text{(\dagger)} & \downarrow \text{pt} \times \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes,-1} \\
 \text{pt} & \xrightarrow{\quad} & \text{pt} \times \text{pt} & \xrightarrow{\rho_{\text{pt}}'^{-1}} & \text{pt} \otimes_{\text{Sets}} \mathbb{1}_{\text{Sets}} \\
 & \downarrow \text{id}_{\text{pt}} \times [a] & \downarrow \text{id}_{\text{pt}} \otimes_{\text{Sets}} [a] & \downarrow \text{id}_{\mathbb{1}_{\text{Sets}}} \times [a] & \\
 & \text{(3)} & \text{(1)} & \text{(4)} & \\
 & \downarrow & \downarrow & \downarrow & \\
 & A \times \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|A,\text{pt}}^{\otimes,-1}} & A \otimes_{\text{Sets}} \text{pt} & \\
 & \nearrow \rho_A^{\text{Sets},-1} & \text{(5)} & \searrow \text{id}_A \times \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes,-1} & \\
 A & \xrightarrow{\quad} & A \times \text{pt} & \xrightarrow{\rho_A'^{-1}} & A \otimes_{\text{Sets}} \mathbb{1}_{\text{Sets}}
 \end{array}$$

Since:

- Subdiagram (5) commutes by the naturality of ρ'^{-1} .
- Subdiagram (\dagger) commutes, as proved above.
- Subdiagram (4) commutes by the naturality of $\text{id}_{\mathbb{1}|\text{Sets}}^{\otimes,-1}$.
- Subdiagram (1) commutes by the naturality of $\text{id}_{\text{Sets}}^{\otimes,-1}$.
- Subdiagram (3) commutes by the naturality of $\rho^{\text{Sets},-1}$.

it follows that the diagram

$$\begin{array}{ccccc}
 & & A \times \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|A,\text{pt}}^{\otimes,-1}} & A \otimes_{\text{Sets}} \text{pt} \\
 & \nearrow \rho_A^{\text{Sets},-1} & & & \searrow \text{id}_A \otimes_{\text{Sets}} \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes,-1} \\
 \text{pt} & \xrightarrow{[a]} & A & \xrightarrow{\rho_A'^{-1}} & A \otimes_{\text{Sets}} \mathbb{1}_{\text{Sets}}
 \end{array}$$

Here's a step-by-step showcase of this argument: [\[Link\]](#). We then have

$$\rho_A'^{-1}(a) = [\rho_A'^{-1} \circ [a]](\star)$$

$$\begin{aligned}
&= \left[\left(\text{id}_A \times \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes, -1} \right) \circ \text{id}_{\text{Sets}|\text{pt}, A}^{\otimes, -1} \circ \rho_A^{\text{Sets}, -1} \circ [a] \right] (\star) \\
&= \left[\left(\text{id}_A \times \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes, -1} \right) \circ \text{id}_{\text{Sets}|\text{pt}, A}^{\otimes, -1} \circ \rho_A^{\text{Sets}, -1} \right] (a)
\end{aligned}$$

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

$$\rho'_A{}^{-1} = \left(\text{id}_A \times \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes, -1} \right) \circ \text{id}_{\text{Sets}|\text{pt}, A}^{\otimes, -1} \circ \rho_A^{\text{Sets}, -1}.$$

Taking inverses then gives

$$\rho'_A = \rho_A^{\text{Sets}} \circ \text{id}_{\text{Sets}|\text{pt}, A}^{\otimes} \circ \left(\text{id}_A \times \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes} \right),$$

showing that the diagram

$$\begin{array}{ccc}
& A \otimes_{\text{Sets}} \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|A, \text{pt}}^{\otimes}} A \times \text{pt} \\
\text{id}_A \otimes_{\text{Sets}} \text{id}_{\mathbb{1}|\text{Sets}}^{\otimes} \nearrow & & \searrow \rho_A^{\text{Sets}} \\
A \otimes_{\text{Sets}} \mathbb{1}_{\text{Sets}} & \xrightarrow{\rho'_A} & A
\end{array}$$

indeed commutes.

Monoidality of the Isomorphism $\otimes_{\text{Sets}} \cong \times$

We have to show that the diagram

$$\begin{array}{ccc}
& (A \otimes_{\text{Sets}} B) \otimes_{\text{Sets}} C & \\
\text{id}_{\text{Sets}|A, B}^{\otimes} \otimes_{\text{Sets}} \text{id}_C^{\otimes} \swarrow & & \searrow \alpha'_{A, B, C} \\
(A \times B) \otimes_{\text{Sets}} C & & A \otimes_{\text{Sets}} (B \otimes_{\text{Sets}} C) \\
\downarrow \text{id}_{\text{Sets}|A \times B, C}^{\otimes} & & \downarrow \text{id}_A \otimes_{\text{Sets}} \text{id}_{\text{Sets}|B, C}^{\otimes} \\
(A \times B) \times C & & A \otimes_{\text{Sets}} (B \times C) \\
\searrow \alpha_{A, B, C}^{\text{Sets}} & & \swarrow \text{id}_{\text{Sets}|A, B \times C}^{\otimes} \\
& A \times (B \times C) &
\end{array}$$

commutes. First, note that the diagram

$$\begin{array}{ccc}
 & (\text{pt} \otimes_{\text{Sets}} \text{pt}) \otimes_{\text{Sets}} \text{pt} & \\
 \text{id}_{\text{Sets}|\text{pt},\text{pt}}^{\otimes} \otimes_{\text{Sets}} \text{id}_{\text{pt}} \swarrow & & \searrow \alpha'_{\text{pt},\text{pt},\text{pt}} \\
 (\text{pt} \times \text{pt}) \otimes_{\text{Sets}} \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \otimes_{\text{Sets}} \text{pt}) \\
 \downarrow \text{id}_{\text{Sets}|\text{pt} \times \text{pt},\text{pt}}^{\otimes} & & \downarrow \text{id}_{\text{pt}} \otimes_{\text{Sets}} \text{id}_{\text{Sets}|\text{pt},\text{pt}}^{\otimes} \\
 (\text{pt} \times \text{pt}) \times \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \times \text{pt}) \\
 \searrow \alpha_{\text{pt},\text{pt},\text{pt}}^{\text{Sets}} & & \swarrow \text{id}_{\text{Sets}|\text{pt},\text{pt} \times \text{pt}}^{\otimes} \\
 & \text{pt} \times (\text{pt} \times \text{pt}) & \\
 & \downarrow !_{\text{pt} \times (\text{pt} \times \text{pt})} & \\
 & \text{pt} &
 \end{array}$$

commutes by the terminality of pt (**Constructions With Sets, Construction 4.1.1.1.2**). Since the map $!_{\text{pt} \times (\text{pt} \times \text{pt})} : \text{pt} \times (\text{pt} \times \text{pt}) \rightarrow \text{pt}$ is an isomorphism (e.g. having inverse $\lambda_{\text{pt}}^{\text{Sets}, -1} \circ \lambda_{\text{pt}}^{\text{Sets}, -1}$), it follows that the diagram

$$\begin{array}{ccc}
 & (\text{pt} \otimes_{\text{Sets}} \text{pt}) \otimes_{\text{Sets}} \text{pt} & \\
 \text{id}_{\text{Sets}|\text{pt},\text{pt}}^{\otimes} \otimes_{\text{Sets}} \text{id}_{\text{pt}} \swarrow & & \searrow \alpha'_{\text{pt},\text{pt},\text{pt}} \\
 (\text{pt} \times \text{pt}) \otimes_{\text{Sets}} \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \otimes_{\text{Sets}} \text{pt}) \\
 \downarrow \text{id}_{\text{Sets}|\text{pt} \times \text{pt},\text{pt}}^{\otimes} & & \downarrow \text{id}_{\text{pt}} \otimes_{\text{Sets}} \text{id}_{\text{Sets}|\text{pt},\text{pt}}^{\otimes} \\
 (\text{pt} \times \text{pt}) \times \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \times \text{pt}) \\
 \searrow \alpha_{\text{pt},\text{pt},\text{pt}}^{\text{Sets}} & & \swarrow \text{id}_{\text{Sets}|\text{pt},\text{pt} \times \text{pt}}^{\otimes} \\
 & \text{pt} \times (\text{pt} \times \text{pt}) &
 \end{array}$$

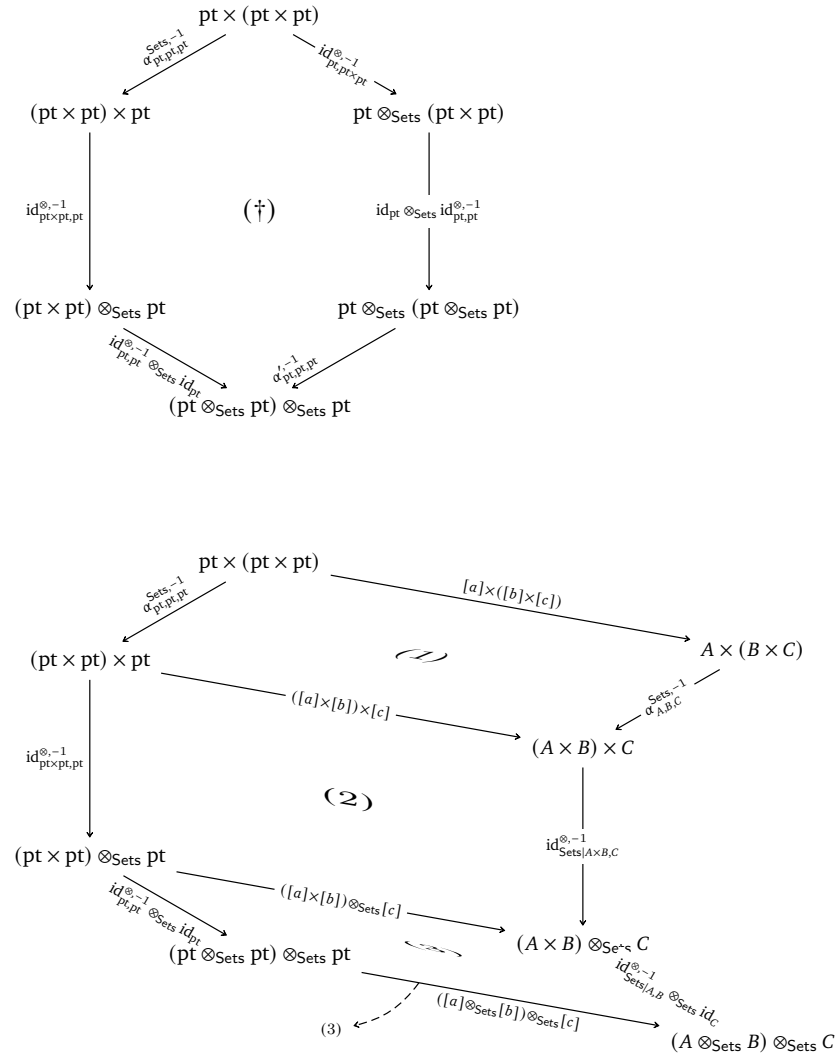
also commutes. Taking inverses, we see that the diagram

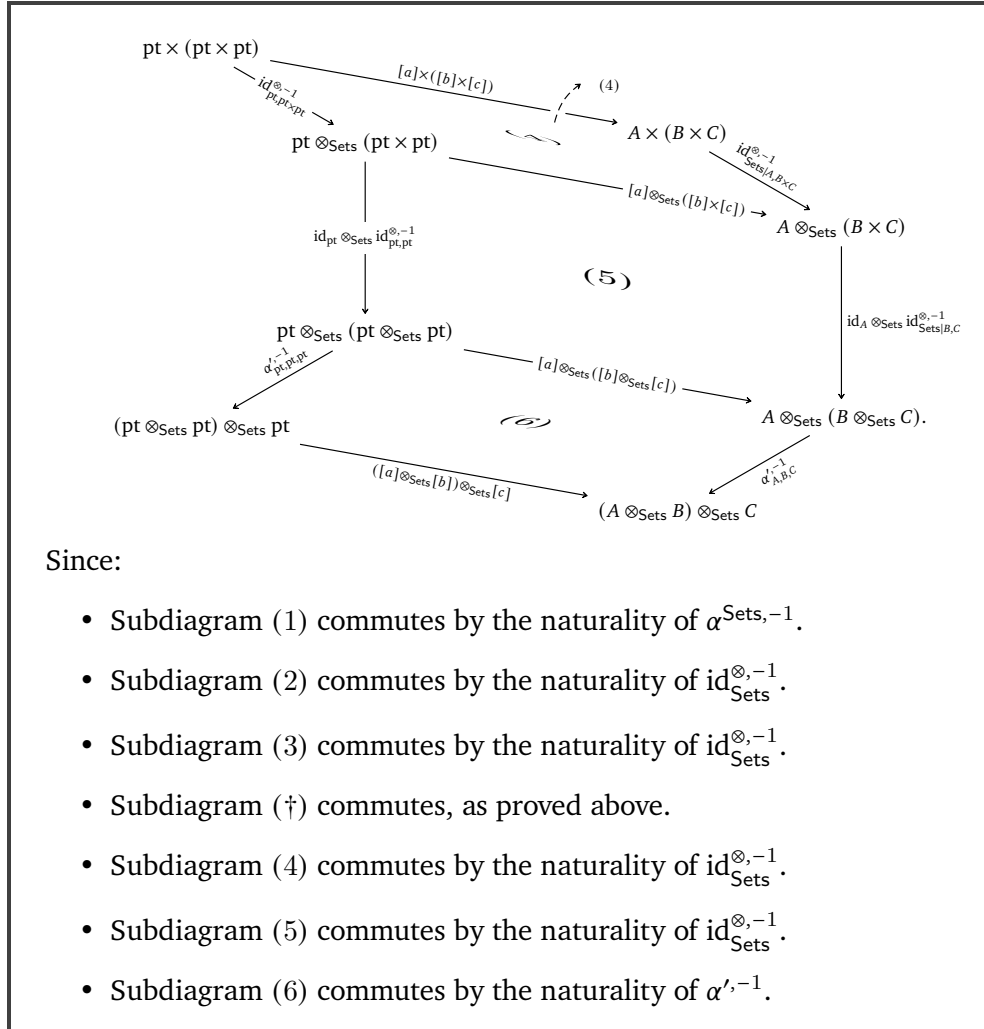
$$\begin{array}{ccc}
 & \text{pt} \times (\text{pt} \times \text{pt}) & \\
 \alpha_{\text{pt}, \text{pt}, \text{pt}}^{\text{Sets}, -1} \swarrow & & \searrow \text{id}_{\text{Sets}|\text{pt}, \text{pt} \times \text{pt}}^{\otimes, -1} \\
 (\text{pt} \times \text{pt}) \times \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \times \text{pt}) \\
 \downarrow \text{id}_{\text{Sets}|\text{pt} \times \text{pt}, \text{pt}}^{\otimes, -1} & (+) & \downarrow \text{id}_{\text{pt}} \otimes_{\text{Sets}} \text{id}_{\text{Sets}|\text{pt}, \text{pt}}^{\otimes, -1} \\
 (\text{pt} \times \text{pt}) \otimes_{\text{Sets}} \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \otimes_{\text{Sets}} \text{pt}) \\
 \downarrow \text{id}_{\text{Sets}|\text{pt}, \text{pt}}^{\otimes, -1} \otimes_{\text{Sets}} \text{id}_{\text{pt}} & & \downarrow \alpha_{\text{pt}, \text{pt}, \text{pt}}^{\prime, -1} \\
 (\text{pt} \otimes_{\text{Sets}} \text{pt}) \otimes_{\text{Sets}} \text{pt} & & (\text{pt} \otimes_{\text{Sets}} \text{pt}) \otimes_{\text{Sets}} \text{pt}
 \end{array}$$

commutes as well. Now, let $A, B, C \in \text{Obj}(\text{Sets})$, let $a \in A$, let $b \in B$, let $c \in C$, and consider the diagram

$$\begin{array}{ccccccc}
 & \text{pt} \times (\text{pt} \times \text{pt}) & & & & & \\
 \alpha_{\text{pt}, \text{pt}, \text{pt}}^{\text{Sets}, -1} \swarrow & & \downarrow \text{id}_{\text{pt}, \text{pt} \times \text{pt}}^{\otimes, -1} & & \searrow [a] \times ([b] \times [c]) & & \\
 (\text{pt} \times \text{pt}) \times \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \times \text{pt}) & & A \times (B \times C) & & \\
 \downarrow \text{id}_{\text{pt} \times \text{pt}, \text{pt}}^{\otimes, -1} & & \downarrow ([a] \times [b]) \times [c] & & \downarrow \alpha_{A, B, C}^{\text{Sets}, -1} & & \downarrow \text{id}_{\text{Sets}|A, B \times C}^{\otimes, -1} \\
 (\text{pt} \times \text{pt}) \otimes_{\text{Sets}} \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \otimes_{\text{Sets}} \text{pt}) & & (A \times B) \times C & & A \otimes_{\text{Sets}} (B \times C) \\
 \downarrow \text{id}_{\text{pt}, \text{pt}}^{\otimes, -1} \otimes_{\text{Sets}} \text{id}_{\text{pt}} & & \downarrow \text{id}_{\text{pt}} \otimes_{\text{Sets}} \text{id}_{\text{pt}, \text{pt}}^{\otimes, -1} & & \downarrow \text{id}_{\text{Sets}|A \times B, C}^{\otimes, -1} & & \downarrow \text{id}_A \otimes_{\text{Sets}} \text{id}_{\text{Sets}|B, C}^{\otimes, -1} \\
 (\text{pt} \otimes_{\text{Sets}} \text{pt}) \otimes_{\text{Sets}} \text{pt} & & \text{pt} \otimes_{\text{Sets}} (\text{pt} \otimes_{\text{Sets}} \text{pt}) & & (A \times B) \otimes_{\text{Sets}} C & & A \otimes_{\text{Sets}} (B \otimes_{\text{Sets}} C) \\
 \downarrow \text{id}_{\text{pt}, \text{pt}}^{\otimes, -1} \otimes_{\text{Sets}} \text{id}_{\text{pt}} & & \downarrow ([a] \times [b]) \otimes_{\text{Sets}} [c] & & \downarrow [a] \otimes_{\text{Sets}} ([b] \otimes_{\text{Sets}} [c]) & & \downarrow \alpha_{A, B, C}^{\prime, -1} \\
 (\text{pt} \otimes_{\text{Sets}} \text{pt}) \otimes_{\text{Sets}} \text{pt} & & (A \times B) \otimes_{\text{Sets}} C & & A \otimes_{\text{Sets}} (B \otimes_{\text{Sets}} C) & & \\
 \downarrow ([a] \otimes_{\text{Sets}} [b]) \otimes_{\text{Sets}} [c] & & \downarrow ([a] \otimes_{\text{Sets}} [b]) \otimes_{\text{Sets}} [c] & & \downarrow \alpha_{A, B, C}^{\prime, -1} & & \\
 (A \otimes_{\text{Sets}} B) \otimes_{\text{Sets}} C & & (A \otimes_{\text{Sets}} B) \otimes_{\text{Sets}} C & & (A \otimes_{\text{Sets}} B) \otimes_{\text{Sets}} C & &
 \end{array}$$

which we partition into subdiagrams as follows:





it follows that the diagram

$$\begin{array}{ccc}
 & \text{pt} \times (\text{pt} \times \text{pt}) & \\
 & \downarrow & \\
 & [a] \times ([b] \times [c]) & \\
 & \downarrow & \\
 & A \times (B \times C) & \\
 \alpha_{A,B,C}^{\text{Sets}, -1} \swarrow & & \searrow \text{id}_{\text{Sets}|A, B \times C}^{\otimes, -1} \\
 (A \times B) \times C & & A \otimes_{\text{Sets}} (B \times C) \\
 \downarrow \text{id}_{\text{Sets}|A \times B, C}^{\otimes, -1} & & \downarrow \text{id}_A \times \text{id}_{\text{Sets}|B, C}^{\otimes, -1} \\
 (A \times B) \otimes_{\text{Sets}} C & & A \otimes_{\text{Sets}} (B \otimes_{\text{Sets}} C) \\
 \downarrow \text{id}_{\text{Sets}|A, B}^{\otimes, -1} \otimes_{\text{Sets}} \text{id}_C & & \downarrow \alpha'_{A,B,C}{}^{\otimes, -1} \\
 & (A \otimes_{\text{Sets}} B) \otimes_{\text{Sets}} C &
 \end{array}$$

also commutes. We then have

$$\begin{aligned}
 & \left[\left(\text{id}_{\text{Sets}|A, B}^{\otimes, -1} \otimes_{\text{Sets}} \text{id}_C \right) \circ \text{id}_{\text{Sets}|A \times B, C}^{\otimes, -1} \right. \\
 & \quad \left. \circ \alpha_{A,B,C}^{\text{Sets}, -1} \right] (a, (b, c)) = \left[\left(\text{id}_{\text{Sets}|A, B}^{\otimes, -1} \otimes_{\text{Sets}} \text{id}_C \right) \circ \text{id}_{\text{Sets}|A \times B, C}^{\otimes, -1} \right. \\
 & \quad \left. \circ \alpha_{A,B,C}^{\text{Sets}, -1} \circ ([a] \times ([b] \times [c])) \right] (\star, (\star, \star)) \\
 & = \left[\alpha'_{A,B,C}{}^{\otimes, -1} \circ \left(\text{id}_A \times \text{id}_{\text{Sets}|B, C}^{\otimes, -1} \right) \right. \\
 & \quad \left. \circ \text{id}_{\text{Sets}|A, B \times C}^{\otimes, -1} \circ ([a] \times ([b] \times [c])) \right] (\star, (\star, \star)) \\
 & = \left[\alpha'_{A,B,C}{}^{\otimes, -1} \circ \left(\text{id}_A \times \text{id}_{\text{Sets}|B, C}^{\otimes, -1} \right) \circ \text{id}_{\text{Sets}|A, B \times C}^{\otimes, -1} \right] (a, (b, c))
 \end{aligned}$$

for each $(a, (b, c)) \in A \times (B \times C)$, and thus we have

$$\left(\text{id}_{\text{Sets}|A, B}^{\otimes, -1} \otimes_{\text{Sets}} \text{id}_C \right) \circ \text{id}_{\text{Sets}|A \times B, C}^{\otimes, -1} \circ \alpha_{A,B,C}^{\text{Sets}, -1} = \alpha'_{A,B,C}{}^{\otimes, -1} \circ \left(\text{id}_A \times \text{id}_{\text{Sets}|B, C}^{\otimes, -1} \right) \circ \text{id}_{\text{Sets}|A, B \times C}^{\otimes, -1}.$$

Taking inverses then gives

$$\alpha_{A,B,C}^{\text{Sets}} \circ \text{id}_{\text{Sets}|A \times B, C}^{\otimes} \circ \left(\text{id}_{\text{Sets}|A, B}^{\otimes} \otimes_{\text{Sets}} \text{id}_C \right) = \text{id}_{\text{Sets}|A, B \times C}^{\otimes} \circ \left(\text{id}_A \times \text{id}_{\text{Sets}|B, C}^{\otimes} \right) \circ \alpha'_{A,B,C},$$

showing that the diagram

$$\begin{array}{ccc}
 (A \otimes_{\text{Sets}} B) \otimes_{\text{Sets}} C & & \\
 \text{id}_{\text{Sets}|A,B}^{\otimes} \otimes_{\text{Sets}} \text{id}_C \swarrow & & \searrow \alpha'_{A,B,C} \\
 (A \times B) \otimes_{\text{Sets}} C & & A \otimes_{\text{Sets}} (B \otimes_{\text{Sets}} C) \\
 \downarrow \text{id}_{\text{Sets}|A \times B,C}^{\otimes} & & \downarrow \text{id}_A \otimes_{\text{Sets}} \text{id}_{\text{Sets}|B,C}^{\otimes} \\
 (A \times B) \times C & & A \otimes_{\text{Sets}} (B \times C) \\
 \searrow \alpha_{A,B,C}^{\text{Sets}} & & \swarrow \text{id}_{\text{Sets}|A,B \times C}^{\otimes} \\
 & A \times (B \times C) &
 \end{array}$$

indeed commutes.

Braidedness of the Isomorphism $\otimes_{\text{Sets}} \cong \times$

We have to show that the diagram

$$\begin{array}{ccc}
 A \otimes_{\text{Sets}} B & \xrightarrow{\text{id}_{\text{Sets}|A,B}^{\otimes}} & A \times B \\
 \sigma'_{A,B} \downarrow & & \downarrow \sigma_{A,B}^{\text{Sets}} \\
 B \otimes_{\text{Sets}} A & \xrightarrow{\text{id}_{\text{Sets}|B,A}^{\otimes}} & B \times A
 \end{array}$$

commutes. First, note that the diagram

$$\begin{array}{ccc}
 \text{pt} \otimes_{\text{Sets}} \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|pt,pt}^{\otimes}} & \text{pt} \times \text{pt} \\
 \sigma'_{pt,pt} \downarrow & & \downarrow \sigma_{pt,pt}^{\text{Sets}} \\
 \text{pt} \otimes_{\text{Sets}} \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|pt,pt}^{\otimes}} & \text{pt} \times \text{pt} \\
 & & \searrow !_{\text{pt} \times \text{pt}} \\
 & & \text{pt}
 \end{array}$$

commutes by the terminality of pt (**Constructions With Sets, Construction 4.1.1.1.2**). Since the map $!_{\text{pt} \times \text{pt}}: \text{pt} \times \text{pt} \rightarrow \text{pt}$ is invertible (e.g. with

inverse $\lambda_{\text{pt}}^{\text{Sets}, -1}$), the diagram

$$\begin{array}{ccc} \text{pt} \otimes_{\text{Sets}} \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|\text{pt}, \text{pt}}^{\otimes}} & \text{pt} \times \text{pt} \\ \sigma'_{\text{pt}, \text{pt}} \downarrow & & \downarrow \sigma_{\text{pt}, \text{pt}}^{\text{Sets}} \\ \text{pt} \otimes_{\text{Sets}} \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|\text{pt}, \text{pt}}^{\otimes}} & \text{pt} \times \text{pt} \end{array}$$

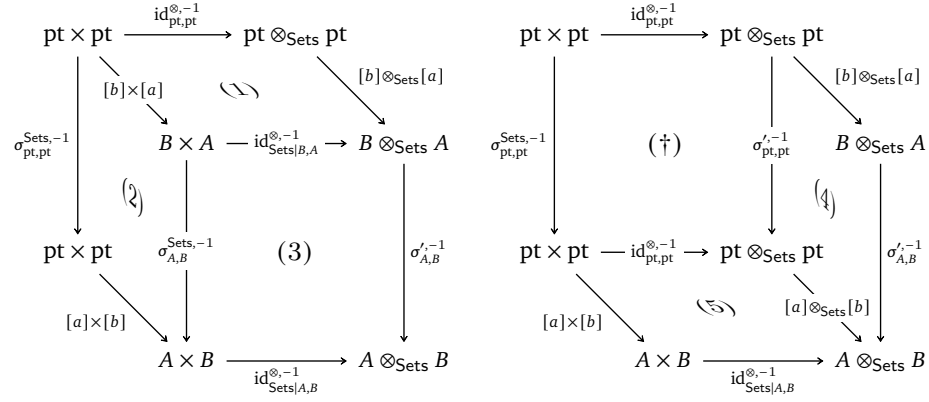
also commutes. Taking inverses, we see that the diagram

$$\begin{array}{ccc} \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|\text{pt}, \text{pt}}^{\otimes, -1}} & \text{pt} \otimes_{\text{Sets}} \text{pt} \\ \sigma_{\text{pt}, \text{pt}}^{\text{Sets}, -1} \downarrow & (\dagger) & \downarrow \sigma'_{\text{pt}, \text{pt}}{}^{-1} \\ \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\text{Sets}|\text{pt}, \text{pt}}^{\otimes, -1}} & \text{pt} \otimes_{\text{Sets}} \text{pt} \end{array}$$

commutes as well. Now, let $A, B \in \text{Obj}(\text{Sets})$, let $a \in A$, let $b \in B$, and consider the diagram

$$\begin{array}{ccccc} \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\text{pt}, \text{pt}}^{\otimes, -1}} & \text{pt} \otimes_{\text{Sets}} \text{pt} & & \\ \downarrow \sigma_{\text{pt}, \text{pt}}^{\text{Sets}, -1} & \searrow [b] \times [a] & \downarrow \sigma'_{\text{pt}, \text{pt}}{}^{-1} & \searrow [b] \otimes_{\text{Sets}} [a] & \\ & B \times A & \xrightarrow{\text{id}_{\text{Sets}|B, A}^{\otimes, -1}} & B \otimes_{\text{Sets}} A & \\ & \downarrow \sigma_{A, B}^{\text{Sets}, -1} & \downarrow & \downarrow \sigma'_{A, B}{}^{-1} & \\ \text{pt} \times \text{pt} & \xrightarrow{\text{id}_{\text{pt}, \text{pt}}^{\otimes, -1}} & \text{pt} \otimes_{\text{Sets}} \text{pt} & & \\ \searrow [a] \times [b] & \downarrow & \searrow [a] \otimes_{\text{Sets}} [b] & & \\ & A \times B & \xrightarrow{\text{id}_{\text{Sets}|A, B}^{\otimes, -1}} & A \otimes_{\text{Sets}} B & \end{array}$$

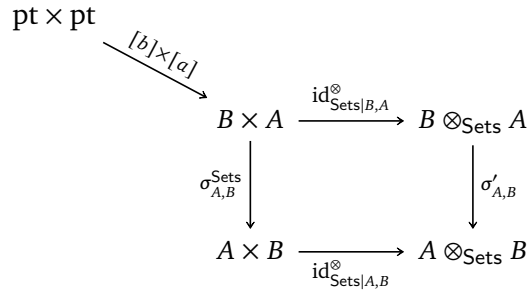
which we partition into subdiagrams as follows:



Since:

- Subdiagram (2) commutes by the naturality of $\sigma^{\text{Sets}, -1}$.
- Subdiagram (5) commutes by the naturality of $\text{id}^{\otimes, -1}$.
- Subdiagram (\dagger) commutes, as proved above.
- Subdiagram (4) commutes by the naturality of σ'^{-1} .
- Subdiagram (1) commutes by the naturality of $\text{id}^{\otimes, -1}$.

it follows that the diagram



commutes. We then have

$$\left[\text{id}_{\text{Sets}|A, B}^{\otimes, -1} \circ \sigma_{A, B}^{\text{Sets}, -1} \right] (b, a) = \left[\text{id}_{\text{Sets}|A, B}^{\otimes, -1} \circ \sigma_{A, B}^{\text{Sets}, -1} \circ ([b] \times [a]) \right] (\star, \star)$$

$$\begin{aligned}
&= \left[\sigma'_{A,B}{}^{-1} \circ \text{id}_{\mathbf{Sets}|B,A}^{\otimes, -1} \circ ([b] \times [a]) \right] (\star, \star) \\
&= \left[\sigma'_{A,B}{}^{-1} \circ \text{id}_{\mathbf{Sets}|B,A}^{\otimes, -1} \right] (b, a)
\end{aligned}$$

for each $(b, a) \in B \times A$, and thus we have

$$\text{id}_{\mathbf{Sets}|A,B}^{\otimes, -1} \circ \sigma_{A,B}^{\mathbf{Sets}, -1} = \sigma'_{A,B}{}^{-1} \circ \text{id}_{\mathbf{Sets}|B,A}^{\otimes, -1}.$$

Taking inverses then gives

$$\sigma_{A,B}^{\mathbf{Sets}} \circ \text{id}_{\mathbf{Sets}|A,B}^{\otimes} = \text{id}_{\mathbf{Sets}|B,A}^{\otimes} \circ \sigma'_{A,B},$$

showing that the diagram

$$\begin{array}{ccc}
A \otimes_{\mathbf{Sets}} B & \xrightarrow{\text{id}_{\mathbf{Sets}|A,B}^{\otimes}} & A \times B \\
\sigma'_{A,B} \downarrow & & \downarrow \sigma_{A,B}^{\mathbf{Sets}} \\
B \otimes_{\mathbf{Sets}} A & \xrightarrow{\text{id}_{\mathbf{Sets}|B,A}^{\otimes}} & B \times A
\end{array}$$

indeed commutes.

Uniqueness of the Isomorphism $\otimes_{\mathbf{Sets}} \cong \times$

Let $\phi, \psi: -_1 \otimes_{\mathbf{Sets}} -_2 \Rightarrow -_1 \times -_2$ be natural isomorphisms. Since these isomorphisms are compatible with the unitors of \mathbf{Sets} with respect to \times and \otimes (as shown above), we have

$$\begin{aligned}
\lambda'_B &= \lambda_B^{\mathbf{Sets}} \circ \phi_{\text{pt}, B} \circ \left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes} \otimes_{\mathbf{Sets}} \text{id}_Y \right), \\
\lambda'_B &= \lambda_B^{\mathbf{Sets}} \circ \psi_{\text{pt}, B} \circ \left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes} \otimes_{\mathbf{Sets}} \text{id}_Y \right).
\end{aligned}$$

Postcomposing both sides with $\lambda_B^{\mathbf{Sets}, -1}$ gives

$$\begin{aligned}
\lambda_B^{\mathbf{Sets}, -1} \circ \lambda'_B &\circ \left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \otimes_{\mathbf{Sets}} \text{id}_Y \right) = \phi_{\text{pt}, B}, \\
\lambda_B^{\mathbf{Sets}, -1} \circ \lambda'_B &\circ \left(\text{id}_{\mathbb{1}|\mathbf{Sets}}^{\otimes, -1} \otimes_{\mathbf{Sets}} \text{id}_Y \right) = \psi_{\text{pt}, B},
\end{aligned}$$

and thus we have

$$\phi_{\text{pt}, B} = \psi_{\text{pt}, B}$$

for each $B \in \text{Obj}(\text{Sets})$. Now, let $a \in A$ and consider the naturality diagrams


$$\begin{array}{ccc}
 \text{pt} \times B & \xrightarrow{[a] \times \text{id}_B} & A \times B \\
 \downarrow \phi_{\text{pt}, B} & & \downarrow \phi_{A, B} \\
 \text{pt} \otimes_{\text{Sets}} B & \xrightarrow{[a] \otimes_{\text{Sets}} \text{id}_B} & A \otimes_{\text{Sets}} B
 \end{array}
 \quad
 \begin{array}{ccc}
 \text{pt} \times B & \xrightarrow{[a] \times \text{id}_B} & A \times B \\
 \downarrow \psi_{\text{pt}, B} & & \downarrow \psi_{A, B} \\
 \text{pt} \otimes_{\text{Sets}} B & \xrightarrow{[a] \otimes_{\text{Sets}} \text{id}_B} & A \otimes_{\text{Sets}} B
 \end{array}$$

for ϕ and ψ with respect to the morphisms $[a]$ and id_B . Having shown that $\phi_{\text{pt}, B} = \psi_{\text{pt}, B}$, we have

$$\begin{aligned}
 \phi_{A, B}(a, b) &= [\phi_{A, B} \circ ([a] \times \text{id}_B)](\star, b) \\
 &= [([a] \otimes_{\text{Sets}} \text{id}_B) \circ \phi_{\text{pt}, B}](\star, b) \\
 &= [([a] \otimes_{\text{Sets}} \text{id}_B) \circ \psi_{\text{pt}, B}](\star, b) \\
 &= [\psi_{A, B} \circ ([a] \times \text{id}_B)](\star, b) \\
 &= \psi_{A, B}(a, b)
 \end{aligned}$$

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

$$\phi_{A, B} = \psi_{A, B}$$

for each $A, B \in \text{Obj}(\text{Sets})$ and thus $\phi = \psi$, showing the isomorphism $\otimes_{\text{Sets}} \cong \times$ to be unique. 

01PH

COROLLARY 5.1.10.1.3 ► A SECOND UNIVERSAL PROPERTY FOR $(\text{Sets}, \times, \text{pt})$

The symmetric monoidal structure on the category Sets of **Proposition 5.1.9.1.1** is uniquely determined by the following requirements:

01PJ

1. *Two-Sided Preservation of Colimits.* The tensor product

$$\otimes_{\text{Sets}} : \text{Sets} \times \text{Sets} \rightarrow \text{Sets}$$

of Sets preserves colimits separately in each variable.


01PK

2. *The Unit Object Is pt.* We have $\mathbb{1}_{\text{Sets}} \cong \text{pt}$.

More precisely, the full subcategory of the category $\mathcal{M}_{\mathbb{B}_{\infty}}(\text{Sets})$ of ?? spanned by the symmetric monoidal categories $(\text{Sets}, \otimes_{\text{Sets}}, \mathbb{1}_{\text{Sets}}, \lambda^{\text{Sets}}, \rho^{\text{Sets}}, \sigma^{\text{Sets}})$ satisfying **Items 1** and **2** is contractible.

|

|

Since \mathbf{Sets} is locally presentable (??), it follows from ?? that **Item 1** is equivalent to the existence of an internal Hom as in **Item 1** of **Theorem 5.1.10.1.1**. The result then follows from **Theorem 5.1.10.1.1**. 

01PL 5.2 The Monoidal Category of Sets and Coproducts

01PM 5.2.1 Coproducts of Sets

See **Constructions With Sets, Section 4.2.3**.

01PN 5.2.2 The Monoidal Unit

01PP DEFINITION 5.2.2.1.1 ► THE MONOIDAL UNIT OF \coprod

The **monoidal unit of the coproduct of sets** is the functor

$$\mathbb{0}^{\mathbf{Sets}} : \mathbf{pt} \rightarrow \mathbf{Sets}$$

defined by

$$\mathbb{0}_{\mathbf{Sets}} \stackrel{\text{def}}{=} \emptyset,$$

where \emptyset is the empty set of **Constructions With Sets, Definition 4.3.1.1.1**.

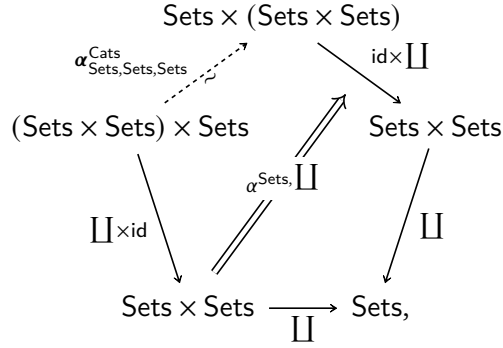
01PQ 5.2.3 The Associator

01PR DEFINITION 5.2.3.1.1 ► THE ASSOCIATOR OF \coprod

The **associator of the coproduct of sets** is the natural isomorphism

$$\alpha^{\mathbf{Sets}, \coprod} : \coprod \circ (\coprod \times \text{id}_{\mathbf{Sets}}) \xrightarrow{\sim} \coprod \circ (\text{id}_{\mathbf{Sets}} \times \coprod) \circ \alpha_{\mathbf{Sets}, \mathbf{Sets}, \mathbf{Sets}}^{\mathbf{Cats}},$$

as in the diagram



whose component

$$\alpha_{X,Y,Z}^{\text{Sets}, \sqcup} : (X \sqcup Y) \sqcup Z \xrightarrow{\sim} X \sqcup (Y \sqcup Z)$$

at (X, Y, Z) is given by

$$\alpha_{X,Y,Z}^{\text{Sets}, \sqcup}(a) \stackrel{\text{def}}{=} \begin{cases} (0, x) & \text{if } a = (0, (0, x)), \\ (1, (0, y)) & \text{if } a = (0, (1, y)), \\ (1, (1, a)) & \text{if } a = (1, z) \end{cases}$$

for each $a \in (X \sqcup Y) \sqcup Z$.

PROOF 5.2.3.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.2.3.1.1

Unwinding the Definitions of $(X \sqcup Y) \sqcup Z$ and $X \sqcup (Y \sqcup Z)$

Firstly, we unwind the expressions for $(X \sqcup Y) \sqcup Z$ and $X \sqcup (Y \sqcup Z)$. We have

$$\begin{aligned} (X \sqcup Y) \sqcup Z &\stackrel{\text{def}}{=} \{(0, a) \in S \mid a \in X \sqcup Y\} \cup \{(1, z) \in S \mid z \in Z\} \\ &= \{(0, (0, x)) \in S \mid x \in X\} \cup \{(0, (1, y)) \in S \mid y \in Y\} \\ &\quad \cup \{(1, z) \in S \mid z \in Z\}, \end{aligned}$$

where $S = \{0, 1\} \times ((X \sqcup Y) \cup Z)$ and

$$X \sqcup (Y \sqcup Z) \stackrel{\text{def}}{=} \{(0, x) \in S' \mid x \in X\} \cup \{(1, a) \in S' \mid a \in Y \sqcup Z\}$$

$$= \{(0, x) \in S' \mid x \in X\} \cup \{(1, (0, y)) \in S' \mid y \in Y\} \\ \cup \{(1, (1, z)) \in S' \mid z \in Z\},$$

where $S' = \{0, 1\} \times (X \cup (Y \amalg Z))$.

Invertibility

The inverse of $\alpha_{X,Y,Z}^{\text{Sets}, \amalg}$ is the map

$$\alpha_{X,Y,Z}^{\text{Sets}, \amalg, -1} : X \amalg (Y \amalg Z) \rightarrow (X \amalg Y) \amalg Z$$

given by

$$\alpha_{X,Y,Z}^{\text{Sets}, \amalg, -1}(a) \stackrel{\text{def}}{=} \begin{cases} (0, (0, x)) & \text{if } a = (0, x), \\ (0, (1, y)) & \text{if } a = (1, (0, y)), \\ (1, z) & \text{if } a = (1, (1, z)) \end{cases}$$

for each $a \in X \amalg (Y \amalg Z)$. Indeed:

- *Invertibility I.* The map $\alpha_{X,Y,Z}^{\text{Sets}, \amalg, -1} \circ \alpha_{X,Y,Z}^{\text{Sets}, \amalg}$ acts on elements as

$$\begin{aligned} (0, (0, x)) &\mapsto (0, x) \mapsto (0, (0, x)), \\ (0, (0, y)) &\mapsto (1, (0, y)) \mapsto (0, (0, y)), \\ (1, z) &\mapsto (1, (1, z)) \mapsto (1, z) \end{aligned}$$

and hence is equal to the identity map of $(X \amalg Y) \amalg Z$.

- *Invertibility II.* The map $\alpha_{X,Y,Z}^{\text{Sets}, \amalg} \circ \alpha_{X,Y,Z}^{\text{Sets}, \amalg, -1}$ acts on elements as

$$\begin{aligned} (0, x) &\mapsto (0, (0, x)) \mapsto (0, x), \\ (1, (0, y)) &\mapsto (0, (0, y)) \mapsto (1, (0, y)), \\ (1, (1, z)) &\mapsto (1, z) \mapsto (1, (1, z)) \end{aligned}$$

and hence is equal to the identity map of $X \amalg (Y \amalg Z)$.

Therefore $\alpha_{X,Y,Z}^{\text{Sets}, \amalg}$ is indeed an isomorphism.

Naturality

We need to show that, given functions

$$f: X \rightarrow X',$$

$$g: Y \rightarrow Y',$$

$$h: Z \rightarrow Z'$$

the diagram


$$\begin{array}{ccc} (X \amalg Y) \amalg Z & \xrightarrow{(f \amalg g) \amalg h} & (X' \amalg Y') \amalg Z' \\ \downarrow \alpha_{X,Y,Z}^{\text{Sets}, \amalg} & & \downarrow \alpha_{X',Y',Z'}^{\text{Sets}, \amalg} \\ X \amalg (Y \amalg Z) & \xrightarrow{f \amalg (g \amalg h)} & X' \amalg (Y' \amalg Z') \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} (0, (0, x)) & & (0, (0, x)) \mapsto (0, (0, f(x))) \\ \downarrow & & \downarrow \\ (0, x) \mapsto (0, f(x)) & & (0, f(x)) \\ \\ (0, (1, y)) & & (0, (1, y)) \mapsto (0, (1, g(y))) \\ \downarrow & & \downarrow \\ (1, (0, y)) \mapsto (1, (0, g(y))) & & (1, (0, g(y))) \\ \\ (1, z) & & (1, z) \mapsto (1, h(z)) \\ \downarrow & & \downarrow \\ (1, (1, z)) \mapsto (1, (1, h(z))) & & (1, (1, h(z))) \end{array}$$

and hence indeed commutes, showing $\alpha^{\text{Sets}, \amalg}$ to be a natural transformation.

Being a Natural Isomorphism

Since $\alpha^{\text{Sets}, \amalg}$ is natural and $\alpha^{\text{Sets}, \amalg, -1}$ is a componentwise inverse to $\alpha^{\text{Sets}, \amalg}$, it follows from **Categories, Item 2** of **Proposition 11.9.7.1.2** that $\lambda^{\text{Sets}, -1}$ is also natural. Thus $\alpha^{\text{Sets}, \amalg}$ is a natural isomorphism. 

01PS 5.2.4 The Left Unitor

01PT DEFINITION 5.2.4.1.1 ► THE LEFT UNITOR OF \amalg

The **left unitor of the coproduct of sets** is the natural isomorphism

$$\lambda^{\text{Sets}, \amalg} : \amalg \circ (\emptyset^{\text{Sets}} \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \lambda_{\text{Sets}}^{\text{Cats}_2}$$

whose component

$$\lambda_X^{\text{Sets}, \amalg} : \emptyset \amalg X \xrightarrow{\sim} X$$

at X is given by

$$\lambda_X^{\text{Sets}, \amalg}((1, x)) \stackrel{\text{def}}{=} x$$

for each $(1, x) \in \emptyset \amalg X$.

PROOF 5.2.4.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.2.4.1.1

Unwinding the Definition of $\emptyset \amalg X$

Firstly, we unwind the expressions for $\emptyset \amalg X$. We have

$$\begin{aligned} \emptyset \amalg X &\stackrel{\text{def}}{=} \{(0, z) \in S \mid z \in \emptyset\} \cup \{(1, x) \in S \mid x \in X\} \\ &= \emptyset \cup \{(1, x) \in S \mid x \in X\} \end{aligned}$$

$$= \{(1, x) \in S \mid x \in X\},$$

where $S = \{0, 1\} \times (\emptyset \sqcup X)$.

Invertibility

The inverse of $\lambda_X^{\text{Sets}, \sqcup}$ is the map

$$\lambda_X^{\text{Sets}, \sqcup, -1} : X \rightarrow \emptyset \sqcup X$$

given by

$$\lambda_X^{\text{Sets}, \sqcup, -1}(x) \stackrel{\text{def}}{=} (1, x)$$

for each $x \in X$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned} \left[\lambda_X^{\text{Sets}, \sqcup, -1} \circ \lambda_X^{\text{Sets}, \sqcup} \right](1, x) &= \lambda_X^{\text{Sets}, \sqcup, -1} \left(\lambda_X^{\text{Sets}, \sqcup}(1, x) \right) \\ &= \lambda_X^{\text{Sets}, \sqcup, -1}(x) \\ &= (1, x) \\ &= [\text{id}_{\emptyset \sqcup X}](1, x) \end{aligned}$$

for each $(1, x) \in \emptyset \sqcup X$, and therefore we have

$$\lambda_X^{\text{Sets}, \sqcup, -1} \circ \lambda_X^{\text{Sets}, \sqcup} = \text{id}_{\emptyset \sqcup X}.$$

- *Invertibility II.* We have

$$\begin{aligned} \left[\lambda_X^{\text{Sets}, \sqcup} \circ \lambda_X^{\text{Sets}, \sqcup, -1} \right](x) &= \lambda_X^{\text{Sets}, \sqcup} \left(\lambda_X^{\text{Sets}, \sqcup, -1}(x) \right) \\ &= \lambda_X^{\text{Sets}, \sqcup, -1}(1, x) \\ &= x \\ &= [\text{id}_X](x) \end{aligned}$$

for each $x \in X$, and therefore we have

$$\lambda_X^{\text{Sets}, \sqcup} \circ \lambda_X^{\text{Sets}, \sqcup, -1} = \text{id}_X.$$

Therefore $\lambda_X^{\text{Sets}, \coprod}$ is indeed an isomorphism.

Naturality

We need to show that, given a function $f: X \rightarrow Y$, the diagram


$$\begin{array}{ccc} \emptyset \coprod X & \xrightarrow{\text{id}_{\emptyset} \coprod f} & \emptyset \coprod Y \\ \lambda_X^{\text{Sets}, \coprod} \downarrow & & \downarrow \lambda_Y^{\text{Sets}, \coprod} \\ X & \xrightarrow{f} & Y \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc} (1, x) & & (1, x) \mapsto (1, f(x)) \\ \downarrow & & \downarrow \\ x & \mapsto & f(x) \end{array}$$

and hence indeed commutes. Therefore $\lambda^{\text{Sets}, \coprod}$ is a natural transformation.

Being a Natural Isomorphism

Since $\lambda^{\text{Sets}, \coprod}$ is natural and $\lambda^{\text{Sets}, -1}$ is a componentwise inverse to $\lambda^{\text{Sets}, \coprod}$, it follows from **Categories, Item 2** of **Proposition 11.9.7.1.2** that $\lambda^{\text{Sets}, -1}$ is also natural. Thus $\lambda^{\text{Sets}, \coprod}$ is a natural isomorphism. 

01PU 5.2.5 The Right Unitor

01PV DEFINITION 5.2.5.1.1 ► THE RIGHT UNITOR OF \coprod

The **right unitor of the coproduct of sets** is the natural isomorphism

$$\rho^{\text{Sets}, \amalg} : \amalg \circ (\text{id} \times \mathbb{0}^{\text{Sets}}) \xrightarrow{\sim} \rho_{\text{Sets}}^{\text{Cats}_2},$$

whose component

$$\rho_X^{\text{Sets}, \amalg} : X \amalg \emptyset \xrightarrow{\sim} X$$

at X is given by

$$\rho_X^{\text{Sets}, \amalg}((0, x)) \stackrel{\text{def}}{=} x$$

for each $(0, x) \in X \amalg \emptyset$.

PROOF 5.2.5.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.2.5.1.1

Unwinding the Definition of $X \amalg \emptyset$

Firstly, we unwind the expression for $X \amalg \emptyset$. We have

$$\begin{aligned} X \amalg \emptyset &\stackrel{\text{def}}{=} \{(0, x) \in S \mid x \in X\} \cup \{(1, z) \in S \mid z \in \emptyset\} \\ &= \{(0, x) \in S \mid x \in X\} \cup \emptyset \\ &= \{(0, x) \in S \mid x \in X\}, \end{aligned}$$

where $S = \{0, 1\} \times (X \cup \emptyset) = \{0, 1\} \times (\emptyset \cup X) = S$.

Invertibility

The inverse of $\rho_X^{\text{Sets}, \amalg}$ is the map

$$\rho_X^{\text{Sets}, \amalg, -1} : X \rightarrow X \amalg \emptyset$$

given by

$$\rho_X^{\text{Sets}, \amalg, -1}(x) \stackrel{\text{def}}{=} (0, x)$$

for each $x \in X$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned}
 \left[\rho_X^{\text{Sets}, \amalg, -1} \circ \rho_X^{\text{Sets}, \amalg} \right] (0, x) &= \rho_X^{\text{Sets}, \amalg, -1} \left(\rho_X^{\text{Sets}, \amalg} (0, x) \right) \\
 &= \rho_X^{\text{Sets}, \amalg, -1} (x) \\
 &= (0, x) \\
 &= [\text{id}_X \amalg \emptyset] (0, x)
 \end{aligned}$$

for each $(0, x) \in \emptyset \amalg X$, and therefore we have

$$\rho_X^{\text{Sets}, \amalg, -1} \circ \rho_X^{\text{Sets}, \amalg} = \text{id}_{\emptyset \amalg X}.$$

- *Invertibility II.* We have

$$\begin{aligned}
 \left[\rho_X^{\text{Sets}, \amalg} \circ \rho_X^{\text{Sets}, \amalg, -1} \right] (x) &= \rho_X^{\text{Sets}, \amalg} \left(\rho_X^{\text{Sets}, \amalg, -1} (x) \right) \\
 &= \rho_X^{\text{Sets}, \amalg, -1} (0, x) \\
 &= x \\
 &= [\text{id}_X] (x)
 \end{aligned}$$

for each $x \in X$, and therefore we have

$$\rho_X^{\text{Sets}, \amalg} \circ \rho_X^{\text{Sets}, \amalg, -1} = \text{id}_X.$$

Therefore $\rho_X^{\text{Sets}, \amalg}$ is indeed an isomorphism.

Naturality

We need to show that, given a function $f: X \rightarrow Y$, the diagram


$$\begin{array}{ccc}
 X \amalg \emptyset & \xrightarrow{f \amalg \text{id}_{\emptyset}} & Y \amalg \emptyset \\
 \rho_X^{\text{Sets}, \amalg} \downarrow & & \downarrow \rho_Y^{\text{Sets}, \amalg} \\
 X & \xrightarrow{f} & Y
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 (0, x) & & (0, x) \mapsto (1, f(x)) \\
 \downarrow & & \downarrow \\
 x & \xrightarrow{\quad} & f(x)
 \end{array}$$

and hence indeed commutes. Therefore $\rho^{\text{Sets}, \amalg}$ is a natural transformation.

Being a Natural Isomorphism

Since $\rho^{\text{Sets}, \amalg}$ is natural and $\rho^{\text{Sets}, -1}$ is a componentwise inverse to $\rho^{\text{Sets}, \amalg}$, it follows from **Categories, Item 2 of Proposition 11.9.7.1.2** that $\rho^{\text{Sets}, -1}$ is also natural. Thus $\rho^{\text{Sets}, \amalg}$ is a natural isomorphism. 

01PW 5.2.6 The Symmetry

01PX DEFINITION 5.2.6.1.1 ► THE SYMMETRY OF \amalg

The **symmetry of the coproduct of sets** is the natural isomorphism

$$\sigma^{\text{Sets}, \amalg} : \amalg \xRightarrow{\sim} \amalg \circ \sigma_{\text{Sets}, \text{Sets}}^{\text{Cats}_2}$$

$$\begin{array}{ccc}
 \text{Sets} \times \text{Sets} & \xrightarrow{\amalg} & \text{Sets} \\
 \sigma_{\text{Sets}, \text{Sets}}^{\text{Cats}_2} \searrow & \downarrow \sigma^{\text{Sets}, \amalg} & \nearrow \amalg \\
 & \text{Sets} \times \text{Sets} &
 \end{array}$$

whose component

$$\sigma_{X,Y}^{\text{Sets}, \amalg} : X \amalg Y \xrightarrow{\sim} Y \amalg X$$

at $X, Y \in \text{Obj}(\text{Sets})$ is defined by

$$\sigma_{X,Y}^{\text{Sets}, \amalg}(x, y) \stackrel{\text{def}}{=} (y, x)$$

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

PROOF 5.2.6.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.2.6.1.1

Unwinding the Definitions of $X \amalg Y$ and $Y \amalg X$

Firstly, we unwind the expressions for $X \amalg Y$ and $Y \amalg X$. We have

$$X \amalg Y \stackrel{\text{def}}{=} \{(0, x) \in S \mid x \in X\} \cup \{(1, y) \in S \mid y \in Y\},$$

where $S = \{0, 1\} \times (X \cup Y)$ and

$$Y \amalg X \stackrel{\text{def}}{=} \{(0, y) \in S' \mid y \in Y\} \cup \{(1, x) \in S' \mid x \in X\},$$

where $S' = \{0, 1\} \times (Y \cup X) = \{0, 1\} \times (X \cup Y) = S$.

Invertibility

The inverse of $\sigma_{X,Y}^{\text{Sets}, \amalg}$ is the map

$$\sigma_{X,Y}^{\text{Sets}, \amalg, -1} : Y \amalg X \rightarrow X \amalg Y$$

defined by

$$\sigma_{X,Y}^{\text{Sets}, \amalg, -1} \stackrel{\text{def}}{=} \sigma_{Y,X}^{\text{Sets}, \amalg}$$

and hence given by

$$\sigma_{X,Y}^{\text{Sets}, \amalg, -1}(z) \stackrel{\text{def}}{=} \begin{cases} (0, x) & \text{if } z = (1, x), \\ (1, y) & \text{if } z = (0, y) \end{cases}$$

for each $z \in Y \amalg X$. Indeed:

- *Invertibility I.* We have

$$\begin{aligned} \left[\sigma_{X,Y}^{\text{Sets}, \amalg, -1} \circ \sigma_{X,Y}^{\text{Sets}, \amalg} \right](0, x) &= \sigma_X^{\text{Sets}, \amalg, -1} \left(\sigma_X^{\text{Sets}, \amalg}(0, x) \right) \\ &= \sigma_X^{\text{Sets}, \amalg, -1}(1, x) \\ &= (0, x) \\ &= \left[\text{id}_{X \amalg Y} \right](0, x) \end{aligned}$$

for each $(0, x) \in X \amalg Y$ and

$$\left[\sigma_{X,Y}^{\text{Sets}, \amalg, -1} \circ \sigma_{X,Y}^{\text{Sets}, \amalg} \right](1, y) = \sigma_X^{\text{Sets}, \amalg, -1} \left(\sigma_X^{\text{Sets}, \amalg}(1, y) \right)$$

$$\begin{aligned}
&= \sigma_X^{\text{Sets}, \amalg, -1}(0, y) \\
&= (1, y) \\
&= [\text{id}_X \amalg_Y](1, y)
\end{aligned}$$

for each $(1, y) \in X \amalg Y$, and therefore we have

$$\sigma_{X,Y}^{\text{Sets}, \amalg, -1} \circ \sigma_{X,Y}^{\text{Sets}, \amalg} = \text{id}_{X \amalg Y}.$$

- *Invertibility II.* We have

$$\begin{aligned}
\left[\sigma_{X,Y}^{\text{Sets}, \amalg} \circ \sigma_{X,Y}^{\text{Sets}, \amalg, -1} \right](0, y) &= \sigma_X^{\text{Sets}, \amalg} \left(\sigma_X^{\text{Sets}, \amalg, -1}(0, y) \right) \\
&= \sigma_X^{\text{Sets}, \amalg, -1}(1, y) \\
&= (0, y) \\
&= [\text{id}_Y \amalg_X](0, y)
\end{aligned}$$

for each $(0, y) \in Y \amalg X$ and

$$\begin{aligned}
\left[\sigma_{X,Y}^{\text{Sets}, \amalg} \circ \sigma_{X,Y}^{\text{Sets}, \amalg, -1} \right](1, x) &= \sigma_X^{\text{Sets}, \amalg} \left(\sigma_X^{\text{Sets}, \amalg, -1}(1, x) \right) \\
&= \sigma_X^{\text{Sets}, \amalg, -1}(0, x) \\
&= (1, x) \\
&= [\text{id}_Y \amalg_X](1, x)
\end{aligned}$$

for each $(1, x) \in Y \amalg X$, and therefore we have

$$\sigma_X^{\text{Sets}, \amalg} \circ \sigma_X^{\text{Sets}, \amalg, -1} = \text{id}_{Y \amalg X}.$$

Therefore $\sigma_{X,Y}^{\text{Sets}, \amalg}$ is indeed an isomorphism.

Naturality

We need to show that, given functions $f: A \rightarrow X$ and $g: B \rightarrow Y$, the diagram


$$\begin{array}{ccc}
A \amalg B & \xrightarrow{f \amalg g} & X \amalg Y \\
\sigma_{A,B}^{\text{Sets}, \amalg} \downarrow & & \downarrow \sigma_{X,Y}^{\text{Sets}, \amalg} \\
B \amalg A & \xrightarrow{g \amalg f} & Y \amalg X
\end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccc}
 (0, a) & & (0, a) \mapsto (0, f(a)) \\
 \downarrow & & \downarrow \\
 (1, a) \mapsto (1, f(a)) & & (1, f(a)) \\
 \\
 (1, b) & & (1, b) \mapsto (1, g(b)) \\
 \downarrow & & \downarrow \\
 (0, b) \mapsto (0, g(b)) & & (0, g(b))
 \end{array}$$

and hence indeed commutes. Therefore $\sigma^{\text{Sets}, \amalg}$ is a natural transformation.

Being a Natural Isomorphism

Since $\sigma^{\text{Sets}, \amalg}$ is natural and $\sigma^{\text{Sets}, -1}$ is a componentwise inverse to $\sigma^{\text{Sets}, \amalg}$, it follows from **Categories, Item 2** of **Proposition 11.9.7.1.2** that $\sigma^{\text{Sets}, -1}$ is also natural. Thus $\sigma^{\text{Sets}, \amalg}$ is a natural isomorphism. 

01PY 5.2.7 The Monoidal Category of Sets and Coproducts

01PZ PROPOSITION 5.2.7.1.1 ► THE MONOIDAL STRUCTURE ON SETS ASSOCIATED TO \amalg

The category **Sets** admits a closed symmetric monoidal category structure consisting of:

- *The Underlying Category.* The category **Sets** of pointed sets.
- *The Monoidal Product.* The coproduct functor

$$\amalg : \text{Sets} \times \text{Sets} \rightarrow \text{Sets}$$

of **Constructions With Sets, Item 1** of **Proposition 4.2.3.1.4**.

- *The Monoidal Unit.* The functor

$$\mathbb{0}^{\text{Sets}} : \text{pt} \rightarrow \text{Sets}$$

of **Definition 5.2.2.1.1**.

- *The Associators.* The natural isomorphism

$$\alpha^{\text{Sets}, \amalg} : \amalg \circ (\amalg \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \amalg \circ (\text{id}_{\text{Sets}} \times \amalg) \circ \alpha_{\text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}}$$

of **Definition 5.2.3.1.1.**

- *The Left Unitors.* The natural isomorphism

$$\lambda^{\text{Sets}, \amalg} : \amalg \circ (\mathbb{0}^{\text{Sets}} \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \lambda_{\text{Sets}}^{\text{Cats}_2}$$

of **Definition 5.2.4.1.1.**

- *The Right Unitors.* The natural isomorphism

$$\rho^{\text{Sets}, \amalg} : \amalg \circ (\text{id} \times \mathbb{0}^{\text{Sets}}) \xrightarrow{\sim} \rho_{\text{Sets}}^{\text{Cats}_2}$$

of **Definition 5.2.5.1.1.**

- *The Symmetry.* The natural isomorphism

$$\sigma^{\text{Sets}, \amalg} : \times \xrightarrow{\sim} \times \circ \sigma_{\text{Sets}, \text{Sets}}^{\text{Cats}_2}$$

of **Definition 5.2.6.1.1.**

PROOF 5.2.7.1.2 ► PROOF OF PROPOSITION 5.2.7.1.1

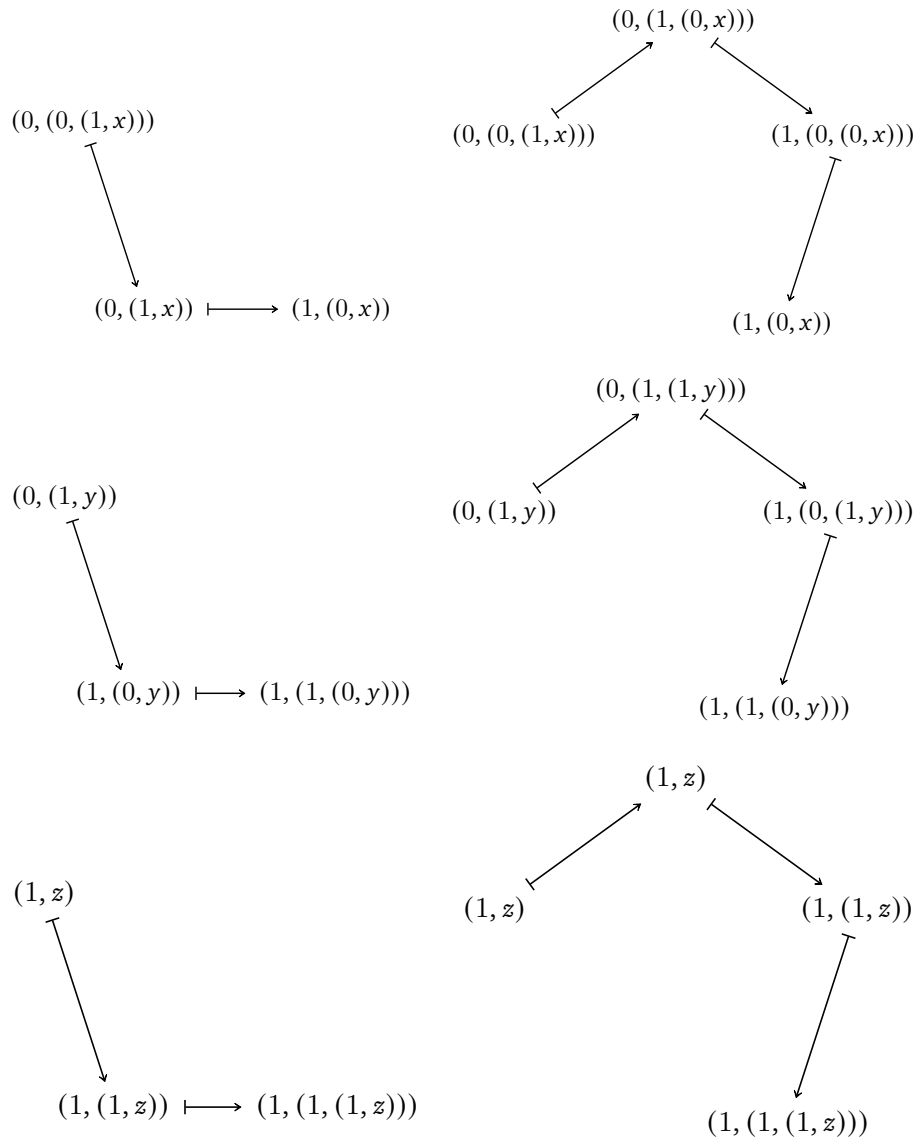
The Pentagon Identity

Let W, X, Y and Z be sets. We have to show that the diagram

$$\begin{array}{ccc}
 & (W \amalg (X \amalg Y)) \amalg Z & \\
 \alpha_{W,X,Y}^{\text{Sets}, \amalg} \amalg \text{id}_Z \nearrow & & \searrow \alpha_{W,X}^{\text{Sets}, \amalg} \amalg \alpha_{Y,Z}^{\text{Sets}, \amalg} \\
 ((W \amalg X) \amalg Y) \amalg Z & & W \amalg ((X \amalg Y) \amalg Z) \\
 \alpha_{W \amalg X, Y, Z}^{\text{Sets}, \amalg} \searrow & & \nearrow \text{id}_W \amalg \alpha_{X,Y,Z}^{\text{Sets}, \amalg} \\
 (W \amalg X) \amalg (Y \amalg Z) & \xrightarrow{\alpha_{W,X,Y}^{\text{Sets}, \amalg} \amalg \alpha_{Z}^{\text{Sets}, \amalg}} & W \amalg (X \amalg (Y \amalg Z))
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc}
 & & (0, (0, w)) & & \\
 & \swarrow & & \searrow & \\
 (0, (0, (0, w))) & & (0, (0, (0, w))) & & (0, w) \\
 \searrow & & & & \nearrow \\
 (0, (0, w)) & \longmapsto & (0, w) & & (0, w)
 \end{array}$$



and therefore the pentagon identity is satisfied.

The Triangle Identity

Let X and Y be sets. We have to show that the diagram

$$\begin{array}{ccc}
 (X \amalg \emptyset) \amalg Y & \xrightarrow{\alpha_{X,\emptyset,Y}^{\text{Sets}, \amalg}} & X \amalg (\emptyset \amalg Y) \\
 \rho_X^{\text{Sets}, \amalg} \amalg \text{id}_Y \searrow & & \swarrow \text{id}_X \amalg \lambda_Y^{\text{Sets}, \amalg} \\
 & X \amalg Y &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

$$\begin{array}{ccccc}
 (0, (1, x)) & & (1, (0, x)) & \xrightarrow{\quad} & (0, x) \\
 & \searrow & & & \swarrow \\
 & (0, x) & & & (0, x) \\
 (1, y) & & (1, y) & \xrightarrow{\quad} & (1, (1, y)) \\
 & \searrow & & & \swarrow \\
 & (1, y) & & & (1, y)
 \end{array}$$

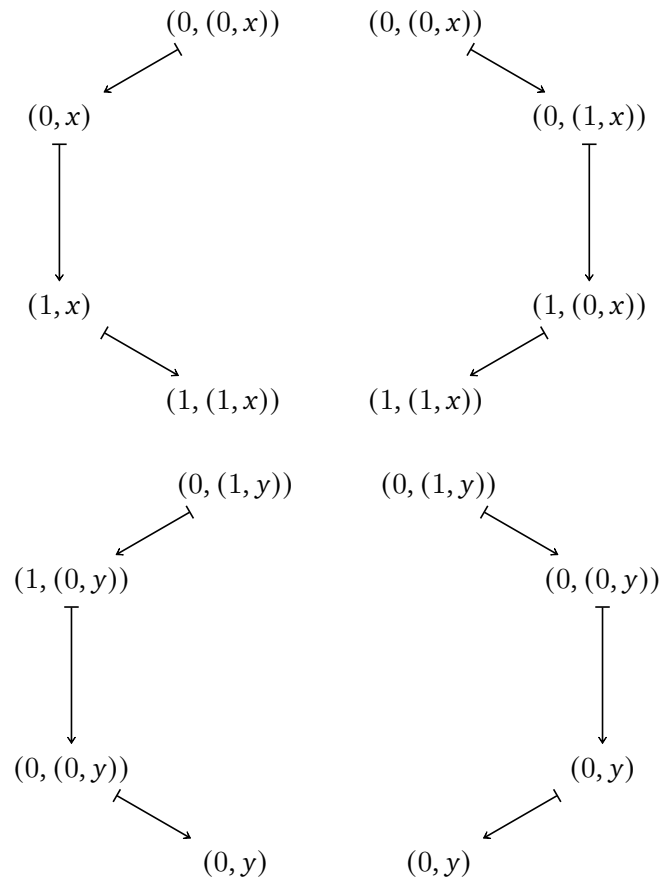
and therefore the triangle identity is satisfied.

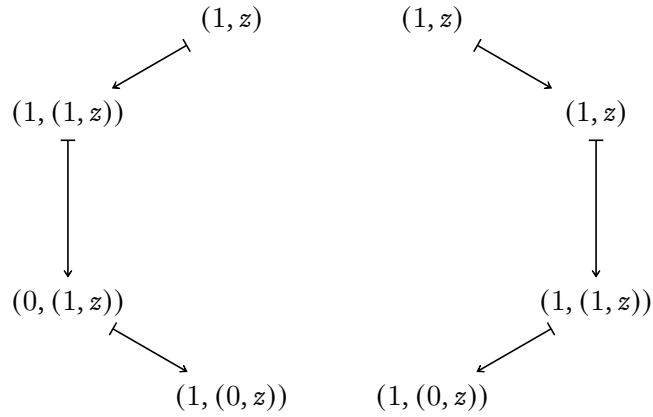
The Left Hexagon Identity

Let X , Y , and Z be sets. We have to show that the diagram

$$\begin{array}{ccc}
 & (X \amalg Y) \amalg Z & \\
 \alpha_{X,Y,Z}^{\text{Sets}} \swarrow & & \searrow \sigma_{X,Y}^{\text{Sets}} \amalg \text{id}_Z \\
 X \amalg (Y \amalg Z) & & (Y \amalg X) \amalg Z \\
 \downarrow \sigma_{X,Y}^{\text{Sets}} \amalg \text{id}_Z & & \downarrow \alpha_{Y,X,Z}^{\text{Sets}} \\
 (Y \amalg Z) \amalg X & & Y \amalg (X \amalg Z) \\
 \searrow \alpha_{Y,Z,X}^{\text{Sets}} & & \swarrow \text{id}_Y \amalg \sigma_{X,Z}^{\text{Sets}} \\
 & Y \amalg (Z \amalg X) &
 \end{array}$$

commutes. Indeed, this diagram acts on elements as

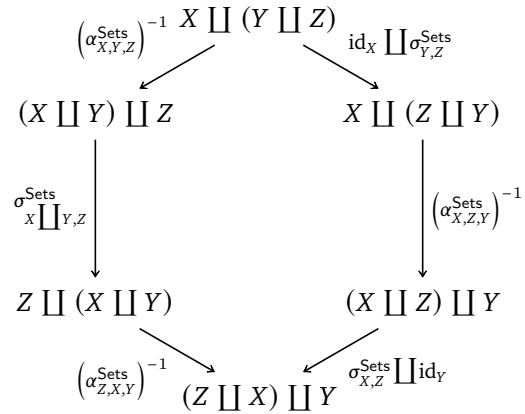




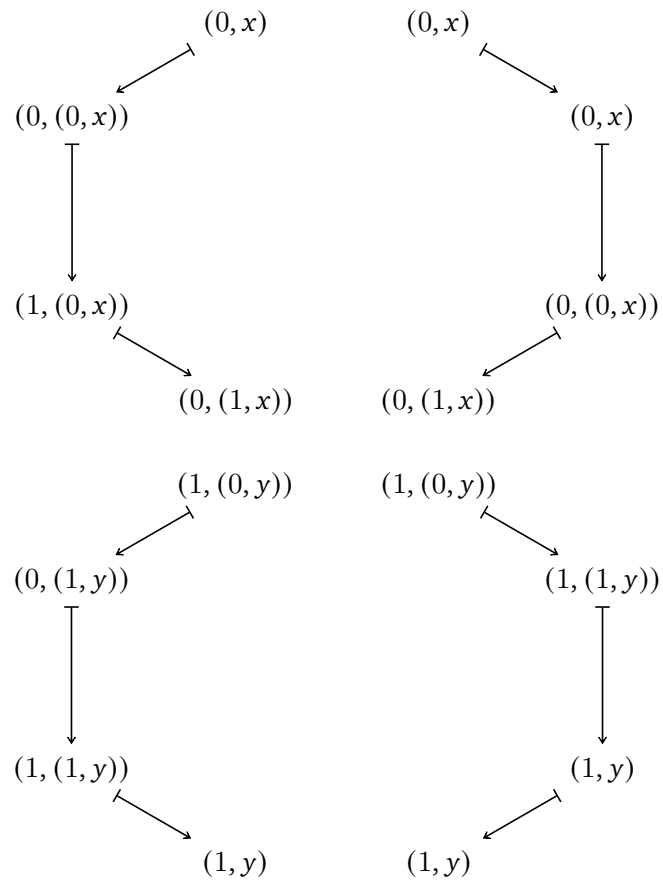
and thus the left hexagon identity is satisfied.

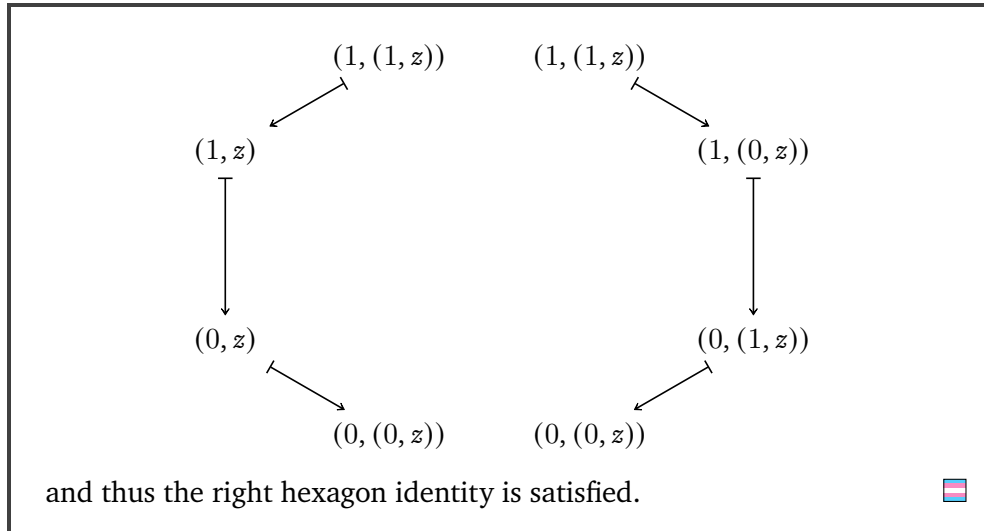
The Right Hexagon Identity

Let X , Y , and Z be sets. We have to show that the diagram



commutes. Indeed, this diagram acts on elements as





01Q0 5.3 The Bimonoidal Category of Sets, Products, and Coproducts

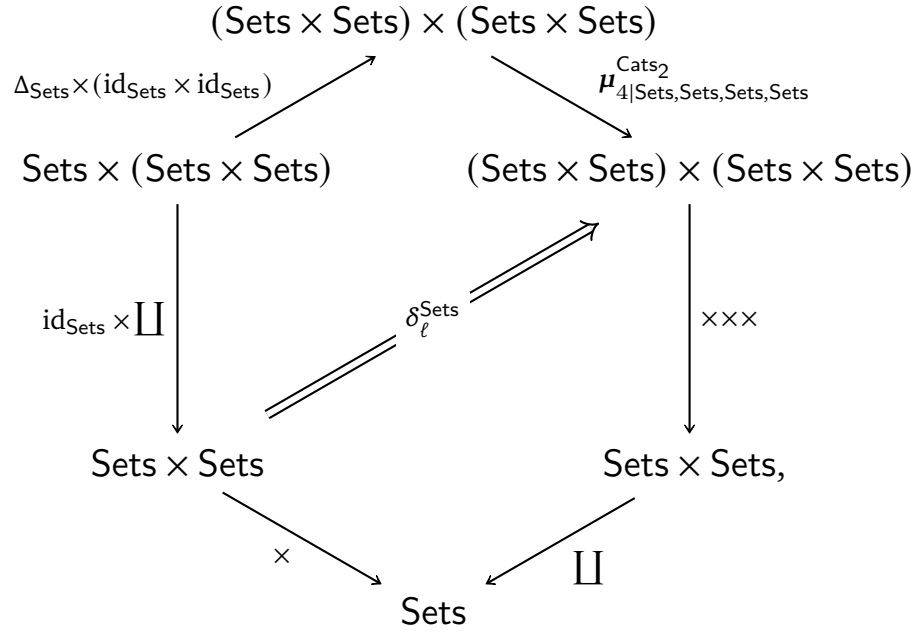
01Q1 5.3.1 The Left Distributor

01Q2 DEFINITION 5.3.1.1.1 ► THE LEFT DISTRIBUTOR OF \times OVER \amalg

The **left distributor of the product of sets over the coproduct of sets** is the natural isomorphism

$$\delta_\ell^{\text{Sets}} : \times \circ (\text{id}_{\text{Sets}} \times \amalg) \xrightarrow{\sim} \amalg \circ (\times \times \times) \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ (\Delta_{\text{Sets}} \times (\text{id}_{\text{Sets}} \times \text{id}_{\text{Sets}}))$$

as in the diagram



whose component

$$\delta_{\ell|X,Y,Z}^{\text{Sets}}: X \times (Y \amalg Z) \dashrightarrow (X \times Y) \amalg (X \times Z)$$

at (X, Y, Z) is defined by

$$\delta_{\ell|X,Y,Z}^{\text{Sets}}(x, a) \stackrel{\text{def}}{=} \begin{cases} (0, (x, y)) & \text{if } a = (0, y), \\ (1, (x, z)) & \text{if } a = (1, z) \end{cases}$$

for each $(x, a) \in X \times (Y \amalg Z)$.

PROOF 5.3.1.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.3.1.1

Omitted.



01Q3 5.3.2 The Right Distributor

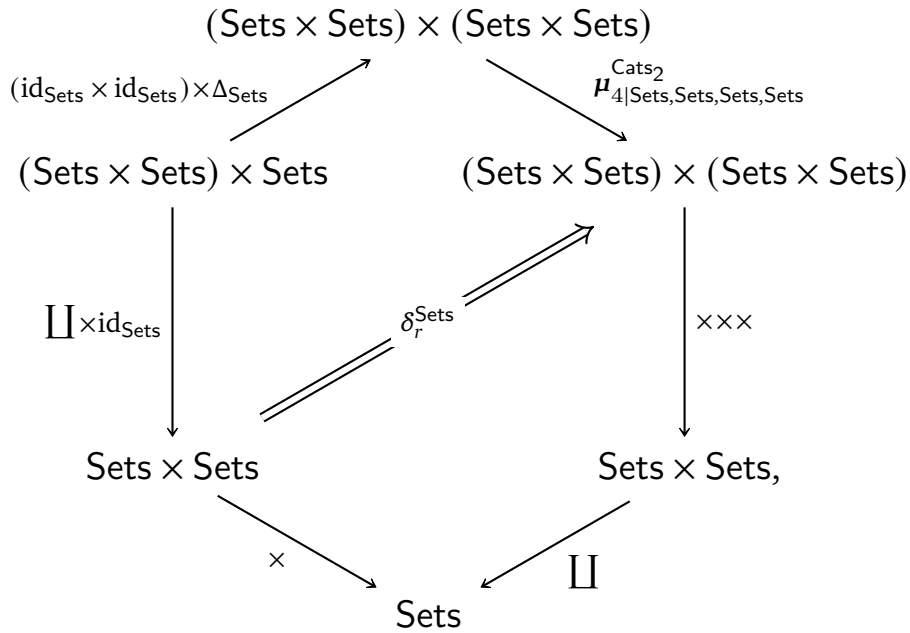
01Q4

DEFINITION 5.3.2.1.1 ► THE RIGHT DISTRIBUTOR OF \times OVER \coprod

The **right distributor of the product of sets over the coproduct of sets** is the natural isomorphism

$$\delta_r^{\text{Sets}} : \times \circ (\coprod \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \coprod \circ (\times \times \times) \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ ((\text{id}_{\text{Sets}} \times \text{id}_{\text{Sets}}) \times \Delta_{\text{Sets}})$$

as in the diagram



whose component


$$\delta_{r|X,Y,Z}^{\text{Sets}} : (X \coprod Y) \times Z \xrightarrow{\sim} (X \times Z) \coprod (Y \times Z)$$

at (X, Y, Z) is defined by

$$\delta_{r|X,Y,Z}^{\text{Sets}}(a, z) \stackrel{\text{def}}{=} \begin{cases} (0, (x, z)) & \text{if } a = (0, x), \\ (1, (y, z)) & \text{if } a = (1, y) \end{cases}$$

for each $(a, z) \in (X \coprod Y) \times Z$.

PROOF 5.3.2.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.3.2.1.1

Omitted. 

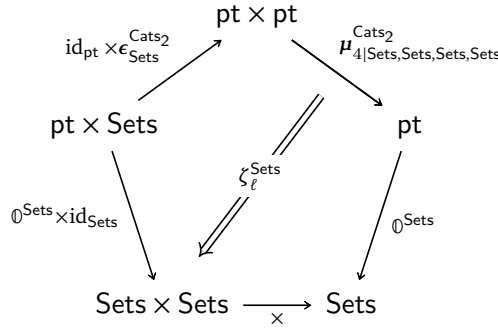
01Q5 5.3.3 The Left Annihilator

01Q6 DEFINITION 5.3.3.1.1 ► THE LEFT ANNIHILATOR OF \times

The **left annihilator of the product of sets** is the natural isomorphism

$$\zeta_{\ell}^{\text{Sets}} : \mathbb{0}^{\text{Sets}} \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ (\text{id}_{\text{pt}} \times \epsilon_{\text{Sets}}^{\text{Cats}_2}) \xrightarrow{\sim} \times \circ (\mathbb{0}^{\text{Sets}} \times \text{id}_{\text{Sets}})$$

as in the diagram



with components

$$\zeta_{\ell|A}^{\text{Sets}} : \emptyset \times A \xrightarrow{\sim} \emptyset.$$

PROOF 5.3.3.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.3.3.1.1

Omitted. For a partial proof, see [Pro25]. 

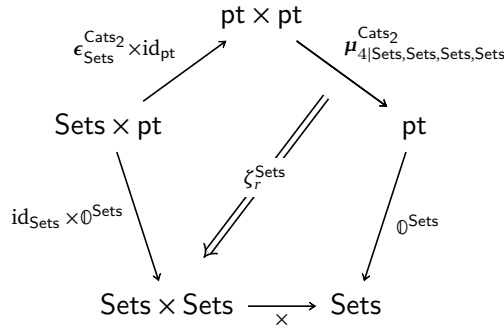
01Q7 5.3.4 The Right Annihilator

01Q8 DEFINITION 5.3.4.1.1 ► THE RIGHT ANNIHILATOR OF \times

The **right annihilator of the product of sets** is the natural isomorphism

$$\zeta_r^{\text{Sets}} : \mathbb{0}^{\text{Sets}} \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ (\epsilon_{\text{Sets}}^{\text{Cats}_2} \times \text{id}_{\text{pt}}) \xrightarrow{\sim} \times \circ (\text{id}_{\text{Sets}} \times \mathbb{0}^{\text{Sets}})$$

as in the diagram



with components

$$\zeta_{r|A}^{\text{Sets}} : A \times \emptyset \dashrightarrow \emptyset.$$

PROOF 5.3.4.1.2 ► PROOF OF THE CLAIMS MADE IN DEFINITION 5.3.4.1.1

Omitted. For a partial proof, see [Pro25].



01Q9 5.3.5 The Bimonoidal Category of Sets, Products, and Coproducts

01QA PROPOSITION 5.3.5.1.1 ► THE BIMONOIDAL STRUCTURE ON SETS ASSOCIATED TO \times AND \coprod

The category **Sets** admits a closed symmetric bimonoidal category structure consisting of:

- *The Underlying Category.* The category **Sets** of pointed sets.
- *The Additive Monoidal Product.* The coproduct functor

$$\coprod : \text{Sets} \times \text{Sets} \rightarrow \text{Sets}$$

of **Constructions With Sets**, Item 1 of Proposition 4.2.3.1.4.

- *The Multiplicative Monoidal Product.* The product functor

$$\times : \text{Sets} \times \text{Sets} \rightarrow \text{Sets}$$

of **Constructions With Sets**, Item 1 of Proposition 4.1.3.1.4.

- *The Monoidal Unit.* The functor

$$\mathbb{1}^{\text{Sets}} : \text{pt} \rightarrow \text{Sets}$$

of **Definition 5.1.3.1.1.**

- *The Monoidal Zero.* The functor

$$\mathbb{0}^{\text{Sets}} : \text{pt} \rightarrow \text{Sets}$$

of **Definition 5.1.3.1.1.**

- *The Internal Hom.* The internal Hom functor

$$\text{Sets} : \text{Sets}^{\text{op}} \times \text{Sets} \rightarrow \text{Sets}$$

of **Constructions With Sets, ?? of ??.**

- *The Additive Associators.* The natural isomorphism

$$\alpha^{\text{Sets}, \amalg} : \amalg \circ (\amalg \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \amalg \circ (\text{id}_{\text{Sets}} \times \amalg) \circ \alpha_{\text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}}$$

of **Definition 5.2.3.1.1.**

- *The Additive Left Unitors.* The natural isomorphism

$$\lambda^{\text{Sets}, \amalg} : \amalg \circ (\mathbb{0}^{\text{Sets}} \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \lambda_{\text{Sets}}^{\text{Cats}_2}$$

of **Definition 5.2.4.1.1.**

- *The Additive Right Unitors.* The natural isomorphism

$$\rho^{\text{Sets}, \amalg} : \amalg \circ (\text{id} \times \mathbb{0}^{\text{Sets}}) \xrightarrow{\sim} \rho_{\text{Sets}}^{\text{Cats}_2}$$

of **Definition 5.2.5.1.1.**

- *The Additive Symmetry.* The natural isomorphism

$$\sigma^{\text{Sets}, \amalg} : \amalg \xrightarrow{\sim} \amalg \circ \sigma_{\text{Sets}, \text{Sets}}^{\text{Cats}_2}$$

of **Definition 5.2.6.1.1.**

- *The Multiplicative Associators.* The natural isomorphism

$$\alpha^{\text{Sets}} : \times \circ (\times \times \text{id}_{\text{Sets}}) \xrightarrow{\sim} \times \circ (\text{id}_{\text{Sets}} \times \times) \circ \alpha_{\text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}}$$

of **Definition 5.1.4.1.1.**

- *The Multiplicative Left Unitors.* The natural isomorphism

$$\lambda^{\text{Sets}} : \times \circ (\mathbb{1}^{\text{Sets}} \times \text{id}_{\text{Sets}}) \xRightarrow{\sim} \lambda_{\text{Sets}}^{\text{Cats}_2}$$

of [Definition 5.1.5.1.1](#).

- *The Multiplicative Right Unitors.* The natural isomorphism

$$\rho^{\text{Sets}} : \times \circ (\text{id} \times \mathbb{1}^{\text{Sets}}) \xRightarrow{\sim} \rho_{\text{Sets}}^{\text{Cats}_2}$$

of [Definition 5.1.6.1.1](#).

- *The Multiplicative Symmetry.* The natural isomorphism

$$\sigma^{\text{Sets}} : \times \xRightarrow{\sim} \times \circ \sigma_{\text{Sets}, \text{Sets}}^{\text{Cats}_2}$$

of [Definition 5.1.7.1.1](#).

- *The Left Distributor.* The natural isomorphism

$$\delta_\ell^{\text{Sets}} : \times \circ (\text{id}_{\text{Sets}} \times \coprod) \xRightarrow{\sim} \coprod \circ (\times \times \times) \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ (\Delta_{\text{Sets}} \times (\text{id}_{\text{Sets}} \times \text{id}_{\text{Sets}}))$$

of [Definition 5.3.1.1.1](#).

- *The Right Distributor.* The natural isomorphism

$$\delta_r^{\text{Sets}} : \times \circ (\coprod \times \text{id}_{\text{Sets}}) \xRightarrow{\sim} \coprod \circ (\times \times \times) \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ ((\text{id}_{\text{Sets}} \times \text{id}_{\text{Sets}}) \times \Delta_{\text{Sets}})$$

of [Definition 5.3.2.1.1](#).

- *The Left Annihilator.* The natural isomorphism

$$\zeta_\ell^{\text{Sets}} : \mathbb{0}^{\text{Sets}} \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ (\text{id}_{\text{pt}} \times \epsilon_{\text{Sets}}^{\text{Cats}_2}) \xRightarrow{\sim} \times \circ (\mathbb{0}^{\text{Sets}} \times \text{id}_{\text{Sets}})$$

of [Definition 5.3.3.1.1](#).

- *The Right Annihilator.* The natural isomorphism

$$\zeta_r^{\text{Sets}} : \mathbb{0}^{\text{Sets}} \circ \mu_{4|\text{Sets}, \text{Sets}, \text{Sets}, \text{Sets}}^{\text{Cats}_2} \circ (\epsilon_{\text{Sets}}^{\text{Cats}_2} \times \text{id}_{\text{pt}}) \xrightarrow{\sim} \times \circ (\text{id}_{\text{Sets}} \times \mathbb{0}^{\text{Sets}})$$

of [Definition 5.3.4.1.1](#).

PROOF 5.3.5.1.2 ► PROOF OF PROPOSITION 5.3.5.1.1

Omitted.



Appendices

A Other Chapters

Preliminaries

1. Introduction
2. A Guide to the Literature

Sets

3. Sets
4. Constructions With Sets
5. Monoidal Structures on the Category of Sets
6. Pointed Sets
7. Tensor Products of Pointed Sets

Relations

8. Relations
9. Constructions With Relations

10. Conditions on Relations

Categories

11. Categories
12. Presheaves and the Yoneda Lemma

Monoidal Categories

13. Constructions With Monoidal Categories

Bicategories

14. Types of Morphisms in Bicategories

Extra Part

15. Notes

References

- [Pro25] Proof Wiki Contributors. *Cartesian Product Is Empty Iff Factor Is Empty* — *Proof Wiki*. 2025. URL: https://proofwiki.org/wiki/Cartesian_Product_is_Empty_iff_Factor_is_Empty (cit. on pp. 62, 63).