Pointed Sets

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This chapter contains some foundational material on pointed sets.

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6.1 Pointed Sets

6.1.1 Foundations

Definition 6.1.1.1.1. A **pointed set**¹ is equivalently:

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

Remark 6.1.1.1.2. In detail, a **pointed set** is a pair (X, x_0) consisting of:

- The Underlying Set. A set X, called the **underlying set of** (X, x_0) .
- The Basepoint. A morphism

$$[x_0]: \mathsf{pt} \to X$$

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

Example 6.1.1.1.3. The 0-sphere² is the pointed set $(S^0, 0)^3$ consisting of:

• The Underlying Set. The set S^0 defined by

$$S^0 \stackrel{\text{def}}{=} \{0, 1\}.$$

• *The Basepoint*. The element 0 of S^0 .

Example 6.1.1.1.4. The **trivial pointed set** is the pointed set (pt, \star) consisting of:

- *The Underlying Set.* The punctual set pt $\stackrel{\text{def}}{=} \{ \star \}$.
- *The Basepoint*. The element ★ of pt.

Example 6.1.1.1.5. The **standard pointed set with** n + 1 **elements** is the pointed set $\langle n \rangle$ consisting of

• *The Underlying Set.* The set $\langle n \rangle$ defined by

$$\langle n \rangle \stackrel{\text{def}}{=} \{*\} \cup \{1, \ldots, n\}.$$

• *The Basepoint*. The element * of $\langle n \rangle$.

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

²Further Terminology: In the context of monoids with zero as models for \mathbb{F}_1 -algebras, the 0-sphere is viewed as the **underlying pointed set of the field with one element**.

³Further Notation: In the context of monoids with zero as models for \mathbb{F}_1 -algebras, S^0 is also

6.1.2 Morphisms of Pointed Sets

Definition 6.1.2.1.1. A morphism of pointed sets^{4,5} is equivalently:

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

Remark 6.1.2.1.2. In detail, a **morphism of pointed sets** $f: (X, x_0) \to (Y, y_0)$ is a morphism of sets $f: X \to Y$ such that the diagram

$$\begin{array}{c|c}
pt \\
[x_0] & [y_0] \\
X & \xrightarrow{f} Y
\end{array}$$

commutes, i.e. such that

$$f(x_0) = y_0.$$

6.1.3 The Category of Pointed Sets

Definition 6.1.3.1.1. The **category of pointed sets** is the category Sets_{*} defined equivalently as:

- The homotopy category of the ∞ -category $\mathsf{Mon}_{\mathbb{E}_0}(\mathsf{N}_{\bullet}(\mathsf{Sets}),\mathsf{pt})$ of $\ref{eq:sets}$??.
- The category Sets* of Constructions With Categories, ??.

Remark 6.1.3.1.2. In detail, the **category of pointed sets** is the category Sets_{*} where:

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

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

of Sets_{*} at (X, x_0) is defined by⁶

$$id_{(X,x_0)}^{Sets_*} \stackrel{\text{def}}{=} id_X$$
.

denoted $(\mathbb{F}_1, 0)$.

⁴Further Terminology: Also called a **pointed function**.

⁵Further Terminology: In the context of monoids with zero as models for \mathbb{F}_1 -algebras, morphisms of pointed sets are also called **morphism of** \mathbb{F}_1 -**modules**.

⁶Note that id_X is indeed a morphism of pointed sets, as we have id_X(x_0) = x_0 .

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

6.1.4 Elementary Properties of Pointed Sets

Proposition 6.1.4.1.1. Let (X, x_0) be a pointed set.

- 1. *Completeness*. The category Sets_{*} of pointed sets and morphisms between them is complete, having in particular:
 - (a) Products, described as in Definition 6.2.3.1.1.
 - (b) Pullbacks, described as in Definition 6.2.4.1.1.
 - (c) Equalisers, described as in Definition 6.2.5.1.1.
- 2. *Cocompleteness*. The category Sets_{*} of pointed sets and morphisms between them is cocomplete, having in particular:
 - (a) Coproducts, described as in Definition 6.3.3.1.1.
 - (b) Pushouts, described as in Definition 6.3.4.1.1;
 - (c) Coequalisers, described as in Definition 6.3.5.1.1.
- 3. Failure To Be Cartesian Closed. The category Sets, is not Cartesian closed.8

$$g(f(x_0)) = g(y_0)$$

$$= z_0,$$

$$X \xrightarrow{f} Y \xrightarrow{g} Z$$

⁷Note that the composition of two morphisms of pointed sets is indeed a morphism of pointed sets, as we have

⁸The category Sets_{*} does admit a natural monoidal closed structure, however; see Tensor Products of Pointed Sets.

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

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

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

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

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

5. Relation to Partial Functions. We have an equivalence of categories 10

$$\mathsf{Sets}_* \stackrel{\mathsf{eq.}}{\cong} \mathsf{Sets}^{\mathsf{part.}}$$

between the category of pointed sets and pointed functions between them and the category of sets and partial functions between them, where:

(a) From Pointed Sets to Sets With Partial Functions. The equivalence

$$\xi \colon \mathsf{Sets}_* \xrightarrow{\cong} \mathsf{Sets}^{\mathsf{part.}}$$

sends:

- i. A pointed set (X, x_0) to X.
- ii. A pointed function

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

to the partial function

$$\xi_f: X \to Y$$

defined on $f^{-1}(Y \setminus y_0)$ and given by

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

for each $x \in f^{-1}(Y \setminus y_0)$.

defined on objects by sending a pointed set to its underlying set is corepresentable by S^0 .

⁹In other words, the forgetful functor

¹⁰ Warning: This is not an isomorphism of categories, only an equivalence.

(b) From Sets With Partial Functions to Pointed Sets. The equivalence

$$\xi^{-1}$$
: Sets^{part.} $\stackrel{\cong}{\to}$ Sets_{*}

sends:

- i. A set *X* is to the pointed set (X, \star) with \star an element that is not in *X*.
- ii. A partial function

$$f: X \to Y$$

defined on $U \subset X$ to the pointed function

$$\xi_f^{-1} \colon (X, x_0) \to (Y, y_0)$$

defined by

$$\xi_f(x) \stackrel{\text{def}}{=} \begin{cases} f(x) & \text{if } x \in U, \\ y_0 & \text{otherwise.} \end{cases}$$

for each $x \in X$.

Proof. Item 1, Completeness: This follows from (the proofs) of Definitions 6.2.3.1.1, 6.2.4.1.1 and 6.2.5.1.1 and ??.

Item 2, Cocompleteness: This follows from (the proofs) of Definitions 6.3.3.1.1, 6.3.4.1.1 and 6.3.5.1.1 and ??.

Item 3, Failure To Be Cartesian Closed: See [MSE 2855868].

Item 4, Morphisms From the Monoidal Unit: Since a morphism from S^0 to a pointed set (X, x_0) sends $0 \in S^0$ to x_0 and then can send $1 \in S^0$ to any element of X, we obtain a bijection between pointed maps $S^0 \to X$ and the elements of X.

The isomorphism then

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

follows by noting that $\Delta_{x_0}: S^0 \to X$, the basepoint of $\mathbf{Sets}_*(S^0, X)$, corresponds to the pointed map $S^0 \to X$ picking the element x_0 of X, and thus we see that the bijection between pointed maps $S^0 \to X$ and elements of X is compatible with basepoints, lifting to an isomorphism of pointed sets.

Item 5, *Relation to Partial Functions*: See [MSE 884460].

6.1.5 Active and Inert Morphisms of Pointed Sets

Definition 6.1.5.1.1. Let $f: (X, x_0) \to (Y, y_0)$ be a morphism of pointed sets.

- 1. The morphism f is **active** if $f^{-1}(y_0) = x_0$.
- 2. The morphism f is **inert** if, for each $y \in Y$, the set $f^{-1}(y)$ has exactly one element.

Notation 6.1.5.1.2. We write $Sets^{actv}_*$ for the wide subcategory of $Sets_*$ spanned by pointed sets and the active maps between them.

Example 6.1.5.1.3. Here are some examples of active and inert maps of pointed sets.

1. The map $\mu: \langle 2 \rangle \to \langle 1 \rangle$ given by

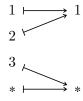


is active but not inert.

2. The map $f: \langle 2 \rangle \rightarrow \langle 2 \rangle$ given by

is inert but not active.

3. The map $f: \langle 3 \rangle \rightarrow \langle 1 \rangle$ given by



is neither inert nor active. However, it factors as $f = a \circ i$, where

$$i: \langle 3 \rangle \to \langle 2 \rangle,$$

 $a: \langle 2 \rangle \to \langle 1 \rangle$

are the morphisms of pointed sets given by

with *i* being inert and *a* being active.

Proposition 6.1.5.1.4. Let (X, x_0) and (Y, y_0) be pointed sets.

1. *Active-Inert Factorisation*. Every morphism of pointed sets $f:(X,x_0) \to (Y,y_0)$ factors uniquely as

$$f = a \circ i$$
,

where:

- (a) The map $i: (X, x_0) \to (K, k_0)$ is an inert morphism of pointed sets
- (b) The map $a: (K, k_0) \to (Y, y_0)$ is an active morphism of pointed sets.

Moreover, this determines an orthogonal factorisation system in Sets*.

Proof. Item 1, *Active-Inert Factorisation*: Let $f: X \to Y$ be a morphism of pointed sets. We can factor f as

$$X \stackrel{i}{\longrightarrow} K \stackrel{a}{\longrightarrow} Y$$
,

where:

• *K* is the pointed set given by

$$K = \{x \in X \mid f(x) \neq y_0\} \cup \{x_0\}$$

= $(X \setminus f^{-1}(y_0)) \cup \{x_0\};$

• $i: X \to K$ is the inert morphism of pointed sets given by

$$i(x) \stackrel{\text{def}}{=} \begin{cases} x & \text{if } x \in K, \\ x_0 & \text{otherwise} \end{cases}$$

for each $x \in X$;

• $a: K \to Y$ is the active morphism of pointed sets given by

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

for each $x \in K$.

Next, let

$$\begin{array}{ccc}
X & \xrightarrow{i} & Y \\
\downarrow f & & \downarrow g \\
A & \xrightarrow{} & B
\end{array}$$

be a commutative diagram in Sets_{*}. Consider the morphism $\phi: Y \to A$ given by

$$\phi(y) = f(i^{-1}(y))$$

for each $y \in Y$ (which is well-defined since, as i is inert, $i^{-1}(y)$ is a singleton for all $y \in Y$). We claim that ϕ is the unique diagonal filler in the diagram

$$\begin{array}{c|c}
X & \xrightarrow{i} & Y \\
\downarrow & & \downarrow & \downarrow & \downarrow g \\
A & \xrightarrow{a} & B.
\end{array}$$

Indeed, this diagram commutes, as we have

$$[\phi \circ i](x) \stackrel{\text{def}}{=} \phi(i(x))$$
$$\stackrel{\text{def}}{=} f(i^{-1}(i(x)))$$
$$= f(x)$$

for each $x \in X$ and

$$[a \circ \phi](y) \stackrel{\text{def}}{=} a(\phi(y))$$

$$\stackrel{\text{def}}{=} a \Big(f \Big(i^{-1}(y) \Big) \Big)$$

$$\stackrel{\text{def}}{=} [a \circ f] \Big(i^{-1}(y) \Big)$$

$$= [g \circ i] \Big(i^{-1}(y) \Big)$$

$$\stackrel{\text{def}}{=} g \Big(i \Big(i^{-1}(y) \Big) \Big)$$

$$\stackrel{\text{def}}{=} g(y)$$

for each $y \in Y$. Moreover, given another morphism ψ such that the diagram

$$\begin{array}{c|c}
X & \xrightarrow{i} & Y \\
f & \downarrow & \downarrow & \downarrow g \\
A & \xrightarrow{g} & B
\end{array}$$

commutes, it follows that we must have $\psi = \phi$, since, given $y \in Y$, there exists a unique $x \in X$ such that i(x) = y, so we have

$$\psi(y) = \psi(i(x))$$

$$= f(x)$$

$$= f(i^{-1}(y))$$

$$\stackrel{\text{def}}{=} \phi(y).$$

This finishes the proof.

6.2 Limits of Pointed Sets

6.2.1 The Terminal Pointed Set

Definition 6.2.1.1.1. The **terminal pointed set** is the terminal object of Sets_{*} as in Limits and Colimits, **??**.

Construction 6.2.1.1.2. Concretely, the **terminal pointed set** is the pair (pt, \star) , $\{!_X\}_{(X,x_0) \in Obj(Sets_*)}$ consisting of:

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

$$\{!_X \colon (X, x_0) \to (\mathsf{pt}, \star)\}_{(X, x_0) \in \mathsf{Obj}(\mathsf{Sets})}$$

defined by

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

for each $x \in X$ and each $(X, x_0) \in \text{Obj}(\mathsf{Sets})$.

Proof. We claim that (pt, \star) is the terminal object of Sets_{*}. Indeed, suppose we

have a diagram of the form

$$(X, x_0)$$
 (pt, \star)

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

$$\phi \colon (X, x_0) \to (\operatorname{pt}, \star)$$

making the diagram

$$(X, x_0) \xrightarrow{-\frac{\phi}{\exists !}} (pt, \star)$$

commute, namely $!_X$.

6.2.2 Products of Families of Pointed Sets

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

Definition 6.2.2.1.1. The **product of** $\{(X_i, x_0^i)\}_{i \in I}$ is the product of $\{(X_i, x_0^i)\}_{i \in I}$ in Sets_{*} as in Limits and Colimits, ??.

Construction 6.2.2.1.2. Concretely, the **product of** $\{(X_i, x_0^i)\}_{i \in I}$ is the pair $(\prod_{i \in I} X_i, (x_0^i)_{i \in I}), \{\operatorname{pr}_i\}_{i \in I})$ consisting of:

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

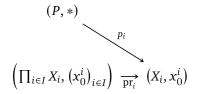
$$\left\{ \operatorname{pr}_{i} : \left(\prod_{i \in I} X_{i}, \left(x_{0}^{i} \right)_{i \in I} \right) \to \left(X_{i}, x_{0}^{i} \right) \right\}_{i \in I}$$

of maps given by

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

for each $(x_j)_{i \in I} \in \prod_{i \in I} X_i$ and each $i \in I$.

Proof. We claim that $\left(\prod_{i\in I} X_i, (x_0^i)_{i\in I}\right)$ is the categorical product of $\left\{(X_i, x_0^i)\right\}_{i\in I}$ in Sets_{*}. Indeed, suppose we have, for each $i\in I$, a diagram of the form



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

$$\phi \colon (P, *) \to \left(\prod_{i \in I} X_i, \left(x_0^i\right)_{i \in I}\right)$$

making the diagram

$$(P, *)$$

$$\phi \downarrow \exists !$$

$$\left(\prod_{i \in I} X_i, (x_0^i)_{i \in I}\right) \xrightarrow{\operatorname{pr}_i} (X_i, x_0^i)$$

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

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

for each $x \in P$. Note that this is indeed a morphism of pointed sets, as we have

$$\phi(*) = (p_i(*))_{i \in I}$$
$$= (x_0^i)_{i \in I},$$

where we have used that p_i is a morphism of pointed sets for each $i \in I$.

Proposition 6.2.2.1.3. Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

1. Functoriality. The assignment $\{(X_i, x_0^i)\}_{i \in I} \mapsto \left(\prod_{i \in I} X_i, (x_0^i)_{i \in I}\right)$ defines a functor $\prod_{i \in I} : \mathsf{Fun}(I_{\mathsf{disc}}, \mathsf{Sets}_*) \to \mathsf{Sets}_*.$

Proof. Item 1, *Functoriality*: This follows from Limits and Colimits, ?? of ??. \Box

6.2.3 Products

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

Definition 6.2.3.1.1. The **product of** (X, x_0) **and** (Y, y_0) is the product of (X, x_0) and (Y, y_0) in Sets_{*} as in Limits and Colimits, ??.

Construction 6.2.3.1.2. Concretely, the **product of** (X, x_0) **and** (Y, y_0) is the pair consisting of:

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- *The Limit.* The pointed set $(X \times Y, (x_0, y_0))$.
- The Cone. The morphisms of pointed sets

$$\operatorname{pr}_1 : (X \times Y, (x_0, y_0)) \to (X, x_0),$$

 $\operatorname{pr}_2 : (X \times Y, (x_0, y_0)) \to (Y, y_0)$

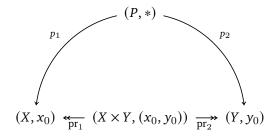
defined by

$$\operatorname{pr}_{1}(x, y) \stackrel{\text{def}}{=} x,$$

 $\operatorname{pr}_{2}(x, y) \stackrel{\text{def}}{=} y$

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

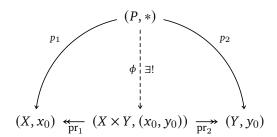
Proof. We claim that $(X \times Y, (x_0, y_0))$ is the categorical product of (X, x_0) and (Y, y_0) in Sets_{*}. Indeed, suppose we have a diagram of the form



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

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

making the diagram



commute, being uniquely determined by the conditions

$$\operatorname{pr}_1 \circ \phi = p_1,$$

 $\operatorname{pr}_2 \circ \phi = p_2$

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via

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

for each $x \in P$. Note that this is indeed a morphism of pointed sets, as we have

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

= $(x_0, y_0),$

where we have used that p_1 and p_2 are morphisms of pointed sets.

Proposition 6.2.3.1.3. Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets.

1. Functoriality. The assignments

$$(X, x_0), (Y, y_0), ((X, x_0), (Y, y_0)) \mapsto (X \times Y, (x_0, y_0))$$

define functors

$$A \times -:$$
 Sets_{*} \rightarrow Sets_{*},
 $- \times B:$ Sets_{*} \rightarrow Sets_{*},
 $-_1 \times -_2:$ Sets_{*} \times Sets_{*} \rightarrow Sets_{*},

defined in the same way as the functors of Constructions With Sets, Item 1 of Definition 4.1.3.1.3.

- 2. *Lack of Adjointness.* The functors $X \times -$ and $\times Y$ do not admit right adjoints.
- 3. Associativity. We have an isomorphism of pointed sets

$$((X \times Y) \times Z, ((x_0, y_0), z_0)) \cong (X \times (Y \times Z), (x_0, (y_0, z_0)))$$

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

4. Unitality. We have isomorphisms of pointed sets

$$(pt, \star) \times (X, x_0) \cong (X, x_0),$$

 $(X, x_0) \times (pt, \star) \cong (X, x_0),$

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

5. Commutativity. We have an isomorphism of pointed sets

$$(X \times Y, (x_0, y_0)) \cong (Y \times X, (y_0, x_0)),$$

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

6. *Symmetric Monoidality*. The triple (Sets_{*}, ×, (pt, ★)) is a symmetric monoidal category.

Proof. Item 1, Functoriality: This is a special case of functoriality of limits, Limits and Colimits, ?? of ??.

Item 2, Lack of Adjointness: See [MSE 2855868].

Item 3, Associativity: This follows from Constructions With Sets, Item 4 of Definition 4.1.3.1.3.

Item 4, Unitality: This follows from Constructions With Sets, Item 5 of Definition 4.1.3.1.3.

Item 5, Commutativity: This follows from Constructions With Sets, Item 6 of Definition 4.1.3.1.3.

Item 6, Symmetric Monoidality: This follows from Constructions With Sets, Item 14 of Definition 4.1.3.1.3.

6.2.4 Pullbacks

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets and let $f: (X, x_0) \to (Z, z_0)$ and $g: (Y, y_0) \to (Z, z_0)$ be morphisms of pointed sets.

Definition 6.2.4.1.1. The **pullback of** (X, x_0) **and** (Y, y_0) **over** (Z, z_0) **along** (f, g) is the pullback of (X, x_0) and (Y, y_0) over (Z, z_0) along (f, g) in Sets_{*} as in Limits and Colimits, ??.

Construction 6.2.4.1.2. Concretely, the **pullback of** (X, x_0) **and** (Y, y_0) **over** (Z, z_0) **along** (f, g) is the pair consisting of:

- The Limit. The pointed set $(X \times_Z Y, (x_0, y_0))$.
- The Cone. The morphisms of pointed sets

$$\operatorname{pr}_1 : (X \times_Z Y, (x_0, y_0)) \to (X, x_0),$$

 $\operatorname{pr}_2 : (X \times_Z Y, (x_0, y_0)) \to (Y, y_0)$

defined by

$$\operatorname{pr}_{1}(x, y) \stackrel{\text{def}}{=} x,$$

 $\operatorname{pr}_{2}(x, y) \stackrel{\text{def}}{=} y$

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

Proof. We claim that $X \times_Z Y$ is the categorical pullback of (X, x_0) and (Y, y_0) over (Z, z_0) with respect to (f, g) in Sets_{*}. First we need to check that the relevant

pullback diagram commutes, i.e. that we have

$$f \circ \operatorname{pr}_{1} = g \circ \operatorname{pr}_{2}, \qquad \operatorname{pr}_{1} \downarrow \qquad \qquad \downarrow g$$

$$(X \times_{Z} Y, (x_{0}, y_{0})) \xrightarrow{\operatorname{pr}_{2}} (Y, y_{0})$$

$$\operatorname{pr}_{1} \downarrow \qquad \qquad \downarrow g$$

$$(X, x_{0}) \xrightarrow{f} (Z, z_{0}).$$

Indeed, given $(x, y) \in X \times_Z Y$, we have

$$[f \circ \operatorname{pr}_1](x, y) = f(\operatorname{pr}_1(x, y))$$

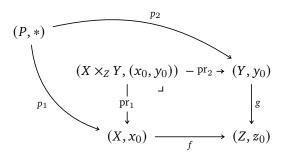
$$= f(x)$$

$$= g(y)$$

$$= g(\operatorname{pr}_2(x, y))$$

$$= [g \circ \operatorname{pr}_2](x, y),$$

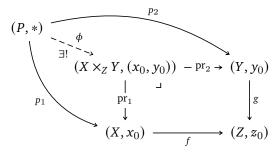
where f(x) = g(y) since $(x, y) \in X \times_Z Y$. Next, we prove that $X \times_Z Y$ satisfies the universal property of the pullback. Suppose we have a diagram of the form



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

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

making the diagram



commute, being uniquely determined by the conditions

$$\operatorname{pr}_1 \circ \phi = p_1,$$

 $\operatorname{pr}_2 \circ \phi = p_2$

via

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

for each $x \in P$, where we note that $(p_1(x), p_2(x)) \in X \times Y$ indeed lies in $X \times_Z Y$ by the condition

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

which gives

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

for each $x \in P$, so that $(p_1(x), p_2(x)) \in X \times_Z Y$. Lastly, we note that ϕ is indeed a morphism of pointed sets, as we have

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

= $(x_0, y_0),$

where we have used that p_1 and p_2 are morphisms of pointed sets.

Proposition 6.2.4.1.3. Let (X, x_0) , (Y, y_0) , (Z, z_0) , and (A, a_0) be pointed sets.

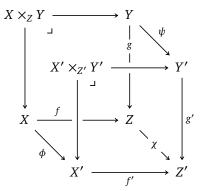
1. Functoriality. The assignment $(X, Y, Z, f, g) \mapsto X \times_{f, Z, g} Y$ defines a functor

$$-1 \times_{-3} -1$$
: Fun(\mathcal{P} , Sets_{*}) \rightarrow Sets_{*},

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



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



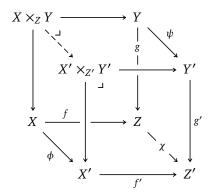
in $Fun(\mathcal{P}, \mathsf{Sets}_*)$ to the morphism of pointed sets

$$\xi \colon (X \times_Z Y, (x_0, y_0)) \xrightarrow{\exists !} (X' \times_{Z'} Y', (x'_0, y'_0))$$

given by

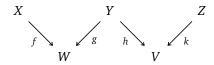
$$\xi(x,y) \stackrel{\text{def}}{=} (\phi(x), \psi(y))$$

for each $(x, y) \in X \times_Z Y$, which is the unique morphism of pointed sets making the diagram



commute.

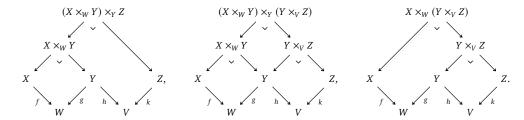
2. Associativity. Given a diagram



in Sets*, we have isomorphisms of pointed sets

$$(X \times_W Y) \times_V Z \cong (X \times_W Y) \times_Y (Y \times_V Z) \cong X \times_W (Y \times_V Z),$$

where these pullbacks are built as in the diagrams



3. Unitality. We have isomorphisms of pointed sets

4. Commutativity. We have an isomorphism of pointed sets

$$A \times_X B \longrightarrow B$$

$$\downarrow \qquad \qquad \downarrow g \qquad A \times_X B \cong B \times_X A \qquad \qquad \downarrow f$$

$$A \xrightarrow{f} X, \qquad \qquad B \xrightarrow{g} X.$$

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

$$X \times_{\text{pt}} Y \cong X \times Y,$$

$$X \times_{\text{pt}} Y \cong X \times Y,$$

$$X \xrightarrow{!_{X}} \text{pt.}$$

6. *Symmetric Monoidality*. The triple (Sets_{*}, \times_X , X) is a symmetric monoidal category.

Proof. 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, Associativity: This follows from Constructions With Sets, Item 4 of Definition 4.1.4.1.5.

Item 3, Unitality: This follows from Constructions With Sets, Item 6 of Definition 4.1.4.1.5.

Item 4, Commutativity: This follows from Constructions With Sets, Item 7 of Definition 4.1.4.1.5.

Item 5, Interaction With Products: This follows from Constructions With Sets, Item 10 of Definition 4.1.4.1.5.

Item 6, Symmetric Monoidality: This follows from Constructions With Sets, Item 11 of Definition 4.1.4.1.5. □

6.2.5 Equalisers

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

Definition 6.2.5.1.1. The **equaliser of** (f, g) is the equaliser of f and g in Sets_{*} as in Limits and Colimits, **??**.

Construction 6.2.5.1.2. Concretely, the **equaliser of** (f, g) is the pair consisting of:

- *The Limit.* The pointed set $(Eq(f, g), x_0)$.
- *The Cone.* The morphism of pointed sets

$$eq(f,g): (Eq(f,g),x_0) \hookrightarrow (X,x_0)$$

given by the canonical inclusion $eq(f,g) \hookrightarrow Eq(f,g) \hookrightarrow X$.

Proof. We claim that $(\text{Eq}(f,g),x_0)$ is the categorical equaliser of f and g in Sets_{*}. First we need to check that the relevant equaliser diagram commutes, i.e. that we have

$$f \circ eq(f,g) = g \circ eq(f,g),$$

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

$$(\text{Eq}(f,g),x_0) \xrightarrow{\text{eq}(f,g)} (X,x_0) \xrightarrow{f} (Y,y_0)$$

$$(E,*)$$

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

$$\phi \colon (E, *) \to (\text{Eq}(f, g), x_0)$$

making the diagram

$$(\operatorname{Eq}(f,g),x_0) \xrightarrow{\operatorname{eq}(f,g)} (X,x_0) \xrightarrow{f} (Y,y_0)$$

$$\downarrow \phi \mid \exists! \qquad e$$

$$(E,*)$$

commute, being uniquely determined by the condition

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

via

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

for each $x \in E$, where we note that $e(x) \in A$ indeed lies in 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 $e(x) \in Eq(f,g)$. Lastly, we note that ϕ is indeed a morphism of pointed sets, as we have

$$\phi(*) = e(*)$$
$$= x_0,$$

where we have used that e is a morphism of pointed sets.

Proposition 6.2.5.1.3. Let (X, x_0) and (Y, y_0) be pointed sets and let $f, g, h: (X, x_0) \rightarrow (Y, y_0)$ be morphisms of pointed sets.

1. Associativity. We have isomorphisms of pointed sets

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

where Eq(f, g, h) is the limit of the diagram

$$(X, x_0) \xrightarrow{f \atop -g \Rightarrow \atop h} (Y, y_0)$$

in Sets*, being explicitly given by

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

2. Unitality. We have an isomorphism of pointed sets

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

3. Commutativity. We have an isomorphism of pointed sets

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

Proof. Item 1, Associativity: This follows from Constructions With Sets, Item 1 of Definition 4.1.5.1.3.

Item 2, Unitality: This follows from Constructions With Sets, Item 4 of Definition 4.1.5.1.3.

Item 3, Commutativity: This follows from Constructions With Sets, Item 5 of Definition 4.1.5.1.3.

6.3 Colimits of Pointed Sets

6.3.1 The Initial Pointed Set

Definition 6.3.1.1.1. The **initial pointed set** is the initial object of Sets_{*} as in Limits and Colimits, ??.

Construction 6.3.1.1.2. Concretely, the **initial pointed set** is the pair $((pt, \star), \{\iota_X\}_{(X,x_0) \in Obj(Sets_*)})$ consisting of:

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

$$\{\iota_X \colon (\mathsf{pt}, \star) \to (X, x_0)\}_{(X, x_0) \in \mathsf{Obj}(\mathsf{Sets})}$$

defined by

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

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

$$(pt, \star)$$
 (X, x_0)

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

$$\phi \colon (\mathsf{pt}, \star) \to (X, x_0)$$

making the diagram

$$(\text{pt}, \star) \xrightarrow{-\frac{\phi}{\exists !}} (X, x_0)$$

commute, namely ι_X .

6.3.2 Coproducts of Families of Pointed Sets

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

Definition 6.3.2.1.1. The **coproduct of the family** $\{(X_i, x_0^i)\}_{i \in I}$ is the coproduct of $\{(X_i, x_0^i)\}_{i \in I}$ in Sets_{*} as in Limits and Colimits, ??.

Construction 6.3.2.1.2. Concretely, the **coproduct of the family** $\{(X_i, x_0^i)\}_{i \in I}$ is the pair $((\bigvee_{i \in I} X_i, p_0), \{\inf_i\}_{i \in I})$ consisting of:

- *The Colimit.* The pointed set $(\bigvee_{i \in I} X_i, p_0)$ consisting of:
 - The Underlying Set. The set $\bigvee_{i \in I} X_i$ defined by

$$\bigvee_{i \in I} X_i \stackrel{\text{def}}{=} \left(\coprod_{i \in I} X_i \right) / \sim,$$

where \sim is the equivalence relation on $\coprod_{i \in I} X_i$ given by declaring

$$(i, x_0^i) \sim (j, x_0^j)$$

for each $i, j \in I$.

- The Basepoint. The element p_0 of $\bigvee_{i \in I} X_i$ defined by

$$p_0 \stackrel{\text{def}}{=} \left[\left(i, x_0^i \right) \right]$$
$$= \left[\left(j, x_0^j \right) \right]$$

for any $i, j \in I$.

• The Cocone. The collection

$$\left\{\inf_{i}: \left(X_{i}, x_{0}^{i}\right) \to \left(\bigvee_{i \in I} X_{i}, p_{0}\right)\right\}_{i \in I}$$

of morphism of pointed sets given by

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

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

Proof. We claim that $(\bigvee_{i \in I} X_i, p_0)$ is the categorical coproduct of $\{(X_i, x_0^i)\}_{i \in I}$ in

¹¹ Further Terminology: Also called the wedge sum of the family $\{(X_i, x_0^i)\}_{i \in I}$.

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

$$(X_i, x_0^i) \xrightarrow{\text{inj}_i} \left(\bigvee_{i \in I} X_i, p_0\right)$$

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

$$\phi: \left(\bigvee_{i\in I} X_i, p_0\right) \to (C, *)$$

making the diagram

$$(C, *)$$

$$\phi \uparrow \exists !$$

$$(X_i, x_0^i) \xrightarrow{\operatorname{inj}_i} \left(\bigvee_{i \in I} X_i, p_0\right)$$

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

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

for each $[(i, x)] \in \bigvee_{i \in I} X_i$, where we note that ϕ is indeed a morphism of pointed sets, as we have

$$\phi(p_0) = \iota_i \left(\left[\left(i, x_0^i \right) \right] \right)$$
= *.

as ι_i is a morphism of pointed sets.

Proposition 6.3.2.1.3. Let $\{(X_i, x_0^i)\}_{i \in I}$ be a family of pointed sets.

1. Functoriality. The assignment $\{(X_i, x_0^i)\}_{i \in I} \mapsto (\bigvee_{i \in I} X_i, p_0)$ defines a functor

$$\bigvee_{i \in I} : \mathsf{Fun}(I_{\mathsf{disc}}, \mathsf{Sets}_*) \to \mathsf{Sets}_*.$$

Proof. Item 1, Functoriality: This follows from Limits and Colimits, ?? of ??. □

6.3.3 Coproducts

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

Definition 6.3.3.1.1. The **coproduct of** (X, x_0) **and** $(Y, y_0)^{12}$ is the coproduct of (X, x_0) and (Y, y_0) in Sets_{*} as in Limits and Colimits, ??.

Construction 6.3.3.1.2. Concretely, the **coproduct of** (X, x_0) **and** (Y, y_0) , also called their **wedge sum**, is the pair consisting of:

- *The Colimit.* The pointed set $(X \vee Y, p_0)$ consisting of:
 - The Underlying Set. The set $X \vee Y$ defined by

$$(X \lor Y, p_0) \stackrel{\text{def}}{=} (X, x_0) \coprod (Y, y_0) \qquad X \lor Y \longleftarrow Y$$

$$\cong \left(X \coprod_{p_t} Y, p_0\right) \qquad \uparrow \qquad \uparrow \qquad \downarrow [y_0]$$

$$\cong (X \coprod Y/\sim, p_0), \qquad X \longleftarrow_{[x_0]} p_t,$$

where \sim is the equivalence relation on $X \coprod Y$ obtained by declaring $(0, x_0) \sim (1, y_0)$.

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

$$p_0 \stackrel{\text{def}}{=} [(0, x_0)]$$

= $[(1, y_0)].$

• The Cocone. The morphisms of pointed sets

$$\begin{split} & \operatorname{inj}_1 \colon (X, x_0) \to (X \vee Y, p_0), \\ & \operatorname{inj}_2 \colon (Y, y_0) \to (X \vee Y, p_0), \end{split}$$

given by

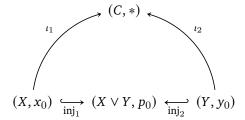
$$inj_1(x) \stackrel{\text{def}}{=} [(0, x)], \\
inj_2(y) \stackrel{\text{def}}{=} [(1, y)],$$

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

Proof. We claim that $(X \vee Y, p_0)$ is the categorical coproduct of (X, x_0) and (Y, y_0)

¹²Further Terminology: Also called the **wedge sum of** (X, x_0) **and** (Y, y_0) .

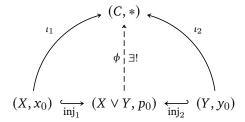
in Sets*. Indeed, suppose we have a diagram of the form



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

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

making the diagram



commute, being uniquely determined by the conditions

$$\phi \circ \operatorname{inj}_X = \iota_X,$$

$$\phi \circ \operatorname{inj}_V = \iota_Y$$

via

$$\phi(z) = \begin{cases} \iota_X(x) & \text{if } z = [(0, x)] \text{ with } x \in X, \\ \iota_Y(y) & \text{if } z = [(1, y)] \text{ with } y \in Y \end{cases}$$

for each $z \in X \vee Y$, where we note that ϕ is indeed a morphism of pointed sets, as we have

$$\phi(p_0) = \iota_X([(0, x_0)])$$

= $\iota_Y([(1, y_0)])$
= *.

as ι_X and ι_Y are morphisms of pointed sets.

Proposition 6.3.3.1.3. Let (X, x_0) and (Y, y_0) be pointed sets.

1. Functoriality. The assignments

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

define functors

$$X \lor -: \mathsf{Sets}_* \to \mathsf{Sets}_*,$$

 $- \lor Y : \mathsf{Sets}_* \to \mathsf{Sets}_*,$
 $-_1 \lor -_2 : \mathsf{Sets}_* \times \mathsf{Sets}_* \to \mathsf{Sets}_*.$

2. Associativity. We have an isomorphism of pointed sets

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

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

3. Unitality. We have isomorphisms of pointed sets

$$(pt, *) \lor (X, x_0) \cong (X, x_0),$$

 $(X, x_0) \lor (pt, *) \cong (X, x_0),$

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

4. Commutativity. We have an isomorphism of pointed sets

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

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

- 5. *Symmetric Monoidality*. The triple (Sets_{*}, ∨, pt) is a symmetric monoidal category.
- 6. The Fold Map. We have a natural transformation

$$\nabla\colon \vee\circ\Delta^{\mathsf{Cats}}_{\mathsf{Sets}_*}\Longrightarrow id_{\mathsf{Sets}_*}, \qquad \stackrel{\Delta^{\mathsf{Cats}}_{\mathsf{Sets}_*}}{\overset{\nabla}{\mathsf{Sets}_*}} \bigvee_{\overset{\nabla}{\mathsf{Sets}_*}} \mathsf{Sets}_*,$$

called the **fold map**, whose component

$$\nabla_X : X \vee X \to X$$

at X is given by

$$\nabla_X(p) \stackrel{\text{def}}{=} \begin{cases} x & \text{if } p = [(0, x)], \\ x & \text{if } p = [(1, x)] \end{cases}$$

for each $p \in X \vee X$.

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

Item 2, Associativity: Omitted.

Item 3, Unitality: Omitted.

Item 4, Commutativity: Omitted.

Item 5, Symmetric Monoidality: Omitted.

Item 6, The Fold Map: Naturality for the transformation ∇ is the statement that, given a morphism of pointed sets $f: (X, x_0) \to (Y, y_0)$, we have

$$\nabla_{Y} \circ (f \vee f) = f \circ \nabla_{X}, \quad X \vee X \xrightarrow{\nabla_{X}} X$$

$$V_{Y} \circ (f \vee f) = f \circ \nabla_{X}, \quad f \vee f \downarrow \qquad \downarrow f$$

$$Y \vee Y \xrightarrow{\nabla_{Y}} Y.$$

Indeed, we have

$$\begin{aligned} [\nabla_Y \circ (f \vee f)]([(i,x)]) &= \nabla_Y([(i,f(x))]) \\ &= f(x) \\ &= f(\nabla_X([(i,x)])) \\ &= [f \circ \nabla_X]([(i,x)]) \end{aligned}$$

for each $[(i, x)] \in X \vee X$, and thus ∇ is indeed a natural transformation.

6.3.4 Pushouts

Let (X, x_0) , (Y, y_0) , and (Z, z_0) be pointed sets and let $f: (Z, z_0) \to (X, x_0)$ and $g: (Z, z_0) \to (Y, y_0)$ be morphisms of pointed sets.

Definition 6.3.4.1.1. The **pushout of** (X, x_0) **and** (Y, y_0) **over** (Z, z_0) **along** (f, g) is the pushout of (X, x_0) and (Y, y_0) over (Z, z_0) along (f, g) in Sets_{*} as in Limits and Colimits, ??.

Construction 6.3.4.1.2. Concretely, the **pushout of** (X, x_0) **and** (Y, y_0) **over** (Z, z_0) **along** (f, g) is the pair consisting of:

• *The Colimit*. The pointed set $(X \coprod_{f,Z,g} Y, p_0)$, where:

- The set $X \coprod_{f,Z,g} Y$ is the pushout (of unpointed sets) of X and Y over Z with respect to f and g;

- We have $p_0 = [x_0] = [y_0]$.
- The Cocone. The morphisms of pointed sets

$$\operatorname{inj}_1 \colon (X, x_0) \to (X \coprod_Z Y, p_0),$$

 $\operatorname{inj}_2 \colon (Y, y_0) \to (X \coprod_Z Y, p_0)$

given by

$$inj_1(x) \stackrel{\text{def}}{=} [(0, x)]
inj_2(y) \stackrel{\text{def}}{=} [(1, y)]$$

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

Proof. Firstly, we note that indeed $[x_0] = [y_0]$, as we have

$$x_0 = f(z_0),$$

$$y_0 = g(z_0)$$

since f and g are morphisms of pointed sets, with the relation \sim on $X \coprod_Z Y$ then identifying $x_0 = f(z_0) \sim g(z_0) = y_0$.

We now claim that $(X \coprod_Z Y, p_0)$ is the categorical pushout of (X, x_0) and (Y, y_0) over (Z, z_0) with respect to (f, g) in Sets_{*}. First we need to check that the relevant pushout diagram commutes, i.e. that we have

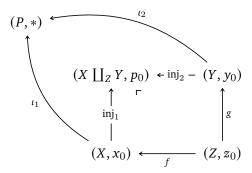
$$(X \coprod_{Z} Y, p_{0}) \stackrel{\text{inj}_{2}}{\longleftarrow} (Y, y_{0})$$

$$\text{inj}_{1} \circ f = \text{inj}_{2} \circ g, \qquad \underset{\text{inj}_{1}}{\text{inj}_{1}} \qquad \qquad \underset{f}{\text{}} \qquad (Z, z_{0}).$$

Indeed, given $z \in Z$, we have

$$\begin{aligned} \left[\inf_{1} \circ f \right](z) &= \inf_{1} (f(z)) \\ &= \left[(0, f(z)) \right] \\ &= \left[(1, g(z)) \right] \\ &= \inf_{2} (g(z)) \\ &= \left[\inf_{2} \circ g \right](z), \end{aligned}$$

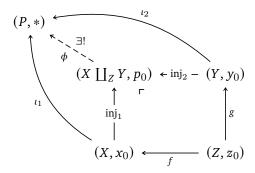
where [(0, f(z))] = [(1, g(z))] by the definition of the relation \sim on $X \coprod Y$ (the coproduct of unpointed sets of X and Y). Next, we prove that $X \coprod ZY$ satisfies the universal property of the pushout. Suppose we have a diagram of the form



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

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

making the diagram



commute, being uniquely determined by the conditions

$$\phi \circ \operatorname{inj}_1 = \iota_1,$$

 $\phi \circ \operatorname{inj}_2 = \iota_2$

via

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

for each $p \in X \coprod_Z Y$, where the well-definedness of ϕ is proven in the same way as in the proof of Constructions With Sets, Definition 4.2.4.1.1. Finally, we show that ϕ is indeed a morphism of pointed sets, as we have

$$\phi(p_0) = \phi([(0, x_0)])$$

$$= \iota_1(x_0)$$
$$= *,$$

or alternatively

$$\phi(p_0) = \phi([(1, y_0)])$$

= $\iota_2(y_0)$
= *.

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

Proposition 6.3.4.1.3. Let (X, x_0) , (Y, y_0) , (Z, z_0) , and (A, a_0) be pointed sets.

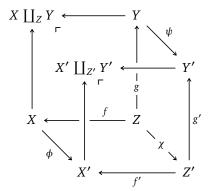
1. Functoriality. The assignment $(X,Y,Z,f,g)\mapsto X\coprod_{f,Z,g}Y$ defines a functor

$$-1 \coprod_{-3} -1$$
: Fun(\mathcal{P} , Sets) \rightarrow Sets_{*},

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



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



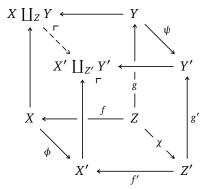
in $Fun(\mathcal{P}, Sets_*)$ to the morphism of pointed sets

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

given by

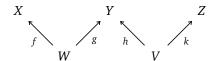
$$\xi(p) \stackrel{\text{def}}{=} \begin{cases} \phi(x) & \text{if } p = [(0, x)], \\ \psi(y) & \text{if } p = [(1, y)] \end{cases}$$

for each $p \in X \coprod_Z Y$, which is the unique morphism of pointed sets making the diagram



commute.

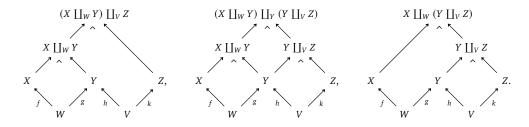
2. Associativity. Given a diagram



in Sets, we have isomorphisms of pointed sets

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

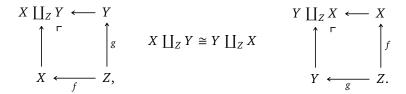
where these pullbacks are built as in the diagrams



3. *Unitality*. We have isomorphisms of sets



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



5. Interaction With Coproducts. We have

$$X \coprod_{\mathsf{pt}} Y \cong X \vee Y, \qquad \bigwedge^{\mathsf{r}} \qquad \bigwedge^{\mathsf{r}} \qquad \bigwedge^{\mathsf{r}} [y_0]$$

$$X \longleftarrow_{[x_0]} \mathsf{pt}.$$

6. *Symmetric Monoidality*. The triple (Sets_{*}, \coprod_X , (X, x_0)) is a symmetric monoidal category.

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

Item 2, Associativity: This follows from Constructions With Sets, Item 3 of Definition 4.2.4.1.6.

Item 3, Unitality: This follows from Constructions With Sets, Item 5 of Definition 4.2.4.1.6.

Item 4, Commutativity: This follows from Constructions With Sets, Item 6 of Definition 4.2.4.1.6.

Item 5, *Interaction With Coproducts*: Omitted.

Item 6, Symmetric Monoidality: Omitted.

6.3.5 Coequalisers

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

Definition 6.3.5.1.1. The **coequaliser of** (f,g) is the pointed set $(CoEq(f,g), [y_0])$.

Construction 6.3.5.1.2. The **coequaliser of** (f, g) is the pair $((CoEq(f, g), [y_0]), coeq(f, g))$ consisting of:

• *The Colimit.* The pointed set $(CoEq(f,g), [y_0])$, where CoEq(f,g) is the coequaliser of f and g as in Constructions With Sets, Definition 4.2.5.1.1.

• The Cocone. The map

$$coeq(f,g): Y \rightarrow (CoEq(f,g), [y_0])$$

given by the quotient map, as in Constructions With Sets, Item 2 of Definition 4.2.5.1.2.

Proof. We claim that $(CoEq(f, g), [y_0])$ is the categorical coequaliser of f and g in Sets_{*}. First we need to check that the relevant coequaliser diagram commutes, i.e. that we have

$$coeq(f, g) \circ f = coeq(f, g) \circ g$$
.

Indeed, we have

$$[\operatorname{coeq}(f,g) \circ f](x) \stackrel{\text{def}}{=} [\operatorname{coeq}(f,g)](f(x))$$

$$\stackrel{\text{def}}{=} [f(x)]$$

$$= [g(x)]$$

$$\stackrel{\text{def}}{=} [\operatorname{coeq}(f,g)](g(x))$$

$$\stackrel{\text{def}}{=} [\operatorname{coeq}(f,g) \circ g](x)$$

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

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

$$(C, *)$$

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 Definition 10.6.2.1.3 that there exists a unique map $\phi \colon \mathsf{CoEq}(f,g) \xrightarrow{\exists !} C$ making the diagram

commute, where we note that ϕ is indeed a morphism of pointed sets since

$$\phi([y_0]) = [\phi \circ \operatorname{coeq}(f, g)]([y_0])$$

$$= c([y_0])$$
$$= *$$

where we have used that c is a morphism of pointed sets.

Proposition 6.3.5.1.3. Let (X, x_0) and (Y, y_0) be pointed sets and let $f, g, h: (X, x_0) \rightarrow (Y, y_0)$ be morphisms of pointed sets.

1. Associativity. We have isomorphisms of pointed sets

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

where CoEq(f, g, h) is the colimit of the diagram

$$(X, x_0) \xrightarrow{f \atop -g \Rightarrow} (Y, y_0)$$

in Sets_{*}.

2. Unitality. We have an isomorphism of pointed sets

$$CoEq(f, f) \cong B$$
.

3. Commutativity. We have an isomorphism of pointed sets

$$CoEq(f, g) \cong CoEq(g, f)$$
.

Proof. Item 1, Associativity: This follows from Constructions With Sets, Item 1 of Definition 4.2.5.1.5.

Item 2, Unitality: This follows from Constructions With Sets, Item 4 of Definition 4.2.5.1.5.

Item 3, Commutativity: This follows from Constructions With Sets, Item 5 of Definition 4.2.5.1.5.

6.4 Constructions With Pointed Sets

6.4.1 Free Pointed Sets

Let *X* be a set.

Definition 6.4.1.1.1. The **free pointed set on** X is the pointed set X^+ consisting of:

• The Underlying Set. The set X^+ defined by ¹³

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

$$\stackrel{\text{def}}{=} X \coprod \{ \star \}.$$

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

Proposition 6.4.1.1.2. Let *X* be a set.

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

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

where:

• Action on Objects. For each $X \in Obj(Sets)$, we have

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

where X^+ is the pointed set of Definition 6.4.1.1.1.

• *Action on Morphisms*. For each morphism $f: X \to Y$ of Sets, the image

$$f^+\colon X^+\to Y^+$$

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

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

2. Adjointness. We have an adjunction

$$((-)^+ \dashv \overline{\bowtie}): \operatorname{Sets}_{\stackrel{(-)^+}{\rightleftarrows}} \operatorname{Sets}_*,$$

witnessed by a bijection of sets

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

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

¹³Further Notation: We sometimes write \star_X for the basepoint of X^+ for clarity, specially when there are multiple free pointed sets involved in the current discussion.

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

$$\left((-)^+,(-)^{+,\coprod},(-)^{+,\coprod}_{\mathbb{1}}\right)\colon(\mathsf{Sets},\coprod,\emptyset)\to(\mathsf{Sets}_*,\vee,\mathsf{pt}),$$

being equipped with isomorphisms of pointed sets

$$(-)_{X,Y}^{+,\coprod}: X^{+} \vee Y^{+} \xrightarrow{\sim} (X \coprod Y)^{+},$$
$$(-)_{1}^{+,\coprod}: \operatorname{pt} \xrightarrow{\sim} \emptyset^{+},$$

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

4. *Symmetric Strong Monoidality With Respect to Smash Products.* The free pointed set functor of Item 1 has a symmetric strong monoidal structure

$$\left((-)^+,(-)^+,(-)^+_{\mathbb{1}}\right)\colon (\mathsf{Sets},\times,\mathsf{pt})\to \left(\mathsf{Sets}_*,\wedge,S^0\right),$$

being equipped with isomorphisms of pointed sets

$$(-)_{X,Y}^+ \colon X^+ \wedge Y^+ \xrightarrow{\sim} (X \times Y)^+,$$
$$(-)_{1}^+ \colon S^0 \xrightarrow{\sim} \mathsf{pt}^+,$$

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

Proof. Item 1, *Functoriality*: We claim that $(-)^+$ is indeed a functor:

• Preservation of Identities. Let $X \in Obj(Sets)$. We have

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

for each $x \in X^+$, so $id_X^+ = id_{X^+}$.

• Preservation of Composition. Given morphisms of sets

$$f: X \to Y$$
, $g: Y \to Z$,

we have

$$[g^+ \circ f^+](x) \stackrel{\text{def}}{=} g^+(f^+(x))$$

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

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

$$\stackrel{\text{def}}{=} [g \circ f]^+(x)$$

for each $x \in X$ and

$$[g^+ \circ f^+](\star_X) \stackrel{\text{def}}{=} g^+(f^+(\star_X))$$

$$\stackrel{\text{def}}{=} g^+(\star_Y)$$

$$\stackrel{\text{def}}{=} \star_Z$$

$$\stackrel{\text{def}}{=} [g \circ f]^+(\star_X),$$

so
$$(g \circ f)^{+} = g^{+} \circ f^{+}$$
.

This finishes the proof.

Item 2, Adjointness: We proceed in a few steps:

• Map I. We define a map

$$\Phi_{X,Y} : \mathsf{Sets}_*(X^+, Y) \to \mathsf{Sets}(X, Y)$$

by sending a morphism of pointed sets

$$\xi \colon (X^+, \star_X) \to (Y, y_0)$$

to the function

$$\xi^{\dagger}: X \to Y$$

given by

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

for each $x \in X$.

• Map II. We define a map

$$\Psi_{X,Y} : \mathsf{Sets}(X,Y) \to \mathsf{Sets}_*(X^+,Y)$$

given by sending a function $\xi: X \to Y$ to the morphism of pointed sets

$$\xi^{\dagger} \colon (X^+, \star_X) \to (Y, y_0)$$

defined by

$$\xi^{\dagger}(x) \stackrel{\text{def}}{=} \begin{cases} \xi(x) & \text{if } x \in X, \\ y_0 & \text{if } x = \star_X \end{cases}$$

for each $x \in X^+$.

• Invertibility I. Given a morphism of pointed sets

$$\xi \colon (X^+, \star_X) \to (Y, y_0),$$

we have

$$\begin{split} \left[\Psi_{X,Y} \circ \Phi_{X,Y}\right] (\xi) &\stackrel{\text{def}}{=} \Psi_{X,Y} \left(\Phi_{X,Y}(\xi)\right) \\ &= \Psi_{X,Y} \left(\xi^{\dagger}\right) \\ &\stackrel{\text{def}}{=} \left[\!\!\left[x \mapsto \begin{cases} \xi^{\dagger}(x) & \text{if } x \in X \\ y_0 & \text{if } x = \star_X \end{cases}\!\!\right] \\ &= \left[\!\!\left[x \mapsto \begin{cases} \xi(x) & \text{if } x \in X \\ y_0 & \text{if } x = \star_X \end{cases}\!\!\right] \\ &= \xi \\ &\stackrel{\text{def}}{=} \left[\text{id}_{\mathsf{Sets}_*(X^+,Y)}\right] (\xi). \end{split}$$

Therefore we have

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \mathrm{id}_{\mathsf{Sets}_*(X^+,Y)}$$
.

• *Invertibility II.* Given a map of sets $\xi: X \to Y$, we have

$$\begin{split} \left[\Phi_{X,Y} \circ \Psi_{X,Y}\right] (\xi) &\stackrel{\text{def}}{=} \Phi_{X,Y} \big(\Psi_{X,Y}(\xi)\big) \\ &= \Phi_{X,Y} \bigg(\xi^{\dagger}\bigg) \\ &= \Phi_{X,Y} \Bigg(\llbracket x \mapsto \begin{cases} \xi(x) & \text{if } x \in X \\ y_0 & \text{if } x = \star_X \end{cases} \rrbracket \bigg) \\ &= \llbracket x \mapsto \xi(x) \rrbracket \\ &= \xi \\ &\stackrel{\text{def}}{=} \left[id_{\mathsf{Sets}(X,Y)} \right] (\xi). \end{split}$$

Therefore we have

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

• Naturality for Φ , Part I. We need to show that, given a morphism of pointed sets

$$f: (X, x_0) \rightarrow (X', x_0'),$$

the diagram

$$\mathsf{Sets}_*(X'^{+},Y) \xrightarrow{\Phi_{X',Y}} \mathsf{Sets}(X',Y)$$

$$f^* \downarrow \qquad \qquad \downarrow f^*$$

$$\mathsf{Sets}_*(X^{+},Y) \xrightarrow{\Phi_{X,Y}} \mathsf{Sets}(X,Y)$$

commutes. Indeed, given a morphism of pointed sets $\xi \colon X'^{,+} \to Y$, we have

$$\begin{split} \big[\Phi_{X,Y} \circ f^* \big] (\xi) &= \Phi_{X,Y} (f^*(\xi)) \\ &= \Phi_{X,Y} (\xi \circ f) \\ &= \xi \circ f \\ &= \Phi_{X',Y} (\xi) \circ f \\ &= f^* \big(\Phi_{X',Y} (\xi) \big) \\ &= f^* \big(\Phi_{X',Y} (\xi) \big) \\ &= \big[f^* \circ \Phi_{X',Y} \big] (\xi). \end{split}$$

Therefore we have

$$\Phi_{X,Y} \circ f^* = f^* \circ \Phi_{X',Y}$$

and the naturality diagram for Φ above indeed commutes.

• Naturality for Φ , Part II. We need to show that, given a morphism of pointed sets

$$g: (Y, y_0) \rightarrow (Y', y_0'),$$

the diagram

$$\begin{aligned} \mathsf{Sets}_*(X^+,Y) & \xrightarrow{\Phi_{X,Y}} & \mathsf{Sets}(X,Y) \\ & \downarrow^{g_*} & & \downarrow^{g_*} \\ \mathsf{Sets}_*(X^+,Y'), & \xrightarrow{\Phi_{X,Y'}} & \mathsf{Sets}(X,Y') \end{aligned}$$

commutes. Indeed, given a morphism of pointed sets

$$\xi^{\dagger}: X^+ \to Y,$$

we have

$$\big[\Phi_{X,Y'}\circ g_*\big](\xi)=\Phi_{X,Y'}(g_*(\xi))$$

$$= \Phi_{X,Y'}(g \circ \xi)$$

$$= g \circ \xi$$

$$= g \circ \Phi_{X,Y'}(\xi)$$

$$= g_* (\Phi_{X,Y'}(\xi))$$

$$= [g_* \circ \Phi_{X,Y'}](\xi).$$

Therefore we have

$$\Phi_{X,Y'}\circ g_*=g_*\circ \Phi_{X,Y'}$$

and the naturality diagram for Φ above indeed commutes.

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 Definition 11.9.7.1.2 that Ψ is also natural in each argument.

This finishes the proof.

Item 3, Symmetric Strong Monoidality With Respect to Wedge Sums: We construct the strong monoidal structure on $(-)^+$ with respect to [] and \lor as follows:

• The Strong Monoidality Constraints. The isomorphism

$$(-)^{+,\coprod}_{X,Y}:X^+\vee Y^+\stackrel{\sim}{\dashrightarrow}(X\coprod Y)^+$$

is given by

$$(-)_{X,Y}^{+,\coprod}(z) = \begin{cases} x & \text{if } z = [(0,x)] \text{ with } x \in X, \\ y & \text{if } z = [(1,y)] \text{ with } y \in Y, \\ \star_{X \coprod Y} & \text{if } z = [(0,\star_X)], \\ \star_{X \coprod Y} & \text{if } z = [(1,\star_Y)] \end{cases}$$

for each $z \in X^+ \vee Y^+$, with inverse

$$(-)_{X,Y}^{+,\coprod,-1}\colon (X\coprod Y)^+\stackrel{\sim}{\longrightarrow} X^+\vee Y^+$$

given by

$$(-)_{X,Y}^{+,\coprod,-1}(z) \stackrel{\text{def}}{=} \begin{cases} [(0,x)] & \text{if } z = [(0,x)], \\ [(1,y)] & \text{if } z = [(1,y)], \\ p_0 & \text{if } z = \star_{X\coprod Y} \end{cases}$$

for each $z \in (X \coprod Y)^+$.

• The Strong Monoidal Unity Constraint. The isomorphism

$$(-)_{X,Y}^{+,\coprod,\mathbb{1}} \colon \operatorname{pt} \xrightarrow{\sim} \emptyset^+$$

is given by sending \star_X to \star_{\emptyset} .

The verification that these isomorphisms satisfy the coherence conditions making the functor $(-)^+$ into a symmetric strong monoidal functor is omitted. *Item 4, Symmetric Strong Monoidality With Respect to Smash Products*: We construct the strong monoidal structure on $(-)^+$ with respect to \times and \wedge as follows:

• The Strong Monoidality Constraints. The isomorphism

$$(-)_{XY}^+: X^+ \wedge Y^+ \xrightarrow{\sim} (X \times Y)^+$$

is given by

$$(-)_{X,Y}^+(x \wedge y) = \begin{cases} (x,y) & \text{if } x \neq \star_X \text{ and } y \neq \star_Y \\ \star_{X \times Y} & \text{otherwise} \end{cases}$$

for each $x \wedge y \in X^+ \wedge Y^+$, with inverse

$$(-)^{+,-1}_{XY} \colon (X \times Y)^+ \xrightarrow{\sim} X^+ \wedge Y^+$$

given by

$$(-)_{X,Y}^{+,-1}(z) \stackrel{\text{def}}{=} \begin{cases} x \wedge y & \text{if } z = (x,y) \text{ with } (x,y) \in X \times Y, \\ \star_X \wedge \star_Y & \text{if } z = \star_{X \times Y}, \end{cases}$$

for each $z \in (X \times Y)^+$.

• The Strong Monoidal Unity Constraint. The isomorphism

$$(-)_{XY}^{+,1} \colon S^0 \xrightarrow{\sim} pt^+$$

is given by sending 0 to \star_{pt} and 1 to \star , where $pt^+ = \{\star, \star_{pt}\}$.

The verification that these isomorphisms satisfy the coherence conditions making the functor $(-)^+$ into a symmetric strong monoidal functor is omitted.

6.4.2 Deleting Basepoints

Let (X, x_0) be a pointed set.

Definition 6.4.2.1.1. The **set with deleted basepoint associated to** X is the set X^- defined by

$$X^{-} \stackrel{\text{def}}{=} X \setminus \{x_0\}.$$

Proposition 6.4.2.1.2. Let (X, x_0) be a pointed set.

1. Functoriality. The assignment $(X, x_0) \mapsto X^-$ defines a functor

$$X^-: \mathsf{Sets}^{\mathsf{actv}}_* \to \mathsf{Sets},$$

where:

• Action on Objects. For each $X \in Obj(Sets^{actv}_*)$, we have

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

where X^- is the set of Definition 6.4.2.1.1.

• *Action on Morphisms*. For each morphism $f: X \to Y$ of $\mathsf{Sets}^\mathsf{actv}_*$, the image

$$f^-: X^- \to Y^-$$

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

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

for each $x \in X^-$.

2. Adjoint Equivalence. We have an adjoint equivalence of categories

$$((-)^- \dashv (-)^+)$$
: Sets^{actv} $\underbrace{-}_{(-)^+}$ Sets,

witnessed by a bijection of sets

$$Sets(X^-, Y) \cong Sets_*(X, Y^+),$$

natural in $X \in \text{Obj}(\mathsf{Sets}_*)$ and $Y \in \text{Obj}(\mathsf{Sets})$, and by isomorphisms

$$(X^{-})^{+} \cong X,$$
$$(Y^{+})^{-} \cong Y,$$

once again natural in $X \in Obj(Sets_*)$ and $Y \in Obj(Sets)$.

3. *Symmetric Strong Monoidality With Respect to Wedge Sums.* The functor of Item 1 has a symmetric strong monoidal structure

$$\left((-)^{-},(-)^{-,\vee},(-)_{\mathbb{1}}^{-,\vee}\right)\colon \left(\mathsf{Sets}^{\mathsf{actv}}_{*},\vee,\mathsf{pt}\right),\to \left(\mathsf{Sets}, \coprod, \emptyset\right),$$

being equipped with isomorphisms of pointed sets

$$(-)_{X,Y}^{-,\vee} \colon X^- \coprod Y^- \xrightarrow{\sim} (X \vee Y)^-,$$
$$(-)_{1}^{-,\vee} \colon \varnothing \xrightarrow{\sim} \mathsf{pt}^-,$$

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

4. Symmetric Strong Monoidality With Respect to Smash Products. The free pointed set functor of Item 1 has a symmetric strong monoidal structure

$$((-)^-, (-)^{-,\times}, (-)^{-,\times}_{\mathbb{1}}) : \left(\mathsf{Sets}^{\mathsf{actv}}_*, \wedge, S^0\right), \to (\mathsf{Sets}, \times, \mathsf{pt})$$

being equipped with isomorphisms of pointed sets

$$(-)_{X,Y}^-: X^- \times Y^- \xrightarrow{\sim} (X \wedge Y)^-,$$

 $(-)_{1}^-: \operatorname{pt} \xrightarrow{\sim} \left(S^0\right)^-,$

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

Proof. Item 1, Functoriality: We claim that $(-)^-$ is indeed a functor:

• Preservation of Identities. Let $X \in Obj(Sets)$. We have

$$id_X^-(x) \stackrel{\text{def}}{=} x$$

for each $x \in X^-$, so $id_X^- = id_{X^-}$.

• Preservation of Composition. Given morphisms of pointed sets

$$f: (X, x_0) \to (Y, y_0),$$

 $g: (Y, y_0) \to (Z, z_0),$

we have

$$[g^{-} \circ f^{-}](x) \stackrel{\text{def}}{=} g^{-}(f^{-}(x))$$

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

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

$$\stackrel{\text{def}}{=} [g \circ f]^{-}(x)$$

for each $x \in X$, so $(g \circ f)^- = g^- \circ f^-$.

This finishes the proof.

Item 2, Adjoint Equivalence: We proceed in a few steps:

1. Map I. We define a map

$$\Phi_{X,Y} : \mathsf{Sets}(X^-, Y) \to \mathsf{Sets}^{\mathsf{actv}}_*(X, Y^+)$$

by sending a map $\xi: X^- \to Y$ to the active morphism of pointed sets

$$\xi^{\dagger}: X \to Y^{+}$$

given by

$$\xi^{\dagger}(x) \stackrel{\text{def}}{=} \begin{cases} \xi(x) & \text{if } x \in X^{-}, \\ \star_{Y} & \text{if } x = x_{0}, \end{cases}$$

for each $x \in X$, where this morphism is indeed active since $\xi(x) \in Y = Y^+ \setminus \{\star_Y\}$ for all $x \in X^-$.

2. Map II. We define a map

$$\Psi_{X,Y} : \mathsf{Sets}^{\mathsf{actv}}_*(X,Y^+) \to \mathsf{Sets}(X^-,Y)$$

given by sending an active morphism of pointed sets $\xi: X \to Y^+$ to the map

$$\xi^{\dagger}: X^{-} \to Y$$

defined by

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

for each $x \in X^-$, which is indeed well-defined (in that $\xi(x) \in Y$ for all $x \in X^-$) since ξ is active.

3. *Invertibility I.* Given a map of sets $\xi: X^- \to Y$, we have

$$\begin{split} \left[\Psi_{X,Y} \circ \Phi_{X,Y} \right] (\xi) &\stackrel{\text{def}}{=} \Psi_{X,Y} \left(\Phi_{X,Y} (\xi) \right) \\ &\stackrel{\text{def}}{=} \Psi_{X,Y} \left(\begin{bmatrix} x \mapsto \begin{cases} \xi(x) & \text{if } x \in X^- \\ \star_Y & \text{if } x = x_0 \end{cases} \end{bmatrix} \right) \\ &= \begin{bmatrix} x \mapsto \xi(x) \end{bmatrix} \\ &= \xi \\ &= \begin{bmatrix} \text{id}_{\mathsf{Sets}(X^-,Y)} \end{bmatrix} (\xi). \end{split}$$

Therefore we have

$$\Psi_{X,Y} \circ \Phi_{X,Y} = \mathrm{id}_{\mathsf{Sets}(X^-Y)}$$
.

4. Invertibility II. Given a morphism of pointed sets

$$\xi \colon (X, x_0) \to (Y^+, \star_Y),$$

we have

$$\begin{split} \left[\Phi_{X,Y} \circ \Psi_{X,Y}\right](\xi) &\stackrel{\text{def}}{=} \Phi_{X,Y}\left(\Psi_{X,Y}(\xi)\right) \\ &= \Phi_{X,Y}(\llbracket x \mapsto \xi(x) \rrbracket) \\ &= \llbracket x \mapsto \begin{cases} \xi(x) & \text{if } x \in X^- \\ \star_Y & \text{if } x = x_0 \end{cases} \rrbracket \\ &= \xi \\ &= \left[id_{\mathsf{Sets}^{\mathsf{actv}}_*(X,Y^+)} \right](\xi). \end{split}$$

Therefore we have

$$\Phi_{X,Y} \circ \Psi_{X,Y} = \mathrm{id}_{\mathsf{Sets}^{\mathsf{actv}}_*(X,Y^+)} \; .$$

5. Naturality for Φ , Part I. We need to show that, given a morphism of pointed sets

$$f: (X, x_0) \rightarrow (X', x_0'),$$

the diagram

commutes. Indeed, given a map of sets $\xi \colon X' \to Y$, we have

$$\begin{split} \left[\Phi_{X,Y} \circ f^* \right] (\xi) &= \Phi_{X,Y} (f^*(\xi)) \\ &= \Phi_{X,Y} (\xi \circ f) \\ &= \left[\! \left[\! x \mapsto \begin{cases} \xi(f(x)) & \text{if } f(x) \in X'^{,-} \\ \star_Y & \text{if } f(x) = x'_0 \end{cases} \right] \right] \\ &= f^* \left(\left[\! \left[\! x' \mapsto \begin{cases} \xi(x') & \text{if } x' \in X'^{,-} \\ \star_Y & \text{if } x' = x'_0 \end{cases} \right] \right) \\ &= f^* \left(\Phi_{X',Y} (\xi) \right) \end{split}$$

$$= \left[f^* \circ \Phi_{X',Y} \right] (\xi).$$

Therefore we have

$$\Phi_{XY} \circ f^* = f^* \circ \Phi_{X'Y},$$

and the naturality diagram for Φ above indeed commutes.

6. Naturality for Φ , Part II. We need to show that, given a morphism of pointed sets

$$g: (Y, y_0) \to (Y', y_0'),$$

the diagram

$$\begin{array}{ccc} \mathsf{Sets}(X^-,Y) & \xrightarrow{\Phi_{X,Y}} & \mathsf{Sets}^{\mathsf{actv}}_*(X,Y^+) \\ & & \downarrow^{g_*} & & \downarrow^{g_*} \\ \mathsf{Sets}(X^-,Y') & \xrightarrow{\Phi_{X,Y'}} & \mathsf{Sets}^{\mathsf{actv}}_*(X,Y'^{,+}) \end{array}$$

commutes. Indeed, given a map of sets $\xi: X^- \to Y$, we have

$$\begin{split} \big[\Phi_{X,Y'} \circ g_* \big] (\xi) &= \Phi_{X,Y'} (g_*(\xi)) \\ &= \Phi_{X,Y'} (g \circ \xi) \\ &= \big[\! \big[x \mapsto \begin{cases} g(\xi(x)) & \text{if } x \in X^- \\ \star_{Y'} & \text{if } x = x_0 \end{cases} \big] \\ &= g_* \bigg(\big[\! \big[x \mapsto \begin{cases} \xi(x) & \text{if } x \in X^- \\ \star_{Y} & \text{if } x = x_0 \end{cases} \big] \bigg) \\ &= g_* \big(\Phi_{X,Y'} (\xi) \big) \\ &= \big[g_* \circ \Phi_{X,Y'} \big] (\xi). \end{split}$$

Therefore we have

$$\Phi_{X,Y'}\circ g_*=g_*\circ \Phi_{X,Y'},$$

and the naturality diagram for Φ above indeed commutes.

7. 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 Definition 11.9.7.1.2 that Ψ is also natural in each argument.

8. Fully Faithfulness of $(-)^-$. We aim to show that the assignment $f \mapsto f^-$ sets up a bijection

$$(-)_{XY}^-: \mathsf{Sets}^{\mathsf{actv}}_*(X,Y) \xrightarrow{\sim} \mathsf{Sets}(X^-,Y^-).$$

Indeed, the inverse map

$$(-)_{X,Y}^{-,-1} : \mathsf{Sets}(X^-,Y^-) \xrightarrow{\sim} \mathsf{Sets}^{\mathsf{actv}}_*(X,Y)$$

is given by sending a map of sets $f: X^- \to Y^-$ to the active morphism of pointed sets $f^{\dagger}: X \to Y$ defined by

$$f^{\dagger}(x) \stackrel{\text{def}}{=} \begin{cases} f(x) & \text{if } x \in X^{-}, \\ y_0 & \text{if } x = x_0 \end{cases}$$

for each $x \in X$.

9. *Essential Surjectivity of* $(-)^-$. We need to show that, given an object $X \in \text{Obj}(\mathsf{Sets})$, there exists some $X' \in \text{Obj}(\mathsf{Sets}^{\mathsf{actv}})$ such that $(X')^- \cong X$. Indeed, taking $X' = X^+$, we have

$$(X^+)^- \stackrel{\text{def}}{=} (X \cup \{\star_X\})^-$$
$$\stackrel{\text{def}}{=} (X \cup \{\star_X\}) \setminus \{\star_X\}$$
$$= X,$$

and thus we have in fact an *equality* $(X^+)^- = X$, showing $(-)^-$ to be essentially surjective.

10. The Functor (-) Is an Equivalence. Since (-) is fully faithful and essentially surjective, it is an equivalence by Categories, Item 1 of Definition 11.6.7.1.2.

This finishes the proof.

Item 3, Symmetric Strong Monoidality With Respect to Wedge Sums: We construct the strong monoidal structure on $(-)^-$ with respect to \vee and [] as follows:

• The Strong Monoidality Constraints. The isomorphism

$$(-)_{X,Y}^{-,\vee}\colon X^-\coprod Y^-\stackrel{\sim}{\dashrightarrow} (X\vee Y)^-$$

is given by

$$(-)_{X,Y}^{-,\vee}(z) = \begin{cases} [(0,x)] & \text{if } z = (0,x) \text{ with } x \in X, \\ [(1,y)] & \text{if } z = (1,y) \text{ with } y \in Y \end{cases}$$

for each $z \in X^- [] Y^-$, with inverse

$$(-)_{XY}^{-,\vee,-1} \colon (X \vee Y)^{-} \xrightarrow{\sim} X^{-} \coprod Y^{-}$$

given by

$$(-)_{X,Y}^{-,\vee,-1}(z) \stackrel{\text{def}}{=} \begin{cases} (0,x) & \text{if } z = [(0,x)], \\ (1,y) & \text{if } z = [(1,y)], \end{cases}$$

for each $z \in (X \vee Y)^-$.

• The Strong Monoidal Unity Constraint. The isomorphism

$$(-)_{X,Y}^{+,\vee,\mathbb{1}} \colon \overset{\sim}{\mathbb{Q}} \xrightarrow{\sim} \mathsf{pt}^{-}$$

is an equality.

The verification that these isomorphisms satisfy the coherence conditions making the functor $(-)^-$ into a symmetric strong monoidal functor is omitted. *Item 4, Symmetric Strong Monoidality With Respect to Smash Products*: We construct the strong monoidal structure on $(-)^+$ with respect to \wedge and \times as follows:

• The Strong Monoidality Constraints. The isomorphism

$$(-)^-_{XY}: X^- \times Y^- \xrightarrow{\sim} (X \wedge Y)^-$$

is given by

$$(-)^-_{X,Y}(x,y)=x\wedge y$$

for each $(x, y) \in X^- \times Y^-$, with inverse

$$(-)_{X,Y}^{-,-1} \colon (X \wedge Y)^{-} \xrightarrow{\sim} X^{-} \times Y^{-}$$

given by

$$(-)_{X,Y}^{-,-1}(x \wedge y) \stackrel{\mathrm{def}}{=} (x,y)$$

for each $x \wedge y \in (X \wedge Y)^-$.

• The Strong Monoidal Unity Constraint. The isomorphism

$$(-)_{X,Y}^{-,1} \colon \operatorname{pt} \xrightarrow{\sim} \left(S^0\right)^{-}$$

is given by sending \star to 1.

The verification that these isomorphisms satisfy the coherence conditions making the functor $(-)^+$ into a symmetric strong monoidal functor is omitted.

Appendices

Other Chapters

- 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

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