

Sets

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0000 This chapter (will eventually) contain material on axiomatic set theory, as well as a couple other things.

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0001 3.1 Sets and Functions

0002 3.1.1 Functions

0003 **Definition 3.1.1.1.1.** A **function** is a functional and total relation.

0004 **Notation 3.1.1.1.2.** Throughout this work, we will sometimes denote a function $f: X \rightarrow Y$ by

$$f \stackrel{\text{def}}{=} \llbracket x \mapsto f(x) \rrbracket.$$

- 01Y2 1. For example, given a function

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

taking values on a set of functions such as $\text{Hom}_{\text{Sets}}(X, Y)$, we will sometimes also write

$$\Phi(f) \stackrel{\text{def}}{=} \Phi(\llbracket x \mapsto f(x) \rrbracket).$$

- 01Y3 2. This notational choice is based on the lambda notation

$$f \stackrel{\text{def}}{=} (\lambda x. f(x)),$$

but uses a “ \mapsto ” symbol for better spacing and double brackets instead of either:

- 01Y4 (a) Square brackets $[x \mapsto f(x)]$;

- 01Y5 (b) Parentheses $(x \mapsto f(x))$;

hoping to improve readability when dealing with e.g.:

- 01Y6 (a) Equivalence classes, cf.:

01Y7 i. $\llbracket [x] \mapsto f([x]) \rrbracket$

01Y8 ii. $[[x] \mapsto f([x])]$

01Y9 iii. $(\lambda [x]. f([x]))$

- 01YA (b) Function evaluations, cf.:

01YB i. $\Phi(\llbracket x \mapsto f(x) \rrbracket)$

01YC ii. $\Phi((x \mapsto f(x)))$

01YD iii. $\Phi((\lambda x. f(x)))$

- 01YE 3. We will also sometimes write $-$, $-_1$, $-_2$, etc. for the arguments of a function. Some examples include:

- 01YF (a) Writing $f(-_1)$ for a function $f: A \rightarrow B$.

- 01YG (b) Writing $f(-_1, -_2)$ for a function $f: A \times B \rightarrow C$.

- 01YH (c) Given a function $f: A \times B \rightarrow C$, writing

$$f(a, -): B \rightarrow C$$

for the function $\llbracket b \mapsto f(a, b) \rrbracket$.

01YJ (d) Denoting a composition of the form

$$A \times B \xrightarrow{\phi \times \text{id}_B} A' \times B \xrightarrow{f} C$$

by $f(\phi(-_1), -_2)$.

01YK 4. Finally, given a function $f: A \rightarrow B$, we will sometimes write

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

for the value of f at some $a \in A$.

For an example of the above notations being used in practice, see the proof of the adjunction

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

stated in **Constructions With Sets, Item 2** of **Definition 4.1.3.1.3**.

0005 3.2 The Enrichment of Sets in Classical Truth Values

0006 3.2.1 (-2) -Categories

0007 **Definition 3.2.1.1.1.** A (-2) -category is the “necessarily true” truth value.^{1,2,3}

0008 3.2.2 (-1) -Categories

0009 **Definition 3.2.2.1.1.** A (-1) -category is a classical truth value.

000A **Remark 3.2.2.1.2.** ⁴ (-1) -categories should be thought of as being “categories enriched in (-2) -categories”, having a collection of objects and, for each pair of objects, a Hom-object $\text{Hom}(x, y)$ that is a (-2) -category (i.e. trivial).

As a result, a (-1) -category C is either:⁵

¹Thus, there is only one (-2) -category.

²A $(-n)$ -category for $n = 3, 4, \dots$ is also the “necessarily true” truth value, coinciding with a (-2) -category.

³For motivation, see [BS10, p. 13].

⁴For more motivation, see [BS10, p. 13].

⁵See [BS10, pp. 33–34].

- 01D2 1. *Empty*, having no objects.
- 01D3 2. *Contractible*, having a collection of objects $\{a, b, c, \dots\}$, but with $\text{Hom}_C(a, b)$ being a (-2) -category (i.e. trivial) for all $a, b \in \text{Obj}(C)$, forcing all objects of C to be uniquely isomorphic to each other.

Thus there are only two (-1) -categories up to equivalence:

- 01D4 1. The (-1) -category false (the empty one);
- 01D5 2. The (-1) -category true (the contractible one).

000B **Definition 3.2.2.1.3.** The **poset of truth values**⁶ is the poset $(\{\text{true}, \text{false}\}, \preceq)$ consisting of:

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

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

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

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

000C **Notation 3.2.2.1.4.** We also write $\{t, f\}$ for the poset $\{\text{true}, \text{false}\}$.

000D **Proposition 3.2.2.1.5.** The poset of truth values $\{t, f\}$ is Cartesian closed with product given by⁸

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

\times	t	f
t	t	f
f	f	f

⁶*Further Terminology:* Also called the **poset of (-1) -categories**.

⁷This partial order coincides with logical implication.

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

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

$$\begin{array}{ll} \mathbf{Hom}_{\{t,f\}}(t, t) = t, & \mathbf{Hom}_{\{t,f\}}(f, t) = t, \\ \mathbf{Hom}_{\{t,f\}}(t, f) = f, & \mathbf{Hom}_{\{t,f\}}(f, f) = t, \end{array} \quad \begin{array}{|c|c|c|} \hline \mathbf{Hom}_{\{t,f\}} & t & f \\ \hline t & t & t \\ \hline f & t & f \\ \hline \end{array}.$$

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

$$\begin{array}{cccc} \begin{array}{c} p_1^1 \quad P_1 \quad p_2^1 \\ \downarrow \quad \quad \downarrow \\ t \xleftarrow{\text{pr}_1} t \times t \xrightarrow{\text{pr}_2} t \end{array} & \begin{array}{c} p_1^2 \quad P_2 \quad p_2^2 \\ \downarrow \quad \quad \downarrow \\ t \xleftarrow{\text{pr}_1} t \times f \xrightarrow{\text{pr}_2} f \end{array} & \begin{array}{c} p_1^3 \quad P_3 \quad p_2^3 \\ \downarrow \quad \quad \downarrow \\ f \xleftarrow{\text{pr}_1} f \times t \xrightarrow{\text{pr}_2} t \end{array} & \begin{array}{c} p_1^4 \quad P_4 \quad p_2^4 \\ \downarrow \quad \quad \downarrow \\ f \xleftarrow{\text{pr}_1} f \times f \xrightarrow{\text{pr}_2} f \end{array} \end{array}$$

where the pr_1 and pr_2 morphisms are the only possible ones (since $\{t, f\}$ is posetal). We claim that there are unique morphisms making the diagrams

$$\begin{array}{cccc} \begin{array}{c} p_1^1 \quad P_1 \quad p_2^1 \\ \downarrow \quad \downarrow \exists! \quad \downarrow \\ t \xleftarrow{\text{pr}_1} t \times t \xrightarrow{\text{pr}_2} t \end{array} & \begin{array}{c} p_1^2 \quad P_2 \quad p_2^2 \\ \downarrow \quad \downarrow \exists! \quad \downarrow \\ t \xleftarrow{\text{pr}_1} t \times f \xrightarrow{\text{pr}_2} f \end{array} & \begin{array}{c} p_1^3 \quad P_3 \quad p_2^3 \\ \downarrow \quad \downarrow \exists! \quad \downarrow \\ f \xleftarrow{\text{pr}_1} f \times t \xrightarrow{\text{pr}_2} t \end{array} & \begin{array}{c} p_1^4 \quad P_4 \quad p_2^4 \\ \downarrow \quad \downarrow \exists! \quad \downarrow \\ f \xleftarrow{\text{pr}_1} f \times f \xrightarrow{\text{pr}_2} f \end{array} \end{array}$$

commute. Indeed:

- 01YL 1. If $P_1 = t$, then $p_1^1 = p_2^1 = \text{id}_t$, so there's a unique morphism from P_1 to t making the diagram commute, namely id_t .
- 01YM 2. If $P_1 = f$, then $p_1^1 = p_2^1$ are given by the unique morphism from f to t , so there's a unique morphism from P_1 to t making the diagram commute, namely the unique morphism from f to t .
- 01YN 3. If $P_2 = t$, then there is no morphism p_2^2 .
- 01YP 4. If $P_2 = f$, then p_1^2 is the unique morphism from f to t while $p_2^2 = \text{id}_f$, so there's a unique morphism from P_2 to f making the diagram commute, namely id_f .
- 01YQ 5. The proof for P_3 is similar to the one for P_2 .
- 01YR 6. If $P_4 = t$, then there is no morphism p_1^4 or p_2^4 .

- 01YS 7. If $P_4 = f$, then $p_1^4 = p_2^4 = \text{id}_f$, so there's a unique morphism from P_4 to f making the diagram commute, namely id_f .

This finishes the existence of products part of the proof.

Cartesian Closedness: We claim there's a bijection

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Since $\{t, f\}$ is posetal, naturality is automatic ([Categories, Item 4 of Definition 11.2.7.1.2](#)). \square

000E 3.2.3 0-Categories

000F **Definition 3.2.3.1.1.** A 0-category is a poset.⁹

000G **Definition 3.2.3.1.2.** A 0-groupoid is a 0-category in which every morphism is invertible.¹⁰

implication operator.

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

¹⁰That is, a set.

000H 3.2.4 Tables of Analogies Between Set Theory and Category Theory

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

01D6 **Remark 3.2.4.1.1.** The basic analogies between set theory and category theory are summarised in the following table:

Set Theory	Category Theory
Enrichment in $\{\text{true}, \text{false}\}$	Enrichment in Sets
Set X	Category \mathcal{C}
Element $x \in X$	Object $X \in \text{Obj}(\mathcal{C})$
Function $f: X \rightarrow Y$	Functor $F: \mathcal{C} \rightarrow \mathcal{D}$
Function $X \rightarrow \{\text{true}, \text{false}\}$	Copresheaf $\mathcal{C} \rightarrow \text{Sets}$
Function $X \rightarrow \{\text{true}, \text{false}\}$	Presheaf $\mathcal{C}^{\text{op}} \rightarrow \text{Sets}$

01D7 **Remark 3.2.4.1.2.** The category of presheaves $\text{PSh}(\mathcal{C})$ and the category of copresheaves $\text{CoPSh}(\mathcal{C})$ on a category \mathcal{C} are the 1-categorical counterparts to the powerset $\mathcal{P}(X)$ of subsets of a set X . The further analogies built upon this are summarised in the following table:

Set Theory	Category Theory
Powerset $\mathcal{P}(X)$	Presheaf category $\mathbf{PSh}(C)$
Characteristic function $\chi_{\{x\}} : X \rightarrow \{t, f\}$	Representable presheaf $h_X : C^{\text{op}} \hookrightarrow \mathbf{Sets}$
Characteristic embedding $\chi_{(-)} : X \hookrightarrow \mathcal{P}(X)$	Yoneda embedding $\mathcal{Y} : C^{\text{op}} \hookrightarrow \mathbf{PSh}(C)$
Characteristic relation $\chi_X(-, -) : X \times X \rightarrow \{t, f\}$	Hom profunctor $\text{Hom}_C(-, -) : C^{\text{op}} \times C \rightarrow \mathbf{Sets}$
The Yoneda lemma for sets $\text{Hom}_{\mathcal{P}(X)}(\chi_x, \chi_U) = \chi_U(x)$	The Yoneda lemma for categories $\text{Nat}(h_X, \mathcal{F}) \cong \mathcal{F}(X)$
The characteristic embedding is fully faithful, $\text{Hom}_{\mathcal{P}(X)}(\chi_x, \chi_y) = \chi_X(x, y)$	The Yoneda embedding is fully faithful, $\text{Nat}(h_X, h_Y) \cong \text{Hom}_C(X, Y)$
Subsets are unions of their elements $U = \bigcup_{x \in U} \{x\}$ or $\chi_U = \text{colim}_{\chi_x \in \mathcal{P}(U)} (\chi_x)$	Presheaves are colimits of representables, $\mathcal{F} \cong \text{colim}_{h_X \in \int_C \mathcal{F}} (h_X)$

01D8 Remark 3.2.4.1.3. We summarise the analogies between un/straightening in set theory and category theory in the following table:

SET THEORY	CATEGORY THEORY
Assignment $U \mapsto \chi_U$	Assignment $\mathcal{F} \mapsto \int_C \mathcal{F}$
Un/straightening isomorphism $\mathcal{P}(X) \cong \mathbf{Sets}(X, \{t, f\})$	Un/straightening equivalence $\mathbf{DFib}(C) \stackrel{\text{eq.}}{\cong} \mathbf{PSh}(C)$

01D9 Remark 3.2.4.1.4. We summarise the analogies between functions $\mathcal{P}(X) \rightarrow \mathcal{P}(Y)$ and functors $\mathbf{PSh}(C) \rightarrow \mathbf{PSh}(D)$ in the following table:

SET THEORY	CATEGORY THEORY
Direct image function $f_! : \mathcal{P}(X) \rightarrow \mathcal{P}(Y)$	Left Kan extension functor $F_! : \text{PSh}(C) \rightarrow \text{PSh}(\mathcal{D})$
Inverse image function $f^{-1} : \mathcal{P}(Y) \rightarrow \mathcal{P}(X)$	Precomposition functor $F^* : \text{PSh}(\mathcal{D}) \rightarrow \text{PSh}(C)$
Codirect image function $f_* : \mathcal{P}(X) \rightarrow \mathcal{P}(Y)$	Right Kan extension functor $F_* : \text{PSh}(C) \rightarrow \text{PSh}(\mathcal{D})$

01DA Remark 3.2.4.1.5. We summarise the analogies between functions, relations and profunctors in the following table:

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

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 | Bicategories |
| 12. Presheaves and the Yoneda Lemma | 14. Types of Morphisms in Bicategories |
| Monoidal Categories | Extra Part |
| 13. Constructions With Monoidal Categories | 15. Notes |

References

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