

Sets

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

Contents

3.1	Sets and Functions.....	1
3.1.1	Functions.....	1
3.2	The Enrichment of Sets in Classical Truth Values.....	3
3.2.1	(-2) -Categories.....	3
3.2.2	(-1) -Categories.....	3
3.2.3	0-Categories.....	8
3.2.4	Tables of Analogies Between Set Theory and Category Theory.....	8
A	Other Chapters.....	10

3.1 Sets and Functions

3.1.1 Functions

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

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

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

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

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

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:

- (a) Square brackets $[x \mapsto f(x)]$;
- (b) Parentheses $(x \mapsto f(x))$;

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

- (a) Equivalence classes, cf.:
 - i. $\llbracket [x] \mapsto f([x]) \rrbracket$
 - ii. $\llbracket [x] \mapsto f([x]) \rrbracket$
 - iii. $(\lambda [x]. f([x]))$
- (b) Function evaluations, cf.:
 - i. $\Phi(\llbracket x \mapsto f(x) \rrbracket)$
 - ii. $\Phi((x \mapsto f(x)))$
 - iii. $\Phi((\lambda x. f(x)))$

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

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

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

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

(d) Denoting a composition of the form

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

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

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

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

stated in [Constructions With Sets, Item 2](#) of [Definition 4.1.3.1.3](#).

3.2 The Enrichment of Sets in Classical Truth Values

3.2.1 (-2) -Categories

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

3.2.2 (-1) -Categories

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

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

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].

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 \mathcal{C} is either:⁵

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

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

1. The (-1) -category **false** (the empty one);
2. The (-1) -category **true** (the contractible one).

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

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

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

Proposition 3.2.2.1.5. The poset of truth values $\{\mathbf{t}, \mathbf{f}\}$ is Cartesian closed

⁵See [BS10, pp. 33–34].

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

⁷This partial order coincides with logical implication.

with product given by⁸

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

\times	\mathbf{t}	\mathbf{f}
\mathbf{t}	\mathbf{t}	\mathbf{f}
\mathbf{f}	\mathbf{f}	\mathbf{f}

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

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

$\mathbf{Hom}_{\{\mathbf{t}, \mathbf{f}\}}$	\mathbf{t}	\mathbf{f}
\mathbf{t}	\mathbf{t}	\mathbf{t}
\mathbf{f}	\mathbf{t}	\mathbf{f}

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

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

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

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

commute. Indeed:

1. If $P_1 = \mathbf{t}$, then $p_1^1 = p_2^1 = \text{id}_{\mathbf{t}}$, so there's a unique morphism from P_1 to \mathbf{t} making the diagram commute, namely $\text{id}_{\mathbf{t}}$.
2. If $P_1 = \mathbf{f}$, then $p_1^1 = p_2^1$ are given by the unique morphism from \mathbf{f} to \mathbf{t} , so there's a unique morphism from P_1 to \mathbf{t} making the diagram commute, namely the unique morphism from \mathbf{f} to \mathbf{t} .
3. If $P_2 = \mathbf{t}$, then there is no morphism p_2^2 .

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

4. If $P_2 = \mathbf{f}$, then p_1^2 is the unique morphism from \mathbf{f} to \mathbf{t} while $p_2^2 = \text{id}_{\mathbf{f}}$, so there's a unique morphism from P_2 to \mathbf{f} making the diagram commute, namely $\text{id}_{\mathbf{f}}$.
5. The proof for P_3 is similar to the one for P_2 .
6. If $P_4 = \mathbf{t}$, then there is no morphism p_1^4 or p_2^4 .
7. If $P_4 = \mathbf{f}$, then $p_1^4 = p_2^4 = \text{id}_{\mathbf{f}}$, so there's a unique morphism from P_4 to \mathbf{f} making the diagram commute, namely $\text{id}_{\mathbf{f}}$.

This finishes the existence of products part of the proof.

Cartesian Closedness: We claim there's a bijection

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

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

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

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

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

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

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

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

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

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

- 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

3.2.3 0-Categories

Definition 3.2.3.1.1. A 0-category is a poset.⁹

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

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.

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 $\mathcal{C} \rightarrow \mathbf{Sets}$
Function $X \rightarrow \{\text{true}, \text{false}\}$	Presheaf $\mathcal{C}^{\text{op}} \rightarrow \mathbf{Sets}$

Remark 3.2.4.1.2. The category of presheaves $\mathbf{PSh}(\mathcal{C})$ and the category of copresheaves $\mathbf{CoPSh}(\mathcal{C})$ 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:

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

¹⁰That is, a *set*.

Set Theory	Category Theory
Powerset $\mathcal{P}(X)$	Presheaf category $\mathbf{PSh}(\mathcal{C})$
Characteristic function $\chi_{\{x\}}: X \rightarrow \{\mathbf{t}, \mathbf{f}\}$	Representable presheaf $h_X: \mathcal{C}^{\text{op}} \hookrightarrow \mathbf{Sets}$
Characteristic embedding $\chi_{(-)}: X \hookrightarrow \mathcal{P}(X)$	Yoneda embedding $\mathfrak{J}: \mathcal{C}^{\text{op}} \hookrightarrow \mathbf{PSh}(\mathcal{C})$
Characteristic relation $\chi_X(-_1, -_2): X \times X \rightarrow \{\mathbf{t}, \mathbf{f}\}$	Hom profunctor $\text{Hom}_{\mathcal{C}}(-_1, -_2): \mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \mathbf{Sets}$
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, $\text{Nat}(h_X, h_Y) \cong \text{Hom}_{\mathcal{C}}(X, Y)$
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, $\mathcal{F} \cong \text{colim}_{h_X \in \int_{\mathcal{C}} \mathcal{F}} (h_X)$

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 $\mathcal{F} \mapsto \int_{\mathcal{C}} \mathcal{F}$
Un/straightening isomorphism $\mathcal{P}(X) \cong \mathbf{Sets}(X, \{\mathbf{t}, \mathbf{f}\})$	Un/straightening equivalence $\mathbf{DFib}(\mathcal{C}) \stackrel{\text{eq.}}{\cong} \mathbf{PSh}(\mathcal{C})$

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

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

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

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

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

12. Presheaves and the Yoneda Lemma 14. Types of Morphisms in Bicategories

Monoidal Categories

13. Constructions With Monoidal Categories **Extra Part**

Bicategories

15. Notes

References

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