

# Categories

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This chapter contains some elementary material about categories, functors, and natural transformations. Notably, we discuss and explore:

1. Categories ([Section 11.1](#)).
2. Examples of categories ([Section 11.2](#)).
3. The quadruple adjunction  $\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}$  between the category of categories and the category of sets ([Section 11.3](#)).
4. Groupoids, categories in which all morphisms admit inverses ([Section 11.4](#)).
5. Functors ([Section 11.5](#)).
6. The conditions one may impose on functors in decreasing order of importance:
  - (a) [Section 11.6](#) introduces the foundationally important conditions one may impose on functors, such as faithfulness, conservativity, essential surjectivity, etc.
  - (b) [Section 11.7](#) introduces more conditions one may impose on functors that are still important but less omni-present than those of [Section 11.6](#), such as being dominant, being a monomorphism, being pseudomonic, etc.
  - (c) [Section 11.8](#) introduces some rather rare or uncommon conditions one may impose on functors that are nevertheless still useful to explicit record in this chapter.

7. Natural transformations ([Section 11.9](#)).
8. The various categorical and 2-categorical structures formed by categories, functors, and natural transformations ([Section 11.10](#)).

This chapter is under active revision. TODO:

- Fix categories having an underlying set of objects by having them have an underlying setoid of objects (not necessarily by definition, as that'll likely be bothersome; at least [Section 11.3](#) should be fixed and several remarks should be added at several points). Related: [Warning 11.3.1.1.3](#)

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## 11.1 Categories

### 11.1.1 Foundations

#### DEFINITION 11.1.1.1 ► CATEGORIES

A **category**  $(C, \circ^C, \mathbb{1}^C)$  consists of:

- *Objects.* A class  $\text{Obj}(C)$  of **objects**.
- *Morphisms.* For each  $A, B \in \text{Obj}(C)$ , a class  $\text{Hom}_C(A, B)$ , called the **class of morphisms of  $C$  from  $A$  to  $B$** .
- *Identities.* For each  $A \in \text{Obj}(C)$ , a map of sets

$$\mathbb{1}_A^C: \text{pt} \rightarrow \text{Hom}_C(A, A),$$

called the **unit map of  $C$  at  $A$** , determining a morphism

$$\text{id}_A: A \rightarrow A$$

of  $C$ , called the **identity morphism of  $A$** .

- *Composition.* For each  $A, B, C \in \text{Obj}(C)$ , a map of sets

$$\circ_{A,B,C}^C: \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) \rightarrow \text{Hom}_C(A, C),$$

called the **composition map of  $C$  at  $(A, B, C)$** .

such that the following conditions are satisfied:

1. *Associativity.* The diagram

$$\begin{array}{ccc}
 & \text{Hom}_C(C, D) \times (\text{Hom}_C(B, C) \times \text{Hom}_C(A, B)) & \\
 \alpha_{\text{Hom}_C(C,D), \text{Hom}_C(B,C), \text{Hom}_C(A,B)}^{\text{Sets}} \nearrow & & \searrow \text{id}_{\text{Hom}_C(C,D)} \times \circ_{A,B,C}^C \\
 (\text{Hom}_C(C, D) \times \text{Hom}_C(B, C)) \times \text{Hom}_C(A, B) & & \text{Hom}_C(C, D) \times \text{Hom}_C(A, B) \\
 \downarrow \circ_{B,C,D}^C \times \text{id}_{\text{Hom}_C(A,B)} & & \downarrow \circ_{A,C,D}^C \\
 & \text{Hom}_C(B, D) \times \text{Hom}_C(A, B) \xrightarrow{\circ_{A,B,D}^C} \text{Hom}_C(A, D) & 
 \end{array}$$

commutes, i.e. for each composable triple  $(f, g, h)$  of morphisms of  $C$ , we have

$$(f \circ g) \circ h = f \circ (g \circ h).$$

2. *Left Unitality.* The diagram

$$\begin{array}{ccc}
 \text{pt} \times \text{Hom}_C(A, B) & & \\
 \downarrow \mathbb{1}_B^C \times \text{id}_{\text{Hom}_C(A,B)} & \searrow \lambda_{\text{Hom}_C(A,B)}^{\text{Sets}} & \\
 \text{Hom}_C(B, B) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,B}^C} & \text{Hom}_C(A, B)
 \end{array}$$

commutes, i.e. for each morphism  $f: A \rightarrow B$  of  $C$ , we have

$$\text{id}_B \circ f = f.$$

3. *Right Unitality*. The diagram

$$\begin{array}{ccc}
 \text{Hom}_C(A, B) \times \text{pt} & & \\
 \downarrow \text{id}_{\text{Hom}_C(A, B)} \times \mathbb{1}_A^C & \searrow \rho_{\text{Hom}_C(A, B)}^{\text{Sets}} & \\
 \text{Hom}_C(A, B) \times \text{Hom}_C(A, A) & \xrightarrow{\circ_{A, A, B}^C} & \text{Hom}_C(A, B)
 \end{array}$$

commutes, i.e. for each morphism  $f: A \rightarrow B$  of  $C$ , we have

$$f \circ \text{id}_A = f.$$

#### NOTATION 11.1.1.1.2 ► FURTHER NOTATION FOR MORPHISMS IN CATEGORIES

Let  $C$  be a category.

1. We also write  $C(A, B)$  for  $\text{Hom}_C(A, B)$ .
2. We write  $\text{Mor}(C)$  for the class of all morphisms of  $C$ .

#### DEFINITION 11.1.1.1.3 ► SIZE CONDITIONS ON CATEGORIES

Let  $\kappa$  be a regular cardinal. A category  $C$  is

1. **Locally small** if, for each  $A, B \in \text{Obj}(C)$ , the class  $\text{Hom}_C(A, B)$  is a set.
2. **Locally essentially small** if, for each  $A, B \in \text{Obj}(C)$ , the class

$$\text{Hom}_C(A, B) / \{\text{isomorphisms}\}$$

is a set.

3. **Small** if  $C$  is locally small and  $\text{Obj}(C)$  is a set.
4.  **$\kappa$ -Small** if  $C$  is locally small,  $\text{Obj}(C)$  is a set, and we have  $\#\text{Obj}(C) < \kappa$ .

### 11.1.2 Subcategories

Let  $C$  be a category.

#### DEFINITION 11.1.2.1.1 ► SUBCATEGORIES

A **subcategory** of  $C$  is a category  $\mathcal{A}$  satisfying the following conditions:

1. *Objects.* We have  $\text{Obj}(\mathcal{A}) \subset \text{Obj}(C)$ .
2. *Morphisms.* For each  $A, B \in \text{Obj}(\mathcal{A})$ , we have

$$\text{Hom}_{\mathcal{A}}(A, B) \subset \text{Hom}_C(A, B).$$

3. *Identities.* For each  $A \in \text{Obj}(\mathcal{A})$ , we have

$$\mathbb{1}_A^{\mathcal{A}} = \mathbb{1}_A^C.$$

4. *Composition.* For each  $A, B, C \in \text{Obj}(\mathcal{A})$ , we have

$$\circ_{A,B,C}^{\mathcal{A}} = \circ_{A,B,C}^C.$$

#### DEFINITION 11.1.2.1.2 ► FULL SUBCATEGORIES

A subcategory  $\mathcal{A}$  of  $C$  is **full** if the canonical inclusion functor  $\mathcal{A} \rightarrow C$  is full, i.e. if, for each  $A, B \in \text{Obj}(\mathcal{A})$ , the inclusion

$$\iota_{A,B}: \text{Hom}_{\mathcal{A}}(A, B) \hookrightarrow \text{Hom}_C(A, B)$$

is surjective (and thus bijective).

#### DEFINITION 11.1.2.1.3 ► STRICTLY FULL SUBCATEGORIES

A subcategory  $\mathcal{A}$  of a category  $C$  is **strictly full** if it satisfies the following conditions:

1. *Fullness.* The subcategory  $\mathcal{A}$  is full.
2. *Closedness Under Isomorphisms.* The class  $\text{Obj}(\mathcal{A})$  is closed under isomorphisms.<sup>1</sup>

<sup>1</sup>That is, given  $A \in \text{Obj}(\mathcal{A})$  and  $C \in \text{Obj}(C)$ , if  $C \cong A$ , then  $C \in \text{Obj}(\mathcal{A})$ .

#### DEFINITION 11.1.2.1.4 ► WIDE SUBCATEGORIES

A subcategory  $\mathcal{A}$  of  $C$  is **wide**<sup>1</sup> if  $\text{Obj}(\mathcal{A}) = \text{Obj}(C)$ .

<sup>1</sup>*Further Terminology:* Also called **lluf**.

### 11.1.3 Skeletons of Categories

#### DEFINITION 11.1.3.1.1 ► SKELETONS OF CATEGORIES

A <sup>1</sup>**skeleton** of a category  $C$  is a full subcategory  $\text{Sk}(C)$  with one object from each isomorphism class of objects of  $C$ .

<sup>1</sup>Due to **Item 3** of **Proposition 11.1.3.1.3**, which states that any two skeletons of a category are equivalent, we often refer to any such full subcategory  $\text{Sk}(C)$  of  $C$  as *the* skeleton of  $C$ .

#### DEFINITION 11.1.3.1.2 ► SKELETAL CATEGORIES

A category  $C$  is **skeletal** if  $C \cong \text{Sk}(C)$ .<sup>1</sup>

<sup>1</sup>That is,  $C$  is **skeletal** if isomorphic objects of  $C$  are equal.

#### PROPOSITION 11.1.3.1.3 ► PROPERTIES OF SKELETONS OF CATEGORIES

Let  $C$  be a category.

1. *Existence.* Assuming the axiom of choice,  $\text{Sk}(C)$  always exists.
2. *Pseudofunctoriality.* The assignment  $C \mapsto \text{Sk}(C)$  defines a pseudo-functor

$$\text{Sk}: \text{Cats}_2 \rightarrow \text{Cats}_2.$$

3. *Uniqueness Up to Equivalence.* Any two skeletons of  $C$  are equivalent.

4. *Inclusions of Skeletons Are Equivalences.* The inclusion

$$\iota_C: \text{Sk}(C) \hookrightarrow C$$

of a skeleton of  $C$  into  $C$  is an equivalence of categories.



## PROOF 11.1.3.1.4 ► PROOF OF PROPOSITION 11.1.3.1.3

Item 1: Existence

See [nLab23, Section “Existence of Skeletons of Categories”].


Item 2: Pseudofunctoriality

See [nLab23, Section “Skeletons as an Endo-Pseudofunctor on  $\mathfrak{Cat}$ ”].

Item 3: Uniqueness Up to Equivalence

Omitted.

Item 4: Inclusions of Skeletons Are Equivalences

Omitted. **11.1.4 Precomposition and Postcomposition**Let  $C$  be a category and let  $A, B, C, X \in \text{Obj}(C)$ .

## DEFINITION 11.1.4.1.1 ► PRECOMPOSITION AND POSTCOMPOSITION FUNCTIONS

Let  $f: A \rightarrow B$  and  $g: B \rightarrow C$  be morphisms of  $C$ .

1. The **precomposition function associated to  $f$**  is the function

$$f^*: \text{Hom}_C(B, X) \rightarrow \text{Hom}_C(A, X)$$

defined by

$$f^*(\phi) \stackrel{\text{def}}{=} \phi \circ f$$

for each  $\phi \in \text{Hom}_C(B, X)$ .

2. The **postcomposition function associated to  $g$**  is the function

$$g_*: \text{Hom}_C(X, B) \rightarrow \text{Hom}_C(X, C)$$

defined by

$$g_*(\phi) \stackrel{\text{def}}{=} g \circ \phi$$

for each  $\phi \in \text{Hom}_C(X, B)$ .

**PROPOSITION 11.1.4.1.2 ► PROPERTIES OF PRE/POSTCOMPOSITION**

Let  $A, B, C, D, X \in \text{Obj}(C)$ .

1. *Interaction Between Precomposition and Postcomposition.* Let  $f: A \rightarrow B$  and  $g: X \rightarrow Y$  be morphisms of  $C$ . We have

$$g_* \circ f^* = f^* \circ g_*,$$

$$\begin{array}{ccc} \text{Hom}_C(B, X) & \xrightarrow{g_*} & \text{Hom}_C(B, Y) \\ f^* \downarrow & & \downarrow f^* \\ \text{Hom}_C(A, X) & \xrightarrow{g_*} & \text{Hom}_C(A, Y). \end{array}$$

2. *Interaction With Composition I.* Let  $f: A \rightarrow B$  and  $g: B \rightarrow C$  be morphisms of  $C$ . We have

$$(g \circ f)_* = g_* \circ f_*,$$

$$\begin{array}{ccc} \text{Hom}_C(X, A) & \xrightarrow{f_*} & \text{Hom}_C(X, B) \\ & \searrow (g \circ f)_* & \downarrow g_* \\ & & \text{Hom}_C(X, C), \end{array}$$

$$(g \circ f)^* = f^* \circ g^*,$$

$$\begin{array}{ccc} \text{Hom}_C(C, X) & \xrightarrow{g^*} & \text{Hom}_C(B, X) \\ & \searrow (g \circ f)^* & \downarrow f^* \\ & & \text{Hom}_C(A, X). \end{array}$$

3. *Interaction With Composition II.* Let  $f: A \rightarrow B$  and  $g: B \rightarrow C$  be morphisms of  $C$ . We have

$$\begin{array}{ccc} \text{pt} & \xrightarrow{[f]} & \text{Hom}_C(A, B) \\ & \searrow [g \circ f] & \downarrow g_* \\ & & \text{Hom}_C(A, C) \end{array} \quad \begin{array}{l} [g \circ f] = g_* \circ [f], \\ [g \circ f] = f^* \circ [g], \end{array} \quad \begin{array}{ccc} \text{pt} & \xrightarrow{[g]} & \text{Hom}_C(B, C) \\ & \searrow [g \circ f] & \downarrow f^* \\ & & \text{Hom}_C(A, C). \end{array}$$

4. *Interaction With Composition III.* Let  $f: X \rightarrow A$  and  $g: C \rightarrow D$  be morphisms of  $\mathcal{C}$ . We have

$$\begin{array}{ccc}
 \text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_{\mathcal{C}}(A, C) \\
 \downarrow \text{id} \times f^* & & \downarrow f^* \\
 \text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(X, B) & \xrightarrow{\circ_{X,B,C}^C} & \text{Hom}_{\mathcal{C}}(X, C), \\
 \\ 
 \text{Hom}_{\mathcal{C}}(B, C) \times \text{Hom}_{\mathcal{C}}(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_{\mathcal{C}}(A, C) \\
 \downarrow g_* \times \text{id} & & \downarrow g_* \\
 \text{Hom}_{\mathcal{C}}(B, D) \times \text{Hom}_{\mathcal{C}}(A, B) & \xrightarrow{\circ_{A,B,D}^C} & \text{Hom}_{\mathcal{C}}(A, D).
 \end{array}$$

$f^* \circ \circ_{A,B,C}^C = \circ_{X,B,C}^C \circ (\text{id} \times f^*),$   
 $g_* \circ \circ_{A,B,C}^C = \circ_{A,B,D}^C \circ (g_* \times \text{id}),$

5. *Interaction With Identities.* We have

$$\begin{aligned}
 \text{id}_A^* &= \text{id}_{\text{Hom}_{\mathcal{C}}(A,B)}, \\
 (\text{id}_B)_* &= \text{id}_{\text{Hom}_{\mathcal{C}}(A,B)}.
 \end{aligned}$$

#### PROOF 11.1.4.1.3 ► PROOF OF PROPOSITION 11.1.4.1.2

##### Item 1: Interaction Between Precomposition and Postcomposition

For each  $\phi \in \text{Hom}_{\mathcal{C}}(B, X)$ , we have

$$\begin{aligned}
 [g_* \circ f^*](\phi) &= g_*(\phi \circ f) \\
 &= g \circ (\phi \circ f) \\
 &= (g \circ \phi) \circ f \\
 &= f^*(g \circ \phi) \\
 &= [f^* \circ g_*](\phi).
 \end{aligned}$$

Thus  $g_* \circ f^* = f^* \circ g_*$ .

##### Item 2: Interaction With Composition I

$$(g \circ f)_* = g_* \circ f_*$$

For each  $\phi \in \text{Hom}_C(X, A)$ , we have

$$\begin{aligned} (g \circ f)_*(\phi) &= (g \circ f) \circ \phi \\ &= g \circ (f \circ \phi) \\ &= g \circ f_*(\phi) \\ &= g_*(f_*(\phi)) \\ &= [g_* \circ f_*](\phi). \end{aligned}$$

Thus  $(g \circ f)_* = g_* \circ f_*$ .

$$(g \circ f)^* = g^* \circ f^*$$

For each  $\phi \in \text{Hom}_C(C, X)$ , we have

$$\begin{aligned} (g \circ f)^*(\phi) &= \phi \circ (g \circ f) \\ &= (\phi \circ g) \circ f \\ &= (g^*(\phi)) \circ f \\ &= f^*(g^*(\phi)) \\ &= [f^* \circ g^*](\phi). \end{aligned}$$

Thus  $(g \circ f)^* = g^* \circ f^*$ .

#### Item 3: Interaction With Composition II

It suffices to show the equalities of the maps on  $\star \in \text{pt}$ . We have

$$\begin{aligned} [g \circ f](\star) &= g \circ f \\ &= g_*(f) \\ &= g_*([f](\star)) \\ &= (g_* \circ [f])(\star), \end{aligned}$$

and

$$[g \circ f](\star) = g \circ f$$

$$\begin{aligned}
&= f^*(g) \\
&= f^*([g](\star)) \\
&= (f^* \circ [g])(\star).
\end{aligned}$$

Thus  $[g \circ f] = g_* \circ [f]$  and  $[g \circ f] = f^* \circ [g]$ .

#### Item 4: Interaction With Composition III

$$f^* \circ \circ_{A,B,C}^C = \circ_{X,B,C}^C \circ (\text{id} \times f^*)$$

For each  $(\psi, \phi) \in \text{Hom}_C(B, C) \times \text{Hom}_C(A, B)$ , we have

$$\begin{aligned}
[f^* \circ \circ_{A,B,C}^C](\psi, \phi) &= f^*(\psi \circ \phi) \\
&= (\psi \circ \phi) \circ f \\
&= \psi \circ (\phi \circ f) \\
&= \circ_{X,B,C}^C(\psi, \phi \circ f) \\
&= \circ_{X,B,C}^C(\psi, f^*(\phi)) \\
&= [\circ_{X,B,C}^C \circ (\text{id} \times f^*)](\psi, \phi).
\end{aligned}$$

Thus  $f^* \circ \circ_{A,B,C}^C = \circ_{X,B,C}^C \circ (\text{id} \times f^*)$ .

$$g_* \circ \circ_{A,B,C}^C = \circ_{A,B,D}^C \circ (g_* \times \text{id})$$

For each  $(\psi, \phi) \in \text{Hom}_C(B, C) \times \text{Hom}_C(A, B)$ , we have

$$\begin{aligned}
[g_* \circ \circ_{A,B,C}^C](\psi, \phi) &= g_*(\psi \circ \phi) \\
&= g \circ (\psi \circ \phi) \\
&= (g \circ \psi) \circ \phi \\
&= \circ_{A,B,D}^C(g \circ \psi, \phi) \\
&= \circ_{A,B,D}^C(g_*(\psi), \phi)
\end{aligned}$$

$$= [\circ_{A,B,D}^C \circ (g_* \times \text{id})](\psi, \phi).$$

Thus  $g_* \circ \circ_{A,B,C}^C = \circ_{A,B,D}^C \circ (g_* \times \text{id})$ .

#### Item 5: Interaction With Identities

We have

$$\begin{aligned} \text{id}_A^*(\phi) &= \phi \circ \text{id}_A \\ &= \phi \\ &= \text{id}_{\text{Hom}_C(A,B)}(\phi) \end{aligned}$$

and

$$\begin{aligned} (\text{id}_B)_*(\phi) &= \text{id}_B \circ \phi \\ &= \phi \\ &= \text{id}_{\text{Hom}_C(A,B)}(\phi) \end{aligned}$$

for each  $\phi \in \text{Hom}_C(A, B)$ .



## 11.2 Examples of Categories

### 11.2.1 The Empty Category

**EXAMPLE 11.2.1.1.1 ► THE EMPTY CATEGORY**

The **empty category** is the category  $\emptyset_{\text{cat}}$  where

- *Objects.* We have

$$\text{Obj}(\emptyset_{\text{cat}}) \stackrel{\text{def}}{=} \emptyset.$$

- *Morphisms.* We have

$$\text{Mor}(\emptyset_{\text{cat}}) \stackrel{\text{def}}{=} \emptyset.$$

- *Identities and Composition.* Having no objects,  $\emptyset_{\text{cat}}$  has no unit nor composition maps.

**11.2.2 The Punctual Category**

**EXAMPLE 11.2.2.1.1 ► THE PUNCTUAL CATEGORY**

The **punctual category**<sup>1</sup> is the category  $\mathbf{pt}$  where

- *Objects.* We have

$$\mathrm{Obj}(\mathbf{pt}) \stackrel{\mathrm{def}}{=} \{\star\}.$$

- *Morphisms.* The unique Hom-set of  $\mathbf{pt}$  is defined by

$$\mathrm{Hom}_{\mathbf{pt}}(\star, \star) \stackrel{\mathrm{def}}{=} \{\mathrm{id}_{\star}\}.$$

- *Identities.* The unit map

$$\mathbb{1}_{\star}^{\mathbf{pt}} : \mathbf{pt} \rightarrow \mathrm{Hom}_{\mathbf{pt}}(\star, \star)$$

of  $\mathbf{pt}$  at  $\star$  is defined by

$$\mathrm{id}_{\star}^{\mathbf{pt}} \stackrel{\mathrm{def}}{=} \mathrm{id}_{\star}.$$

- *Composition.* The composition map

$$\circ_{\star, \star, \star}^{\mathbf{pt}} : \mathrm{Hom}_{\mathbf{pt}}(\star, \star) \times \mathrm{Hom}_{\mathbf{pt}}(\star, \star) \rightarrow \mathrm{Hom}_{\mathbf{pt}}(\star, \star)$$

of  $\mathbf{pt}$  at  $(\star, \star, \star)$  is given by the bijection  $\mathbf{pt} \times \mathbf{pt} \cong \mathbf{pt}$ .

<sup>1</sup>Further Terminology: Also called the **singleton category**.

**11.2.3 Monoids as One-Object Categories****EXAMPLE 11.2.3.1.1 ► MONOIDS AS ONE-OBJECT CATEGORIES**

We have an isomorphism of categories<sup>1</sup>

$$\begin{array}{ccc} \mathbf{Mon} & \longrightarrow & \mathbf{Cats} \\ \downarrow \lrcorner & & \downarrow \mathrm{Obj} \\ \mathbf{pt} & \xrightarrow{[\mathbf{pt}]} & \mathbf{Sets} \end{array}$$

$\mathbf{Mon} \cong \mathbf{pt} \times_{\mathbf{Sets}} \mathbf{Cats},$

via the delooping functor  $B : \mathbf{Mon} \rightarrow \mathbf{Cats}$  of ?? of ??, exhibiting monoids as exactly those categories having a single object.



<sup>1</sup>This can be enhanced to an isomorphism of 2-categories

$$\text{Mon}_{2\text{disc}} \cong \text{pt}_{\text{bi}} \times_{\text{Sets}_{2\text{disc}}} \text{Cats}_{2,*}$$

$$\begin{array}{ccc} \text{Mon}_{2\text{disc}} & \longrightarrow & \text{Cats}_{2,*} \\ \downarrow & \lrcorner & \downarrow \text{Obj} \\ \text{pt}_{\text{bi}} & \xrightarrow{[\text{pt}]} & \text{Sets}_{2\text{disc}} \end{array}$$

between the discrete 2-category  $\text{Mon}_{2\text{disc}}$  on  $\text{Mon}$  and the 2-category of pointed categories with one object.

#### PROOF 11.2.3.1.2 ► PROOF OF EXAMPLE 11.2.3.1.1

Omitted.



## 11.2.4 Ordinal Categories

### EXAMPLE 11.2.4.1.1 ► ORDINAL CATEGORIES

The  **$n$ th ordinal category** is the category  $\mathfrak{n}$  where<sup>1</sup>

- *Objects.* We have

$$\text{Obj}(\mathfrak{n}) \stackrel{\text{def}}{=} \{[0], \dots, [n]\}.$$

- *Morphisms.* For each  $[i], [j] \in \text{Obj}(\mathfrak{n})$ , we have

$$\text{Hom}_{\mathfrak{n}}([i], [j]) \stackrel{\text{def}}{=} \begin{cases} \{\text{id}_{[i]}\} & \text{if } [i] = [j], \\ \{[i] \rightarrow [j]\} & \text{if } [j] < [i], \\ \emptyset & \text{if } [j] > [i]. \end{cases}$$

- *Identities.* For each  $[i] \in \text{Obj}(\mathfrak{n})$ , the unit map

$$\mathbb{1}_{[i]}^{\mathfrak{n}} : \text{pt} \rightarrow \text{Hom}_{\mathfrak{n}}([i], [i])$$

of  $\mathfrak{n}$  at  $[i]$  is defined by

$$\text{id}_{[i]}^{\mathfrak{n}} \stackrel{\text{def}}{=} \text{id}_{[i]}.$$

- *Composition.* For each  $[i], [j], [k] \in \text{Obj}(\mathfrak{n})$ , the composition map

$$\circ_{[i],[j],[k]}^{\mathfrak{n}} : \text{Hom}_{\mathfrak{n}}([j], [k]) \times \text{Hom}_{\mathfrak{n}}([i], [j]) \rightarrow \text{Hom}_{\mathfrak{n}}([i], [k])$$

of  $\mathfrak{n}$  at  $([i], [j], [k])$  is defined by

$$\begin{aligned} \text{id}_{[i]} \circ \text{id}_{[j]} &= \text{id}_{[i]}, \\ ([j] \rightarrow [k]) \circ ([i] \rightarrow [j]) &= ([i] \rightarrow [k]). \end{aligned}$$

<sup>1</sup>In other words,  $\mathfrak{n}$  is the category associated to the poset

$$[0] \rightarrow [1] \rightarrow \cdots \rightarrow [n-1] \rightarrow [n].$$

The category  $\mathfrak{n}$  for  $n \geq 2$  may also be defined in terms of  $\mathbb{0}$  and joins (Constructions With Categories, ??): we have isomorphisms of categories

$$\begin{aligned} 1 &\cong \mathbb{0} \star \mathbb{0}, \\ 2 &\cong 1 \star \mathbb{0} \\ &\cong (\mathbb{0} \star \mathbb{0}) \star \mathbb{0}, \\ 3 &\cong 2 \star \mathbb{0} \\ &\cong (1 \star \mathbb{0}) \star \mathbb{0} \\ &\cong ((\mathbb{0} \star \mathbb{0}) \star \mathbb{0}) \star \mathbb{0}, \\ 4 &\cong 3 \star \mathbb{0} \\ &\cong (2 \star \mathbb{0}) \star \mathbb{0} \\ &\cong ((1 \star \mathbb{0}) \star \mathbb{0}) \star \mathbb{0} \\ &\cong (((\mathbb{0} \star \mathbb{0}) \star \mathbb{0}) \star \mathbb{0}) \star \mathbb{0}, \end{aligned}$$

and so on.

## 11.2.5 The Walking Arrow

### DEFINITION 11.2.5.1.1 ► THE WALKING ARROW

The **walking arrow** is the category  $\mathbb{1}$  defined as the first ordinal category.

**REMARK 11.2.5.1.2 ► UNWINDING DEFINITION 11.2.5.1.1**

In detail, the walking arrow is the category  $\mathbb{1}$  where:

- *Objects.* We have  $\text{Obj}(\mathbb{1}) = \{0, 1\}$ .
- *Morphisms.* We have

$$\text{Hom}_{\mathbb{1}}(0, 0) = \{\text{id}_0\},$$

$$\text{Hom}_{\mathbb{1}}(1, 1) = \{\text{id}_1\},$$

$$\text{Hom}_{\mathbb{1}}(0, 1) = \{f_{01}\},$$

$$\text{Hom}_{\mathbb{1}}(1, 0) = \emptyset.$$

- *Identities and Composition.* The identities and composition of  $\mathbb{1}$  are completely determined by the unitality and associativity axioms for  $\mathbb{1}$ .

**11.2.6 More Examples of Categories****EXAMPLE 11.2.6.1.1 ► MORE EXAMPLES OF CATEGORIES**

Here we list some of the other categories appearing throughout this work.

1. The category  $\text{Sets}_*$  of pointed sets of **Pointed Sets**, **Definition 6.1.3.1.1**.
2. The category  $\text{Rel}$  of sets and relations of **Relations**, **Definition 8.3.2.1.1**.
3. The category  $\text{Span}(A, B)$  of spans from a set  $A$  to a set  $B$  of **??**, **??**.
4. The category  $\text{ISets}(K)$  of  $K$ -indexed sets of **Indexed Sets**, **??**.
5. The category  $\text{ISets}$  of indexed sets of **Indexed Sets**, **??**.
6. The category  $\text{FibSets}(K)$  of  $K$ -fibred sets of **Fibred Sets**, **??**.
7. The category  $\text{FibSets}$  of fibred sets of **Fibred Sets**, **??**.

8. Categories of functors  $\text{Fun}(\mathcal{C}, \mathcal{D})$  as in [Definition 11.10.1.1.1](#).
9. The category of categories  $\text{Cats}$  of [Definition 11.10.2.1.1](#).
10. The category of groupoids  $\text{Grpd}$  of [Definition 11.10.4.1.1](#).

### 11.2.7 Posetal Categories

## DEFINITION 11.2.7.1.1 ► POSETAL CATEGORIES

Let  $(X, \preceq_X)$  be a poset.

1. The **posetal category associated to**  $(X, \preceq_X)$  is the category  $X_{\text{pos}}$  where

- *Objects.* We have

$$\text{Obj}(X_{\text{pos}}) \stackrel{\text{def}}{=} X.$$

- *Morphisms.* For each  $a, b \in \text{Obj}(X_{\text{pos}})$ , we have

$$\text{Hom}_{X_{\text{pos}}}(a, b) \stackrel{\text{def}}{=} \begin{cases} \text{pt} & \text{if } a \preceq_X b, \\ \emptyset & \text{otherwise.} \end{cases}$$

- *Identities.* For each  $a \in \text{Obj}(X_{\text{pos}})$ , the unit map

$$\mathbb{1}_a^{X_{\text{pos}}} : \text{pt} \rightarrow \text{Hom}_{X_{\text{pos}}}(a, a)$$

of  $X_{\text{pos}}$  at  $a$  is given by the identity map.

- *Composition.* For each  $a, b, c \in \text{Obj}(X_{\text{pos}})$ , the composition map

$$\circ_{a,b,c}^{X_{\text{pos}}} : \text{Hom}_{X_{\text{pos}}}(b, c) \times \text{Hom}_{X_{\text{pos}}}(a, b) \rightarrow \text{Hom}_{X_{\text{pos}}}(a, c)$$

of  $X_{\text{pos}}$  at  $(a, b, c)$  is defined as either the inclusion  $\emptyset \hookrightarrow \text{pt}$  or the identity map of  $\text{pt}$ , depending on whether we have  $a \preceq_X b$ ,  $b \preceq_X c$ , and  $a \preceq_X c$ .

2. A category  $C$  is **posetal**<sup>1</sup> if  $C$  is equivalent to  $X_{\text{pos}}$  for some poset  $(X, \preceq_X)$ .

<sup>1</sup>Further Terminology: Also called a **thin** category or a **(0, 1)-category**.

## PROPOSITION 11.2.7.1.2 ► PROPERTIES OF POSETAL CATEGORIES

Let  $(X, \preceq_X)$  be a poset and let  $C$  be a category.

1. *Functoriality.* The assignment  $(X, \preceq_X) \mapsto X_{\text{pos}}$  defines a functor

$$(-)_{\text{pos}} : \text{Pos} \rightarrow \text{Cats}.$$

where:

- *Action on Objects.* For each  $X \in \text{Obj}(\text{Pos})$ , we have

$$[(-)_{\text{pos}}](X) \stackrel{\text{def}}{=} X_{\text{pos}},$$

where  $X_{\text{pos}}$  is the category of of **Item 1** of **Definition 11.2.7.1.1**.

- *Action on Morphisms.* For each morphism of posets  $f: X \rightarrow Y$  in  $\text{Pos}$ , the image

$$f_{\text{pos}}: X_{\text{pos}} \rightarrow Y_{\text{pos}}$$

of  $f$  by  $(-)_{\text{pos}}$  is the functor defined as follows:

- *The Action of  $f_{\text{pos}}$  on Objects.* For each  $x \in \text{Obj}(X_{\text{pos}})$ , we have

$$f_{\text{pos}}(x) \stackrel{\text{def}}{=} f(x).$$

- *The Action of  $f_{\text{pos}}$  on Morphisms.* For each  $x, y \in \text{Obj}(X_{\text{pos}})$ , the action

$$f_{\text{pos}|x,y}: \text{Hom}_{X_{\text{pos}}}(x, y) \rightarrow \text{Hom}_{Y_{\text{pos}}}(f(x), f(y))$$

of  $f$  at  $(x, y)$  is given by

$$f_{\text{pos}|x,y}(\text{pt}_{\text{Hom}_{X_{\text{pos}}}(x,y)}) \stackrel{\text{def}}{=} \text{pt}_{\text{Hom}_{Y_{\text{pos}}}(f(x), f(y))}$$

if  $x \preceq_X y$  or, otherwise, by the inclusion of the empty set into  $\text{Hom}_{Y_{\text{pos}}}(f(x), f(y))$ .

2. *Fully Faithfulness.* The functor  $(-)_{\text{pos}}$  of **Item 1** is fully faithful.
3. *Characterisations.* The following conditions are equivalent:
  - (a) The category  $C$  is posetal.
  - (b) For each  $A, B \in \text{Obj}(C)$  and each  $f, g \in \text{Hom}_C(A, B)$ , we have  $f = g$ .
4. *Automatic Commutativity of Diagrams.* Every diagram in a posetal category commutes.

## PROOF 11.2.7.1.3 ► PROOF OF PROPOSITION 11.2.7.1.2

## Item 1: Functoriality

First, note that given a morphism of posets  $f: X \rightarrow Y$ , the corresponding functor  $f_{\text{pos}}: X_{\text{pos}} \rightarrow Y_{\text{pos}}$  is indeed a functor: since all morphisms in the Hom-sets of  $Y_{\text{pos}}$  are equal, it preserves identities and compositions trivially.

Next, we claim that  $(-)_{\text{pos}}$  is indeed a functor:

- *Preservation of Identities.* Let  $X \in \text{Obj}(\text{Pos})$ . Given  $x, y \in X$  with  $x \preceq_X y$ , we have

$$\begin{aligned} (\text{id}_X)_{\text{pos}}(x) &= \text{id}_X(x) \\ &= \text{id}_{X_{\text{pos}}}(x), \end{aligned}$$

so  $(\text{id}_X)_{\text{pos}}$  acts like the identity functor of  $X_{\text{pos}}$  on objects, and

$$\begin{aligned} (\text{id}_X)_{\text{pos}}(\text{pt}_{\text{Hom}_{X_{\text{pos}}}(x,y)}) &= \text{pt}_{\text{Hom}_{X_{\text{pos}}}((\text{id}_X)_{\text{pos}}(x), (\text{id}_X)_{\text{pos}}(y))} \\ &= \text{pt}_{\text{Hom}_{X_{\text{pos}}}(a,b)}, \end{aligned}$$

so the same holds for morphisms. Thus  $(\text{id}_X)_{\text{pos}} = \text{id}_{X_{\text{pos}}}$ .

- *Preservation of Composition.* Let  $X, Y, Z \in \text{Obj}(\text{Pos})$ . Given morphisms of posets  $f: X \rightarrow Y$  and  $g: Y \rightarrow Z$ , we need to show

$$(g \circ f)_{\text{pos}} = g_{\text{pos}} \circ f_{\text{pos}}.$$

Indeed, given  $x \in X$ , we have

$$\begin{aligned} (g \circ f)_{\text{pos}}(x) &= (g \circ f)(x) \\ &= g(f(x)) \\ &= g_{\text{pos}}(f_{\text{pos}}(x)) \\ &= [g_{\text{pos}} \circ f_{\text{pos}}](x), \end{aligned}$$

so the identity holds on objects. Since  $Z_{\text{pos}}$  is a posetal category, the identity automatically holds on morphisms since

$$(g \circ f)_{\text{pos}}(\text{pt}_{\text{Hom}_{X_{\text{pos}}}(x,y)}) = \text{pt}_{\text{Hom}_{Z_{\text{pos}}}(g_{\text{pos}}(f_{\text{pos}}(x)), g_{\text{pos}}(f_{\text{pos}}(y)))}$$

$$= [g_{\text{pos}} \circ f_{\text{pos}}](\text{pt}_{\text{Hom}_{X_{\text{pos}}}(x,y)})$$

for each  $x, y \in X$  with  $x \preceq_X y$ .

Thus  $(-)_{\text{pos}}$  is indeed a functor.


Item 2: Fully Faithfulness

Omitted.

Item 3: Characterisations

Omitted.

Item 4: Automatic Commutativity of Diagrams

This follows from the fact that if  $C$  is posetal, then there is at most one morphism between any two objects, namely  $\text{pt}$ . 

## 11.3 The Quadruple Adjunction With Sets

### 11.3.1 Statement

Let  $C$  be a category.

#### PROPOSITION 11.3.1.1.1 ► THE QUADRUPLE ADJUNCTION BETWEEN Sets AND Cats

We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}): \quad \text{Sets} \quad \begin{array}{c} \xrightarrow{\pi_0} \\ \downarrow \perp \\ \xrightarrow{(-)_{\text{disc}}} \\ \downarrow \perp \\ \xleftarrow{\text{Obj}} \\ \downarrow \perp \\ \xleftarrow{(-)_{\text{indisc}}} \end{array} \quad \text{Cats},$$

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\text{Sets}}(\pi_0(C), X) &\cong \text{Hom}_{\text{Cats}}(C, X_{\text{disc}}), \\ \text{Hom}_{\text{Cats}}(X_{\text{disc}}, C) &\cong \text{Hom}_{\text{Sets}}(X, \text{Obj}(C)), \\ \text{Hom}_{\text{Sets}}(\text{Obj}(C), X) &\cong \text{Hom}_{\text{Cats}}(C, X_{\text{indisc}}), \end{aligned}$$



natural in  $C \in \text{Obj}(\text{Cats})$  and  $X \in \text{Obj}(\text{Sets})$ , where

- The functor

$$\pi_0: \text{Cats} \rightarrow \text{Sets},$$

the **connected components functor**, is the functor sending a category to its set of connected components of [Definition 11.3.2.2.1](#).

- The functor

$$(-)_{\text{disc}}: \text{Sets} \rightarrow \text{Cats},$$

the **discrete category functor**, is the functor sending a set to its associated discrete category of [Item 1](#).

- The functor

$$\text{Obj}: \text{Cats} \rightarrow \text{Sets},$$

the **object functor**, is the functor sending a category to its set of objects.

- The functor

$$(-)_{\text{indisc}}: \text{Sets} \rightarrow \text{Cats},$$

the **indiscrete category functor**, is the functor sending a set to its associated indiscrete category of [Item 1](#).

#### PROOF 11.3.1.1.2 ► PROOF OF PROPOSITION 11.3.1.1.1

Omitted.



#### WARNING 11.3.1.1.3 ► PROPOSITION 11.3.1.1.1 CANNOT BE ENHANCED TO A 2-CATEGORICAL ADJUNCTION



(This is a stub, to be revised and expanded upon later.)

The discrete category functor of [Proposition 11.3.1.1.1](#) lifts to a 2-functor, but it fails to preserve 2-categorical colimits, and hence lacks a right 2-adjoint. For instance, the 2-pushout of  $\text{pt} \leftarrow S^0 \rightarrow \text{pt}$  in  $\text{Sets}_{\text{disc}}$  is  $\text{pt}$ , but in  $\text{Cats}_2$  it is given by  $B\mathbb{Z}$ .

### 11.3.2 Connected Components and Connected Categories

#### 11.3.2.1 Connected Components of Categories

Let  $C$  be a category.

##### DEFINITION 11.3.2.1.1 ► CONNECTED COMPONENTS OF CATEGORIES

A **connected component** of  $C$  is a full subcategory  $\mathcal{I}$  of  $C$  satisfying the following conditions:<sup>1</sup>

1. *Non-Emptiness.* We have  $\text{Obj}(\mathcal{I}) \neq \emptyset$ .
2. *Connectedness.* There exists a zigzag of arrows between any two objects of  $\mathcal{I}$ .

<sup>1</sup>In other words, a **connected component** of  $C$  is an element of the set  $\text{Obj}(C)/\sim$  with  $\sim$  the equivalence relation generated by the relation  $\sim'$  obtained by declaring  $A \sim' B$  iff there exists a morphism of  $C$  from  $A$  to  $B$ .

#### 11.3.2.2 Sets of Connected Components of Categories

Let  $C$  be a category.

##### DEFINITION 11.3.2.2.1 ► SETS OF CONNECTED COMPONENTS OF CATEGORIES

The **set of connected components** of  $C$  is the set  $\pi_0(C)$  whose elements are the connected components of  $C$ .

##### PROPOSITION 11.3.2.2.2 ► PROPERTIES OF SETS OF CONNECTED COMPONENTS

Let  $C$  be a category.

1. *Functoriality.* The assignment  $C \mapsto \pi_0(C)$  defines a functor

$$\pi_0: \text{Cats} \rightarrow \text{Sets}.$$

2. *Adjointness.* We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}): \text{Sets} \begin{array}{c} \xrightarrow{\pi_0} \\ \downarrow \perp \\ \xrightarrow{(-)_{\text{disc}}} \\ \downarrow \perp \\ \text{Obj} \\ \downarrow \perp \\ \xrightarrow{(-)_{\text{indisc}}} \end{array} \text{Cats}.$$

3. *Interaction With Groupoids.* If  $C$  is a groupoid, then we have an isomorphism of categories

$$\pi_0(C) \cong K(C),$$

where  $K(C)$  is the set of isomorphism classes of  $C$  of??.

4. *Preservation of Colimits.* The functor  $\pi_0$  of **Item 1** preserves colimits. In particular, we have bijections of sets

$$\begin{aligned} \pi_0(C \amalg \mathcal{D}) &\cong \pi_0(C) \amalg \pi_0(\mathcal{D}), \\ \pi_0(C \amalg_{\mathcal{E}} \mathcal{D}) &\cong \pi_0(C) \amalg_{\pi_0(\mathcal{E})} \pi_0(\mathcal{D}), \\ \pi_0(\text{CoEq}(C \xrightarrow[F]{G} \mathcal{D})) &\cong \text{CoEq}(\pi_0(C) \xrightarrow[\pi_0(G)]{\pi_0(F)} \pi_0(\mathcal{D})), \end{aligned}$$

natural in  $C, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$ .

5. *Symmetric Strong Monoidality With Respect to Coproducts.* The connected components functor of **Item 1** has a symmetric strong monoidal structure

$$(\pi_0, \pi_0^{\amalg}, \pi_0^{\amalg|1}): (\text{Cats}, \amalg, \emptyset_{\text{cat}}) \rightarrow (\text{Sets}, \amalg, \emptyset),$$

being equipped with isomorphisms

$$\begin{aligned} \pi_0^{\amalg|C, \mathcal{D}}: \pi_0(C) \amalg \pi_0(\mathcal{D}) &\xrightarrow{\sim} \pi_0(C \amalg \mathcal{D}), \\ \pi_0^{\amalg|1}: \emptyset &\xrightarrow{\sim} \pi_0(\emptyset_{\text{cat}}), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ .

6. *Symmetric Strong Monoidality With Respect to Products.* The connected components functor of **Item 1** has a symmetric strong monoidal structure

$$(\pi_0, \pi_0^\times, \pi_{0|1}^\times) : (\mathbf{Cats}, \times, \mathbf{pt}) \rightarrow (\mathbf{Sets}, \times, \mathbf{pt}),$$

being equipped with isomorphisms

$$\pi_{0|C, \mathcal{D}}^\times : \pi_0(C) \times \pi_0(\mathcal{D}) \xrightarrow{\sim} \pi_0(C \times \mathcal{D}),$$

$$\pi_{0|1}^\times : \mathbf{pt} \xrightarrow{\sim} \pi_0(\mathbf{pt}),$$

natural in  $C, \mathcal{D} \in \mathbf{Obj}(\mathbf{Cats})$ .

#### PROOF 11.3.2.2.3 ► PROOF OF PROPOSITION 11.3.2.2.2

Item 1: Functoriality

Omitted.

Item 2: Adjointness

This is proved in **Proposition 11.3.1.1.1**.

Item 3: Interaction With Groupoids

Omitted.


Item 4: Preservation of Colimits

This follows from **Item 2** and ?? of ??.

Item 5: Symmetric Strong Monoidality With Respect to Coproducts

Omitted.

Item 6: Symmetric Strong Monoidality With Respect to Products

Omitted. 

**11.3.2.3 Connected Categories****DEFINITION 11.3.2.3.1 ► CONNECTED CATEGORIES**

A category  $C$  is **connected** if  $\pi_0(C) \cong \text{pt.}$ <sup>1,2</sup>

<sup>1</sup>*Further Terminology:* A category is **disconnected** if it is not connected.

<sup>2</sup>*Example:* A groupoid is connected iff any two of its objects are isomorphic.

**11.3.3 Discrete Categories**

## DEFINITION 11.3.3.1.1 ► DISCRETE CATEGORIES

Let  $X$  be a set.

1. The **discrete category on  $X$**  is the category  $X_{\text{disc}}$  where

- *Objects.* We have

$$\text{Obj}(X_{\text{disc}}) \stackrel{\text{def}}{=} X.$$

- *Morphisms.* For each  $A, B \in \text{Obj}(X_{\text{disc}})$ , we have

$$\text{Hom}_{X_{\text{disc}}}(A, B) \stackrel{\text{def}}{=} \begin{cases} \text{id}_A & \text{if } A = B, \\ \emptyset & \text{if } A \neq B. \end{cases}$$

- *Identities.* For each  $A \in \text{Obj}(X_{\text{disc}})$ , the unit map

$$\mathbb{1}_A^{X_{\text{disc}}} : \text{pt} \rightarrow \text{Hom}_{X_{\text{disc}}}(A, A)$$

of  $X_{\text{disc}}$  at  $A$  is defined by

$$\text{id}_A^{X_{\text{disc}}} \stackrel{\text{def}}{=} \text{id}_A.$$

- *Composition.* For each  $A, B, C \in \text{Obj}(X_{\text{disc}})$ , the composition map

$$\circ_{A,B,C}^{X_{\text{disc}}} : \text{Hom}_{X_{\text{disc}}}(B, C) \times \text{Hom}_{X_{\text{disc}}}(A, B) \rightarrow \text{Hom}_{X_{\text{disc}}}(A, C)$$

of  $X_{\text{disc}}$  at  $(A, B, C)$  is defined by

$$\text{id}_A \circ \text{id}_A \stackrel{\text{def}}{=} \text{id}_A.$$

2. A category  $C$  is **discrete** if it is equivalent to  $X_{\text{disc}}$  for some set  $X$ .

## PROPOSITION 11.3.3.1.2 ► PROPERTIES OF DISCRETE CATEGORIES ON SETS

Let  $X$  be a set.

1. *Functoriality.* The assignment  $X \mapsto X_{\text{disc}}$  defines a functor

$$(-)_{\text{disc}} : \text{Sets} \rightarrow \text{Cats}.$$

2. *Adjointness.* We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}): \text{Sets} \begin{array}{c} \xrightarrow{\pi_0} \\ \text{---} \downarrow \text{---} \\ \text{---} \downarrow \text{---} \\ \text{---} \downarrow \text{---} \\ \xrightarrow{(-)_{\text{indisc}}} \end{array} \text{Cats.}$$

$\begin{array}{c} \perp \\ (-)_{\text{disc}} \\ \perp \\ \text{Obj} \\ \perp \end{array}$

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

$$((-)_{\text{disc}}, (-)_{\text{disc}}^{\coprod}, (-)_{\text{disc}|\mathbb{1}}^{\coprod}): (\text{Sets}, \coprod, \emptyset) \rightarrow (\text{Cats}, \coprod, \emptyset_{\text{cat}}),$$

being equipped with isomorphisms

$$\begin{aligned} (-)_{\text{disc}|\mathbb{1}}^{\coprod} &: X_{\text{disc}} \coprod Y_{\text{disc}} \xrightarrow{\sim} (X \coprod Y)_{\text{disc}}, \\ (-)_{\text{disc}|\mathbb{1}}^{\coprod} &: \emptyset_{\text{cat}} \xrightarrow{\sim} \emptyset_{\text{disc}}, \end{aligned}$$

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

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

$$((-)_{\text{disc}}, (-)_{\text{disc}}^{\times}, (-)_{\text{disc}|\mathbb{1}}^{\times}): (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Cats}, \times, \text{pt}),$$

being equipped with isomorphisms

$$\begin{aligned} (-)_{\text{disc}|\mathbb{1}}^{\times} &: X_{\text{disc}} \times Y_{\text{disc}} \xrightarrow{\sim} (X \times Y)_{\text{disc}}, \\ (-)_{\text{disc}|\mathbb{1}}^{\times} &: \text{pt} \xrightarrow{\sim} \text{pt}_{\text{disc}}, \end{aligned}$$

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

## PROOF 11.3.3.1.3 ► PROOF OF PROPOSITION 11.3.3.1.2

Item 1: Functoriality

Omitted.


Item 2: Adjointness

This is proved in **Proposition 11.3.1.1.1**.

Item 3: Symmetric Strong Monoidality With Respect to Coproducts

Omitted.

Item 4: Symmetric Strong Monoidality With Respect to Products

Omitted. 

## 11.3.4 Indiscrete Categories

## DEFINITION 11.3.4.1.1 ► INDISCRETE CATEGORIES

Let  $X$  be a set.

1. The **indiscrete category on  $X$** <sup>1</sup> is the category  $X_{\text{indisc}}$  where

- *Objects.* We have

$$\text{Obj}(X_{\text{indisc}}) \stackrel{\text{def}}{=} X.$$

- *Morphisms.* For each  $A, B \in \text{Obj}(X_{\text{indisc}})$ , we have

$$\begin{aligned} \text{Hom}_{X_{\text{disc}}}(A, B) &\stackrel{\text{def}}{=} \{[A] \rightarrow [B]\} \\ &\cong \text{pt}. \end{aligned}$$

- *Identities.* For each  $A \in \text{Obj}(X_{\text{indisc}})$ , the unit map

$$\mathbb{1}_A^{X_{\text{indisc}}} : \text{pt} \rightarrow \text{Hom}_{X_{\text{indisc}}}(A, A)$$

of  $X_{\text{indisc}}$  at  $A$  is defined by

$$\text{id}_A^{X_{\text{indisc}}} \stackrel{\text{def}}{=} \{[A] \rightarrow [A]\}.$$



- *Composition.* For each  $A, B, C \in \text{Obj}(X_{\text{indisc}})$ , the composition map

$$\circ_{A,B,C}^{X_{\text{indisc}}} : \text{Hom}_{X_{\text{indisc}}}(B, C) \times \text{Hom}_{X_{\text{indisc}}}(A, B) \rightarrow \text{Hom}_{X_{\text{indisc}}}(A, C)$$

of  $X_{\text{disc}}$  at  $(A, B, C)$  is defined by

$$([B] \rightarrow [C]) \circ ([A] \rightarrow [B]) \stackrel{\text{def}}{=} ([A] \rightarrow [C]).$$

2. A category  $\mathcal{C}$  is **indiscrete** if it is equivalent to  $X_{\text{indisc}}$  for some set  $X$ .

<sup>1</sup>*Further Terminology:* Sometimes called the **chaotic category on  $X$** .

#### PROPOSITION 11.3.4.1.2 ► PROPERTIES OF INDISCRETE CATEGORIES ON SETS

Let  $X$  be a set.

1. *Functoriality.* The assignment  $X \mapsto X_{\text{indisc}}$  defines a functor

$$(-)_{\text{indisc}} : \text{Sets} \rightarrow \text{Cats}.$$

2. *Adjointness.* We have a quadruple adjunction

$$(\pi_0 \dashv (-)_{\text{disc}} \dashv \text{Obj} \dashv (-)_{\text{indisc}}) : \text{Sets} \begin{array}{c} \xrightarrow{\pi_0} \\ \xleftarrow{(-)_{\text{disc}}} \\ \xrightarrow{\text{Obj}} \\ \xleftarrow{(-)_{\text{indisc}}} \end{array} \text{Cats}.$$

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

$$((-)_{\text{indisc}}, (-)_{\text{indisc}}^{\times}, (-)_{\text{indisc}|\mathbb{1}}^{\times}) : (\text{Sets}, \times, \text{pt}) \rightarrow (\text{Cats}, \times, \text{pt}),$$

being equipped with isomorphisms

$$(-)_{\text{indisc}|X,Y}^{\times} : X_{\text{indisc}} \times Y_{\text{indisc}} \xrightarrow{\sim} (X \times Y)_{\text{indisc}},$$

$$(-)_{\text{indisc}|\mathbb{1}}^{\times} : \text{pt} \xrightarrow{\sim} \text{pt}_{\text{indisc}},$$

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

|

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Item 1: Functoriality

Omitted.

Item 2: Adjointness

This is proved in [Proposition 11.3.1.1.1](#).

Item 3: Symmetric Strong Monoidality With Respect to Products

Omitted.



## 11.4 Groupoids

### 11.4.1 Isomorphisms

Let  $C$  be a category.

#### DEFINITION 11.4.1.1.1 ► ISOMORPHISMS

A morphism  $f: A \rightarrow B$  of  $C$  is an **isomorphism** if there exists a morphism  $f^{-1}: B \rightarrow A$  of  $C$  such that

$$\begin{aligned} f \circ f^{-1} &= \text{id}_B, \\ f^{-1} \circ f &= \text{id}_A. \end{aligned}$$

#### NOTATION 11.4.1.1.2 ► THE SET OF ISOMORPHISMS BETWEEN TWO OBJECTS IN A CATEGORY

We write  $\text{Iso}_C(A, B)$  for the set of all isomorphisms in  $C$  from  $A$  to  $B$ .

### 11.4.2 Groupoids

#### DEFINITION 11.4.2.1.1 ► GROUPOIDS

A **groupoid** is a category in which every morphism is an isomorphism.

**EXAMPLE 11.4.2.1.2 ► GROUPS AS ONE-OBJECT GROUPOIDS**

The isomorphism of categories of [Example 11.2.3.1.1](#) restricts to an isomorphism

$$\begin{array}{ccc} \text{Grp} & \longrightarrow & \text{Grpd} \\ \downarrow & \lrcorner & \downarrow \text{Obj} \\ \text{pt} & \xrightarrow{[\text{pt}]} & \text{Sets} \end{array}$$

$\text{Grp} \cong \text{pt} \times_{\text{Sets}} \text{Grpd},$

where  $\text{Grpd}$  is the full subcategory of  $\text{Cats}$  spanned by the groupoids. In other words, we have an identification

$$\{\text{Groups}\} \cong \{\text{One-object groupoids}\}.$$

**11.4.3 The Groupoid Completion of a Category**

Let  $C$  be a category.

**DEFINITION 11.4.3.1.1 ► THE GROUPOID COMPLETION OF A CATEGORY**

The **groupoid completion of  $C$** <sup>1</sup> is the pair  $(K_0(C), \iota_C)$  consisting of

- A groupoid  $K_0(C)$ ;
- A functor  $\iota_C : C \rightarrow K_0(C)$ ;

satisfying the following universal property:<sup>2</sup>

**(UP)** Given another such pair  $(\mathcal{G}, i)$ , there exists a unique functor

$$K_0(C) \xrightarrow{\exists!} \mathcal{G}$$

$$\begin{array}{ccc} & K_0(C) & \\ \iota_C \nearrow & & \downarrow \exists! \\ C & \xrightarrow{i} & \mathcal{G} \end{array}$$


commute.

<sup>1</sup>*Further Terminology:* Also called the **Grothendieck groupoid of  $C$**  or the **Grothendieck groupoid completion of  $C$** .  
 See [Item 5 of Proposition 11.4.3.1.4](#) for an explicit construction.

#### CONSTRUCTION 11.4.3.1.2 ► CONSTRUCTION OF THE GROUPOID COMPLETION OF A CATEGORY

Concretely, the groupoid completion of  $C$  is the Gabriel–Zisman localisation  $\text{Mor}(C)^{-1}C$  of  $C$  at the set  $\text{Mor}(C)$  of all morphisms of  $C$ ; see [Constructions With Categories, ??](#).  
 (To be expanded upon later on.)

#### PROOF 11.4.3.1.3 ► PROOF OF CONSTRUCTION 11.4.3.1.2

Omitted. 

#### PROPOSITION 11.4.3.1.4 ► PROPERTIES OF GROUPOID COMPLETION

Let  $C$  be a category.

1. *Functoriality.* The assignment  $C \mapsto K_0(C)$  defines a functor

$$K_0: \text{Cats} \rightarrow \text{Grpd}.$$

2. *2-Functoriality.* The assignment  $C \mapsto K_0(C)$  defines a 2-functor

$$K_0: \text{Cats}_2 \rightarrow \text{Grpd}_2.$$

3. *Adjointness.* We have an adjunction

$$(K_0 \dashv \iota): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp \\ \xleftarrow{\iota} \end{array} \text{Grpd},$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Grpd}}(K_0(C), \mathcal{G}) \cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}),$$

natural in  $C \in \text{Obj}(\text{Cats})$  and  $\mathcal{G} \in \text{Obj}(\text{Grpd})$ , forming, together with the functor  $\text{Core}$  of [Item 1 of Proposition 11.4.4.1.5](#), a triple

adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \quad \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp \\ \xleftarrow{\iota} \\ \perp \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\text{Grpd}}(K_0(C), \mathcal{G}) &\cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}), \\ \text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) &\cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$  and  $\mathcal{G} \in \text{Obj}(\text{Grpd})$ .

4. *2-Adjointness*. We have a 2-adjunction

$$(K_0 \dashv \iota): \quad \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp_2 \\ \xleftarrow{\iota} \end{array} \text{Grpd},$$

witnessed by an isomorphism of categories

$$\text{Fun}(K_0(C), \mathcal{G}) \cong \text{Fun}(C, \mathcal{G}),$$

natural in  $C \in \text{Obj}(\text{Cats})$  and  $\mathcal{G} \in \text{Obj}(\text{Grpd})$ , forming, together with the 2-functor  $\text{Core}$  of [Item 2](#) of [Proposition 11.4.4.1.5](#), a triple 2-adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \quad \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp_2 \\ \xleftarrow{\iota} \\ \perp_2 \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by isomorphisms of categories

$$\begin{aligned} \text{Fun}(K_0(C), \mathcal{G}) &\cong \text{Fun}(C, \mathcal{G}), \\ \text{Fun}(\mathcal{G}, \mathcal{D}) &\cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$  and  $\mathcal{G} \in \text{Obj}(\text{Grpd})$ .

5. *Interaction With Classifying Spaces.* We have an isomorphism of groupoids

$$K_0(C) \cong \Pi_{\leq 1}(|N_\bullet(C)|),$$

natural in  $C \in \text{Obj}(\text{Cats})$ ; i.e. the diagram

$$\begin{array}{ccc} \text{Cats} & \xrightarrow{K_0} & \text{Grp} \\ \downarrow N_\bullet & \uparrow \{ \text{dashed} \} & \uparrow \Pi_{\leq 1} \\ \text{sSets} & \xrightarrow{|\cdot|} & \Pi \end{array}$$

commutes up to natural isomorphism.

6. *Symmetric Strong Monoidality With Respect to Coproducts.* The groupoid completion functor of **Item 1** has a symmetric strong monoidal structure

$$(K_0, K_0^{\coprod}, K_0^{\coprod|1}): (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Grpd}, \coprod, \emptyset_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned} K_0^{\coprod|C, \mathcal{D}}: K_0(C) \coprod K_0(\mathcal{D}) &\xrightarrow{\sim} K_0(C \coprod \mathcal{D}), \\ K_0^{\coprod|1}: \emptyset_{\text{cat}} &\xrightarrow{\sim} K_0(\emptyset_{\text{cat}}), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ .

7. *Symmetric Strong Monoidality With Respect to Products.* The groupoid completion functor of **Item 1** has a symmetric strong monoidal structure

$$(K_0, K_0^\times, K_0^\times|1): (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned} K_0^\times|C, \mathcal{D}: K_0(C) \times K_0(\mathcal{D}) &\xrightarrow{\sim} K_0(C \times \mathcal{D}), \\ K_0^\times|1: \text{pt} &\xrightarrow{\sim} K_0(\text{pt}), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ .

## PROOF 11.4.3.1.5 ► PROOF OF PROPOSITION 11.4.3.1.4

Item 1: Functoriality

Omitted.

Item 2: 2-Functoriality

Omitted.

Item 3: Adjointness

Omitted.

Item 4: 2-Adjointness

Omitted.

Item 5: Interaction With Classifying Spaces

See Corollary 18.33 of <https://web.ma.utexas.edu/users/dafr/M392C-2012/Notes/lecture18.pdf>.

Item 6: Symmetric Strong Monoidality With Respect to Coproducts

Omitted.

Item 7: Symmetric Strong Monoidality With Respect to Products

Omitted.



## 11.4.4 The Core of a Category

Let  $C$  be a category.

## DEFINITION 11.4.4.1.1 ► THE CORE OF A CATEGORY

The **core** of  $C$  is the pair  $(\text{Core}(C), \iota_C)$  consisting of

- A groupoid  $\text{Core}(C)$ ;
- A functor  $\iota_C : \text{Core}(C) \hookrightarrow C$ ;

satisfying the following universal property:

(UP) Given another such pair  $(\mathcal{G}, i)$ , there exists a unique functor  $\mathcal{G} \xrightarrow{\exists!}$



$\text{Core}(C)$  making the diagram

$$\begin{array}{ccc} & \text{Core}(C) & \\ \exists! \nearrow & \downarrow i_C & \\ \mathcal{G} & \xrightarrow{i} & C \end{array}$$

commute.

#### NOTATION 11.4.4.1.2 ► ALTERNATIVE NOTATION FOR THE CORE OF A CATEGORY

We also write  $C^\simeq$  for  $\text{Core}(C)$ .

#### CONSTRUCTION 11.4.4.1.3 ► CONSTRUCTION OF THE CORE OF A CATEGORY

The core of  $C$  is the wide subcategory of  $C$  spanned by the isomorphisms of  $C$ , i.e. the category  $\text{Core}(C)$  where<sup>1</sup>


1. *Objects.* We have

$$\text{Obj}(\text{Core}(C)) \stackrel{\text{def}}{=} \text{Obj}(C).$$

2. *Morphisms.* The morphisms of  $\text{Core}(C)$  are the isomorphisms of  $C$ .

<sup>1</sup>*Slogan:* The groupoid  $\text{Core}(C)$  is the maximal subgroupoid of  $C$ .

#### PROOF 11.4.4.1.4 ► PROOF OF CONSTRUCTION 11.4.4.1.3

This follows from the fact that functors preserve isomorphisms (Item 1 of Proposition 11.5.1.1.8). 

#### PROPOSITION 11.4.4.1.5 ► PROPERTIES OF THE CORE OF A CATEGORY

Let  $C$  be a category.

1. *Functoriality.* The assignment  $C \mapsto \text{Core}(C)$  defines a functor

$$\text{Core}: \text{Cats} \rightarrow \text{Grpd}.$$

2. *2-Functoriality.* The assignment  $C \mapsto \text{Core}(C)$  defines a 2-functor

$$\text{Core}: \text{Cats}_2 \rightarrow \text{Grpd}_2.$$

3. *Adjointness.* We have an adjunction

$$(\iota \dashv \text{Core}): \text{Grpd} \begin{array}{c} \xrightarrow{\iota} \\ \perp \\ \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

witnessed by a bijection of sets

$$\text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) \cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

natural in  $\mathcal{G} \in \text{Obj}(\text{Grpd})$  and  $\mathcal{D} \in \text{Obj}(\text{Cats})$ , forming, together with the functor  $K_0$  of [Item 1](#) of [Proposition 11.4.3.1.4](#), a triple adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp \\ \xleftarrow{\iota} \\ \perp \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\text{Grpd}}(K_0(C), \mathcal{G}) &\cong \text{Hom}_{\text{Cats}}(C, \mathcal{G}), \\ \text{Hom}_{\text{Cats}}(\mathcal{G}, \mathcal{D}) &\cong \text{Hom}_{\text{Grpd}}(\mathcal{G}, \text{Core}(\mathcal{D})), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$  and  $\mathcal{G} \in \text{Obj}(\text{Grpd})$ .

4. *2-Adjointness.* We have an adjunction

$$(\iota \dashv \text{Core}): \text{Grpd} \begin{array}{c} \xrightarrow{\iota} \\ \perp_2 \\ \xleftarrow{\text{Core}} \end{array} \text{Cats},$$

witnessed by an isomorphism of categories

$$\text{Fun}(\mathcal{G}, \mathcal{D}) \cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})),$$

natural in  $\mathcal{G} \in \text{Obj}(\text{Grpd})$  and  $\mathcal{D} \in \text{Obj}(\text{Cats})$ , forming, together with the 2-functor  $K_0$  of **Item 2** of **Proposition 11.4.3.1.4**, a triple 2-adjunction

$$(K_0 \dashv \iota \dashv \text{Core}): \quad \text{Cats} \begin{array}{c} \xrightarrow{K_0} \\ \perp_2 \\ \xleftarrow{\iota} \\ \perp_2 \\ \xrightarrow{\text{Core}} \end{array} \text{Grpd},$$

witnessed by isomorphisms of categories

$$\begin{aligned} \text{Fun}(K_0(C), \mathcal{G}) &\cong \text{Fun}(C, \mathcal{G}), \\ \text{Fun}(\mathcal{G}, \mathcal{D}) &\cong \text{Fun}(\mathcal{G}, \text{Core}(\mathcal{D})), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$  and  $\mathcal{G} \in \text{Obj}(\text{Grpd})$ .

5. *Symmetric Strong Monoidality With Respect to Products.* The core functor of **Item 1** has a symmetric strong monoidal structure

$$(\text{Core}, \text{Core}^\times, \text{Core}_{\mathbb{1}}^\times): (\text{Cats}, \times, \text{pt}) \rightarrow (\text{Grpd}, \times, \text{pt})$$

being equipped with isomorphisms

$$\begin{aligned} \text{Core}_{C, \mathcal{D}}^\times: \text{Core}(C) \times \text{Core}(\mathcal{D}) &\xrightarrow{\sim} \text{Core}(C \times \mathcal{D}), \\ \text{Core}_{\mathbb{1}}^\times: \text{pt} &\xrightarrow{\sim} \text{Core}(\text{pt}), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ .

6. *Symmetric Strong Monoidality With Respect to Coproducts.* The core functor of **Item 1** has a symmetric strong monoidal structure

$$(\text{Core}, \text{Core}^{\coprod}, \text{Core}_{\mathbb{1}}^{\coprod}): (\text{Cats}, \coprod, \emptyset_{\text{cat}}) \rightarrow (\text{Grpd}, \coprod, \emptyset_{\text{cat}})$$

being equipped with isomorphisms

$$\begin{aligned} \text{Core}_{C, \mathcal{D}}^{\coprod}: \text{Core}(C) \coprod \text{Core}(\mathcal{D}) &\xrightarrow{\sim} \text{Core}(C \coprod \mathcal{D}), \\ \text{Core}_{\mathbb{1}}^{\coprod}: \emptyset_{\text{cat}} &\xrightarrow{\sim} \text{Core}(\emptyset_{\text{cat}}), \end{aligned}$$

natural in  $C, \mathcal{D} \in \text{Obj}(\text{Cats})$ .

**PROOF 11.4.4.1.6 ► PROOF OF PROPOSITION 11.4.4.1.5**

Item 1: Functoriality

Omitted.

Item 2: 2-Functoriality

Omitted.

Item 3: Adjointness

Omitted.

Item 4: 2-Adjointness

Omitted.

Item 5: Symmetric Strong Monoidality With Respect to Products

Omitted.

Item 6: Symmetric Strong Monoidality With Respect to Coproducts

Omitted.



## 11.5 Functors

### 11.5.1 Foundations

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.5.1.1.1 ► FUNCTORS**

A **functor**  $F: \mathcal{C} \rightarrow \mathcal{D}$  **from**  $\mathcal{C}$  **to**  $\mathcal{D}$ <sup>1</sup> consists of:

1. *Action on Objects.* A map of sets

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D}),$$

called the **action on objects of  $F$** .

2. *Action on Morphisms.* For each  $A, B \in \text{Obj}(\mathcal{C})$ , a map

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(A), F(B)),$$

called the **action on morphisms of  $F$  at  $(A, B)$** <sup>2</sup>.

satisfying the following conditions:

1. *Preservation of Identities.* For each  $A \in \text{Obj}(C)$ , the diagram

$$\begin{array}{ccc} \text{pt} & & \\ \downarrow \mathbb{1}_A^C & \searrow \mathbb{1}_{F(A)}^{\mathcal{D}} & \\ \text{Hom}_C(A, A) & \xrightarrow{F_{A,A}} & \text{Hom}_{\mathcal{D}}(F(A), F(A)) \end{array}$$

commutes, i.e. we have

$$F(\text{id}_A) = \text{id}_{F(A)}.$$

2. *Preservation of Composition.* For each  $A, B, C \in \text{Obj}(C)$ , the diagram

$$\begin{array}{ccc} \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & \xrightarrow{\circ_{A,B,C}^C} & \text{Hom}_C(A, C) \\ \downarrow F_{B,C} \times F_{A,B} & & \downarrow F_{A,C} \\ \text{Hom}_{\mathcal{D}}(F(B), F(C)) \times \text{Hom}_{\mathcal{D}}(F(A), F(B)) & \xrightarrow{\circ_{F(A),F(B),F(C)}^{\mathcal{D}}} & \text{Hom}_{\mathcal{D}}(F(A), F(C)) \end{array}$$

commutes, i.e. for each composable pair  $(g, f)$  of morphisms of  $C$ , we have

$$F(g \circ f) = F(g) \circ F(f).$$

<sup>1</sup>*Further Terminology:* Also called a **covariant functor**.

<sup>2</sup>*Further Terminology:* Also called **action on Hom-sets of  $F$  at  $(A, B)$** .

#### NOTATION 11.5.1.1.2 ► SUBSCRIPT AND SUPERScript NOTATION FOR FUNCTORS

Let  $C$  and  $\mathcal{D}$  be categories, and write  $C^{\text{op}}$  for the opposite category of  $C$  of Constructions With Categories, ??.

1. Given a functor

$$F: C \rightarrow \mathcal{D},$$

we also write  $F_A$  for  $F(A)$ .

2. Given a functor

$$F: C^{\text{op}} \rightarrow \mathcal{D},$$

we also write  $F^A$  for  $F(A)$ .

3. Given a functor

$$F: C \times C \rightarrow \mathcal{D},$$

we also write  $F_{A,B}$  for  $F(A, B)$ .

4. Given a functor

$$F: C^{\text{op}} \times C \rightarrow \mathcal{D},$$

we also write  $F_B^A$  for  $F(A, B)$ .

We employ a similar notation for morphisms, writing e.g.  $F_f$  for  $F(f)$  given a functor  $F: C \rightarrow \mathcal{D}$ .

#### NOTATION 11.5.1.1.3 ► ADDITIONAL NOTATION FOR FUNCTORS

Following the notation  $\llbracket x \mapsto f(x) \rrbracket$  for a function  $f: X \rightarrow Y$  introduced in **Sets**, **Notation 3.1.1.2**, we will sometimes denote a functor  $F: C \rightarrow \mathcal{D}$  by

$$F \stackrel{\text{def}}{=} \llbracket A \mapsto F(A) \rrbracket,$$

specially when the action on morphisms of  $F$  is clear from its action on objects.

#### EXAMPLE 11.5.1.1.4 ► IDENTITY FUNCTORS

The **identity functor** of a category  $C$  is the functor  $\text{id}_C: C \rightarrow C$  where

1. *Action on Objects.* For each  $A \in \text{Obj}(C)$ , we have

$$\text{id}_C(A) \stackrel{\text{def}}{=} A.$$

2. *Action on Morphisms.* For each  $A, B \in \text{Obj}(C)$ , the action on mor-

phisms

$$(\mathrm{id}_C)_{A,B}: \mathrm{Hom}_C(A, B) \rightarrow \underbrace{\mathrm{Hom}_C(\mathrm{id}_C(A), \mathrm{id}_C(B))}_{\stackrel{\mathrm{def}}{=} \mathrm{Hom}_C(A, B)}$$

of  $\mathrm{id}_C$  at  $(A, B)$  is defined by

$$(\mathrm{id}_C)_{A,B} \stackrel{\mathrm{def}}{=} \mathrm{id}_{\mathrm{Hom}_C(A, B)}.$$

#### PROOF 11.5.1.1.5 ► PROOF OF EXAMPLE 11.5.1.1.4


##### Preservation of Identities

We have  $\mathrm{id}_C(\mathrm{id}_A) \stackrel{\mathrm{def}}{=} \mathrm{id}_A$  for each  $A \in \mathrm{Obj}(C)$  by definition.

##### Preservation of Compositions

For each composable pair  $A \xrightarrow{f} B \xrightarrow{g} C$  of morphisms of  $C$ , we have

$$\begin{aligned} \mathrm{id}_C(g \circ f) &\stackrel{\mathrm{def}}{=} g \circ f \\ &\stackrel{\mathrm{def}}{=} \mathrm{id}_C(g) \circ \mathrm{id}_C(f). \end{aligned}$$

This finishes the proof. 

#### DEFINITION 11.5.1.1.6 ► COMPOSITION OF FUNCTORS

The **composition** of two functors  $F: C \rightarrow D$  and  $G: D \rightarrow E$  is the functor  $G \circ F$  where

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

$$[G \circ F](A) \stackrel{\mathrm{def}}{=} G(F(A)).$$

- *Action on Morphisms.* For each  $A, B \in \mathrm{Obj}(C)$ , the action on morphisms

$$(G \circ F)_{A,B}: \mathrm{Hom}_C(A, B) \rightarrow \mathrm{Hom}_E(G_{F_A}, G_{F_B})$$

of  $G \circ F$  at  $(A, B)$  is defined by

$$[G \circ F](f) \stackrel{\mathrm{def}}{=} G(F(f)).$$

|

|



### Preservation of Identities


For each  $A \in \text{Obj}(C)$ , we have

$$\begin{aligned} G_{F_{\text{id}_A}} &= G_{\text{id}_{F_A}} && \text{(functoriality of } F) \\ &= \text{id}_{G_{F_A}}. && \text{(functoriality of } G) \end{aligned}$$

### Preservation of Composition

For each composable pair  $(g, f)$  of morphisms of  $C$ , we have

$$\begin{aligned} G_{F_{g \circ f}} &= G_{F_g \circ F_f} && \text{(functoriality of } F) \\ &= G_{F_g} \circ G_{F_f}. && \text{(functoriality of } G) \end{aligned}$$

This finishes the proof. 

## PROPOSITION 11.5.1.1.8 ► ELEMENTARY PROPERTIES OF FUNCTORS

Let  $F: C \rightarrow \mathcal{D}$  be a functor.

1. *Preservation of Isomorphisms.* If  $f$  is an isomorphism in  $C$ , then  $F(f)$  is an isomorphism in  $\mathcal{D}$ .<sup>1</sup>

<sup>1</sup>When the converse holds, we call  $F$  *conservative*, see [Definition 11.6.4.1.1](#).

## PROOF 11.5.1.1.9 ► PROOF OF PROPOSITION 11.5.1.1.8

### Item 1: Preservation of Isomorphisms

Indeed, we have


$$\begin{aligned} F(f)^{-1} \circ F(f) &= F(f^{-1} \circ f) \\ &= F(\text{id}_A) \\ &= \text{id}_{F(A)} \end{aligned}$$

and

$$F(f) \circ F(f)^{-1} = F(f \circ f^{-1})$$

$$= F(\text{id}_B)$$

$$= \text{id}_{F(B)},$$

showing  $F(f)$  to be an isomorphism. 

### 11.5.2 Contravariant Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories, and let  $\mathcal{C}^{\text{op}}$  denote the opposite category of  $\mathcal{C}$  of Constructions With Categories, ??.

#### DEFINITION 11.5.2.1.1 ► CONTRAVARIANT FUNCTORS

A **contravariant functor** from  $\mathcal{C}$  to  $\mathcal{D}$  is a functor from  $\mathcal{C}^{\text{op}}$  to  $\mathcal{D}$ .

#### REMARK 11.5.2.1.2 ► UNWINDING DEFINITION 11.5.2.1.1

In detail, a **contravariant functor** from  $\mathcal{C}$  to  $\mathcal{D}$  consists of:

1. *Action on Objects.* A map of sets

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D}),$$

called the **action on objects of  $F$** .

2. *Action on Morphisms.* For each  $A, B \in \text{Obj}(\mathcal{C})$ , a map

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(B), F(A)),$$

called the **action on morphisms of  $F$  at  $(A, B)$** .

satisfying the following conditions:

1. *Preservation of Identities.* For each  $A \in \text{Obj}(\mathcal{C})$ , the diagram

$$\begin{array}{ccc} \text{pt} & & \\ \text{\scriptsize $\mathbb{1}_A^{\mathcal{C}}$} \downarrow & \searrow \text{\scriptsize $\mathbb{1}_{F(A)}^{\mathcal{D}}$} & \\ \text{Hom}_{\mathcal{C}}(A, A) & \xrightarrow{\text{\scriptsize $F_{A,A}$}} & \text{Hom}_{\mathcal{D}}(F(A), F(A)) \end{array}$$

commutes, i.e. we have

$$F(\text{id}_A) = \text{id}_{F(A)}.$$

2. *Preservation of Composition.* For each  $A, B, C \in \text{Obj}(C)$ , the diagram

$$\begin{array}{ccc}
 & \text{Hom}_{\mathcal{D}}(F(C), F(B)) \times \text{Hom}_{\mathcal{D}}(F(B), F(A)) & \\
 F_{B,C} \times F_{A,B} \nearrow & & \searrow \sigma_{\text{Hom}_{\mathcal{D}}(F(C), F(B)), \text{Hom}_{\mathcal{D}}(F(B), F(A))}^{\text{Sets}} \\
 \text{Hom}_C(B, C) \times \text{Hom}_C(A, B) & & \text{Hom}_{\mathcal{D}}(F(B), F(A)) \times \text{Hom}_{\mathcal{D}}(F(C), F(B)) \\
 \circ_{A,B,C}^C \searrow & & \searrow \circ_{F(C), F(B), F(A)}^{\mathcal{D}} \\
 \text{Hom}_C(A, C) & \xrightarrow{F_{A,C}} & \text{Hom}_{\mathcal{D}}(F(C), F(A))
 \end{array}$$

commutes, i.e. for each composable pair  $(g, f)$  of morphisms of  $C$ , we have

$$F(g \circ f) = F(f) \circ F(g).$$

#### REMARK 11.5.2.1.3 ► ON THE TERM CONTRAVARIANT FUNCTOR

Throughout this work we will not use the term “contravariant” functor, speaking instead simply of functors  $F: C^{\text{op}} \rightarrow \mathcal{D}$ . We will usually, however, write

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(B), F(A))$$

for the action on morphisms

$$F_{A,B}: \text{Hom}_{C^{\text{op}}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F(A), F(B))$$

of  $F$ , as well as write  $F(g \circ f) = F(f) \circ F(g)$ .

### 11.5.3 Forgetful Functors

#### DEFINITION 11.5.3.1.1 ► FORGETFUL FUNCTORS

There isn't a precise definition of a **forgetful functor**.

#### REMARK 11.5.3.1.2 ► UNWINDING DEFINITION 11.5.3.1.1

Despite there not being a formal or precise definition of a forgetful functor, the term is often very useful in practice, similarly to the word “canonical”. The idea is that a “forgetful functor” is a functor that forgets structure or properties, and is best explained through examples, such as the ones below (see [Examples 11.5.3.1.3](#) and [11.5.3.1.4](#)).

#### EXAMPLE 11.5.3.1.3 ► FORGETFUL FUNCTORS THAT FORGET STRUCTURE

Examples of forgetful functors that forget structure include:

1. *Forgetting Group Structures.* The functor  $\text{Grp} \rightarrow \text{Sets}$  sending a group  $(G, \mu_G, \eta_G)$  to its underlying set  $G$ , forgetting the multiplication and unit maps  $\mu_G$  and  $\eta_G$  of  $G$ .
2. *Forgetting Topologies.* The functor  $\Pi \rightarrow \text{Sets}$  sending a topological space  $(X, \mathcal{T}_X)$  to its underlying set  $X$ , forgetting the topology  $\mathcal{T}_X$ .
3. *Forgetting Fibrations.* The functor  $\text{FibSets}(K) \rightarrow \text{Sets}$  sending a  $K$ -fibred set  $\phi_X: X \rightarrow K$  to the set  $X$ , forgetting the map  $\phi_X$  and the base set  $K$ .

#### EXAMPLE 11.5.3.1.4 ► FORGETFUL FUNCTORS THAT FORGET PROPERTIES

Examples of forgetful functors that forget properties include:

1. *Forgetting Commutativity.* The inclusion functor  $\iota: \text{CMon} \hookrightarrow \text{Mon}$  which forgets the property of being commutative.
2. *Forgetting Inverses.* The inclusion functor  $\iota: \text{Grp} \hookrightarrow \text{Mon}$  which forgets the property of having inverses.

## NOTATION 11.5.3.1.5 ► NOTATION FOR FORGETFUL FUNCTORS THAT FORGET STRUCTURE

Throughout this work, we will denote forgetful functors that forget structure by 忘, e.g. as in

$$\text{忘} : \text{Grp} \rightarrow \text{Sets}.$$

The symbol 忘, pronounced *wasureru* (see [Item 1](#) of [Remark 11.5.3.1.6](#) below), means *to forget*, and is a kanji found in the following words in Japanese and Chinese:

1. 忘れる, transcribed as *wasureru*, meaning *to forget*.
2. 忘却関手, transcribed as *boukyaku kanshu*, meaning *forgetful functor*.
3. 忘记 or 忘記, transcribed as *wàngjì*, meaning *to forget*.
4. 遗忘函子 or 遺忘函子, transcribed as *yíwàng hánzǐ*, meaning *forgetful functor*.

## REMARK 11.5.3.1.6 ► PRONUNCIATION OF THE WORDS IN NOTATION 11.5.3.1.5

Here we collect the pronunciation of the words in [Notation 11.5.3.1.5](#) for accuracy and completeness.

1. Pronunciation of 忘れる:
  - See [here](#).
  - IPA broad transcription: [wäsureru].
  - IPA narrow transcription: [ʷäsi̯r̥ɐɹ̥u̯].
2. Pronunciation of 忘却関手: Pronunciation:
  - See [here](#).
  - IPA broad transcription: [bɔ:käku kãũɕu].
  - IPA narrow transcription: [bɔ:käku̯ kãũɕu̯].
3. Pronunciation of 忘记:
  - See [here](#).

- Broad IPA transcription: [waŋtɕi].
- Sinological IPA transcription: [waŋ<sup>51-53</sup>tɕi<sup>51</sup>].

4. Pronunciation of 遗忘函子:

- See [here](#).
- Broad IPA transcription: [iwaŋ xänfɕzi].
- Sinological IPA transcription: [i<sup>35</sup>waŋ<sup>51</sup> xän<sup>35</sup>fɕz<sup>214-21(4)</sup>].

### 11.5.4 The Natural Transformation Associated to a Functor

#### DEFINITION 11.5.4.1.1 ► THE NATURAL TRANSFORMATION ASSOCIATED TO A FUNCTOR

Every functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  defines a natural transformation<sup>1</sup>

$$F^\dagger: \text{Hom}_{\mathcal{C}} \Rightarrow \text{Hom}_{\mathcal{D}} \circ (F^{\text{op}} \times F),$$

called the **natural transformation associated to  $F$** , consisting of the collection

$$\left\{ F_{A,B}^\dagger: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B) \right\}_{(A,B) \in \text{Obj}(\mathcal{C}^{\text{op}} \times \mathcal{C})}$$

with

$$F_{A,B}^\dagger \stackrel{\text{def}}{=} F_{A,B}.$$

<sup>1</sup>This is the 1-categorical version of **Constructions With Sets**, ?? of ??.

**PROOF 11.5.4.1.2 ► PROOF OF DEFINITION 11.5.4.1.1**

The naturality condition for  $F^\dagger$  is the requirement that for each morphism


$$(\phi, \psi): (X, Y) \rightarrow (A, B)$$

of  $C^{\text{op}} \times C$ , the diagram

$$\begin{array}{ccc} \text{Hom}_C(X, Y) & \xrightarrow{\phi^* \circ \psi_* = \psi_* \circ \phi^*} & \text{Hom}_C(A, B) \\ \downarrow F_{X,Y} & & \downarrow F_{A,B} \\ \text{Hom}_{\mathcal{D}}(F_X, F_Y) & \xrightarrow{F(\phi)^* \circ F(\psi)_* = F(\psi)_* \circ F(\phi)^*} & \text{Hom}_{\mathcal{D}}(F_A, F_B), \end{array}$$

acting on elements as

$$\begin{array}{ccc} f & \xrightarrow{\quad} & \psi \circ f \circ \phi \\ \downarrow & & \downarrow \\ F(f) & \xrightarrow{\quad} & F(\psi) \circ F(f) \circ F(\phi) = F(\psi \circ f \circ \phi) \end{array}$$

commutes, which follows from the functoriality of  $F$ . 

**PROPOSITION 11.5.4.1.3 ► PROPERTIES OF NATURAL TRANSFORMATIONS ASSOCIATED TO FUNCTORS**

Let  $F: C \rightarrow \mathcal{D}$  and  $G: \mathcal{D} \rightarrow \mathcal{E}$  be functors.

1. *Interaction With Natural Isomorphisms.* The following conditions are equivalent:

- (a) The natural transformation  $F^\dagger: \text{Hom}_C \Rightarrow \text{Hom}_{\mathcal{D}} \circ (F^{\text{op}} \times F)$  associated to  $F$  is a natural isomorphism.
- (b) The functor  $F$  is fully faithful.

2. *Interaction With Composition.* We have an equality of pasting dia-

grams

$$\begin{array}{ccc}
 C^{\text{op}} \times C & \xrightarrow{F^{\text{op}} \times F} & \mathcal{D}^{\text{op}} \times \mathcal{D} \xrightarrow{G^{\text{op}} \times G} \mathcal{E}^{\text{op}} \times \mathcal{E} \\
 \searrow \text{Hom}_C & \begin{array}{c} \nearrow F^\dagger \\ \downarrow \text{Hom}_{\mathcal{D}} \\ \searrow G^\dagger \end{array} & \swarrow \text{Hom}_{\mathcal{E}} \\
 & \text{Sets} &
 \end{array}
 =
 \begin{array}{ccc}
 C^{\text{op}} \times C & \xrightarrow{(G \circ F)^{\text{op}} \times (G \circ F)} & \mathcal{E}^{\text{op}} \times \mathcal{E} \\
 \searrow \text{Hom}_C & \nearrow (G \circ F)^\dagger & \swarrow \text{Hom}_{\mathcal{E}} \\
 & \text{Sets} &
 \end{array}$$

in  $\text{Cats}_2$ , i.e. we have

$$(G \circ F)^\dagger = (G^\dagger \star \text{id}_{F^{\text{op}} \times F}) \circ F^\dagger.$$

3. *Interaction With Identities.* We have

$$\text{id}_C^\dagger = \text{id}_{\text{Hom}_C(-, -)},$$

i.e. the natural transformation associated to  $\text{id}_C$  is the identity natural transformation of the functor  $\text{Hom}_C(-, -)$ .

#### PROOF 11.5.4.1.4 ► PROOF OF PROPOSITION 11.5.4.1.3


Item 1: Interaction With Natural Isomorphisms

Omitted.

Item 2: Interaction With Composition

Omitted.

Item 3: Interaction With Identities

Omitted. 

## 11.6 Conditions on Functors

### 11.6.1 Faithful Functors

Let  $C$  and  $\mathcal{D}$  be categories.



**DEFINITION 11.6.1.1.1 ► FAITHFUL FUNCTORS**

A functor  $F: C \rightarrow \mathcal{D}$  is **faithful** if, for each  $A, B \in \text{Obj}(C)$ , the action on morphisms

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of  $F$  at  $(A, B)$  is injective.

**PROPOSITION 11.6.1.1.2 ► PROPERTIES OF FAITHFUL FUNCTORS**

Let  $F: C \rightarrow \mathcal{D}$  and  $G: \mathcal{D} \rightarrow \mathcal{E}$  be functors.

1. *Interaction With Composition.* If  $F$  and  $G$  are faithful, then so is  $G \circ F$ .
2. *Interaction With Postcomposition.* The following conditions are equivalent:

- (a) The functor  $F: C \rightarrow \mathcal{D}$  is faithful.
- (b) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is faithful.

- (c) The functor  $F: C \rightarrow \mathcal{D}$  is a representably faithful morphism in  $\text{Cats}_2$  in the sense of **Types of Morphisms in Bicategories**, **Definition 14.1.1.1.1**.

3. *Interaction With Precomposition I.* Let  $F: C \rightarrow \mathcal{D}$  be a functor.

- (a) If  $F$  is faithful, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

**can fail** to be faithful.

- (b) Conversely, if the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is faithful, then  $F$  **can fail** to be faithful.

4. *Interaction With Precomposition II.* If  $F$  is essentially surjective, then the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is faithful.

5. *Interaction With Precomposition III.* The following conditions are equivalent:

- (a) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is faithful.

- (b) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is conservative.

- (c) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is monadic.

- (d) The functor  $F : C \rightarrow \mathcal{D}$  is a corepresentably faithful morphism in  $\text{Cats}_2$  in the sense of [Types of Morphisms in Bicategories, Definition 14.2.1.1.1](#).

- (e) The components

$$\eta_G : G \Longrightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta : \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})} \Longrightarrow \text{Ran}_F \circ F^*$$

of the adjunction  $F^* \dashv \text{Ran}_F$  are all monomorphisms.

(f) The components

$$\epsilon_G : \text{Lan}_F(G \circ F) \Longrightarrow G$$

of the counit

$$\epsilon : \text{Lan}_F \circ F^* \Longrightarrow \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction  $\text{Lan}_F \dashv F^*$  are all epimorphisms.

(g) The functor  $F$  is dominant (**Definition 11.7.1.1.1**), i.e. every object of  $\mathcal{D}$  is a retract of some object in  $\text{Im}(F)$ :

(★) For each  $B \in \text{Obj}(\mathcal{D})$ , there exist:

- An object  $A$  of  $\mathcal{C}$ ;
- A morphism  $s : B \rightarrow F(A)$  of  $\mathcal{D}$ ;
- A morphism  $r : F(A) \rightarrow B$  of  $\mathcal{D}$ ;

such that  $r \circ s = \text{id}_B$ .

#### PROOF 11.6.1.1.3 ► PROOF OF PROPOSITION 11.6.1.1.2

##### Item 1: Interaction With Composition

Since the map

$$(G \circ F)_{A,B} : \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(G_{F_A}, G_{F_B}),$$

defined as the composition

$$\text{Hom}_{\mathcal{C}}(A, B) \xrightarrow{F_{A,B}} \text{Hom}_{\mathcal{D}}(F_A, F_B) \xrightarrow{G_{F(A), F(B)}} \text{Hom}_{\mathcal{D}}(G_{F_A}, G_{F_B}),$$

is a composition of injective functions, it follows from ?? that it is also injective. Therefore  $G \circ F$  is faithful.

##### Item 2: Interaction With Postcomposition

Omitted.

##### Item 3: Interaction With Precomposition I

See [MSE 733163] for **Item 3a**. **Item 3b** follows from **Item 4** and the fact that there are essentially surjective functors that are not faithful.


#### Item 4: Interaction With Precomposition II

Omitted, but see [https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.precomp\\_fully\\_faithful.html](https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.precomp_fully_faithful.html) for a formalised proof.

#### Item 5: Interaction With Precomposition III

We claim **Items 5a** to **5g** are equivalent:

- **Items 5a and 5d Are Equivalent:** This is true by the definition of corepresentably faithful morphism; see **Types of Morphisms in Bicat**, **Definition 14.2.1.1.1**.
- **Items 5a to 5c and 5g Are Equivalent:** See [Adá+01, Proposition 4.1] or alternatively [Fre09, Lemmas 3.1 and 3.2] for the equivalence between **Items 5a** and **5g**.
- **Items 5a, 5e and 5f Are Equivalent:** See ??, ?? of ??.

This finishes the proof. 

## 11.6.2 Full Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

### DEFINITION 11.6.2.1.1 ► FULL FUNCTORS

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **full** if, for each  $A, B \in \text{Obj}(\mathcal{C})$ , the action on morphisms

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of  $F$  at  $(A, B)$  is surjective.

### PROPOSITION 11.6.2.1.2 ► PROPERTIES OF FULL FUNCTORS

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  and  $G: \mathcal{D} \rightarrow \mathcal{E}$  be functors.

1. *Interaction With Composition.* If  $F$  and  $G$  are full, then so is  $G \circ F$ .

2. *Interaction With Postcomposition I.* If  $F$  is full, then the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

**can fail** to be full.

3. *Interaction With Postcomposition II.* If, for each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is full, then  $F$  is also full.

4. *Interaction With Precomposition I.* If  $F$  is full, then the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

**can fail** to be full.

5. *Interaction With Precomposition II.* If, for each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is full, then  $F$  **can fail** to be full.

6. *Interaction With Precomposition III.* If  $F$  is essentially surjective and full, then the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is full (and also faithful by [Item 4 of Proposition 11.6.1.1.2](#)).

7. *Interaction With Precomposition IV.* The following conditions are equivalent:

- (a) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is full.

- (b) The functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is a corepresentably full morphism in  $\mathbf{Cats}_2$  in the sense of **Types of Morphisms in Bicategories**, **Definition 14.2.1.1.1**.

- (c) The components

$$\eta_G: G \Longrightarrow \mathrm{Ran}_F(G \circ F)$$

of the unit

$$\eta: \mathrm{id}_{\mathrm{Fun}(\mathcal{D}, \mathcal{X})} \Longrightarrow \mathrm{Ran}_F \circ F^*$$

of the adjunction  $F^* \dashv \mathrm{Ran}_F$  are all retractions/split epimorphisms.

- (d) The components

$$\epsilon_G: \mathrm{Lan}_F(G \circ F) \Longrightarrow G$$

of the counit

$$\epsilon: \mathrm{Lan}_F \circ F^* \Longrightarrow \mathrm{id}_{\mathrm{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction  $\mathrm{Lan}_F \dashv F^*$  are all sections/split monomorphisms.

- (e) For each  $B \in \mathrm{Obj}(\mathcal{D})$ , there exist:

- An object  $A_B$  of  $\mathcal{C}$ ;
- A morphism  $s_B: B \rightarrow F(A_B)$  of  $\mathcal{D}$ ;
- A morphism  $r_B: F(A_B) \rightarrow B$  of  $\mathcal{D}$ ;

satisfying the following condition:

- (★) For each  $A \in \mathrm{Obj}(\mathcal{C})$  and each pair of morphisms

$$\begin{aligned} r: F(A) &\rightarrow B, \\ s: B &\rightarrow F(A) \end{aligned}$$

of  $\mathcal{D}$ , we have

$$[(A_B, s_B, r_B)] = [(A, s, r \circ s_B \circ r_B)]$$

$$\text{in } \int^{A \in \mathcal{C}} h_{F_A}^{B'} \times h_B^{F_A}.$$

## PROOF 11.6.2.1.3 ► PROOF OF PROPOSITION 11.6.2.1.2

## Item 1: Interaction With Composition

Since the map

$$(G \circ F)_{A,B} : \text{Hom}_C(A, B) \rightarrow \text{Hom}_D(G_{F_A}, G_{F_B}),$$

defined as the composition

$$\text{Hom}_C(A, B) \xrightarrow{F_{A,B}} \text{Hom}_D(F_A, F_B) \xrightarrow{G_{F(A), F(B)}} \text{Hom}_D(G_{F_A}, G_{F_B}),$$

is a composition of surjective functions, it follows from ?? that it is also surjective. Therefore  $G \circ F$  is full.

## Item 2: Interaction With Postcomposition I

We follow the proof (completely formalised in cubical Agda!) given by Naïm Camille Favier in **[favier:postcompose-not-full]**. Let  $C$  be the category where:

- *Objects.* We have  $\text{Obj}(C) = \{A, B\}$ .
- *Morphisms.* We have

$$\text{Hom}_C(A, A) = \{e_A, \text{id}_A\},$$

$$\text{Hom}_C(B, B) = \{e_B, \text{id}_B\},$$

$$\text{Hom}_C(A, B) = \{f, g\},$$

$$\text{Hom}_C(B, A) = \emptyset.$$

- *Composition.* The nontrivial compositions in  $C$  are the following:

$$e_A \circ e_A = \text{id}_A, \quad f \circ e_A = g, \quad e_B \circ f = f,$$

$$e_B \circ e_B = \text{id}_B, \quad g \circ e_A = f, \quad e_B \circ g = g.$$

We may picture  $C$  as follows:

$$e_A \circlearrowleft A \begin{matrix} \xrightarrow{f} \\ \xleftarrow{g} \end{matrix} B \circlearrowright e_B.$$

Next, let  $\mathcal{D}$  be the walking arrow category  $\mathbb{1}$  of [Definition 11.2.5.1.1](#) and let  $F: \mathcal{C} \rightarrow \mathbb{1}$  be the functor given on objects by

$$\begin{aligned} F(A) &= 0, \\ F(B) &= 1 \end{aligned}$$

and on non-identity morphisms by

$$\begin{aligned} F(f) &= f_{01}, & F(e_A) &= \text{id}_0, \\ F(g) &= f_{01}, & F(e_B) &= \text{id}_1. \end{aligned}$$

Finally, let  $\mathcal{X} = \mathbb{B}\mathbb{Z}/2$  be the walking involution and let  $\iota_A, \iota_B: \mathbb{B}\mathbb{Z}/2 \rightrightarrows \mathcal{C}$  be the inclusion functors from  $\mathbb{B}\mathbb{Z}/2$  to  $\mathcal{C}$  with

$$\begin{aligned} \iota_A(\bullet) &= A, \\ \iota_B(\bullet) &= B. \end{aligned}$$

Since every morphism in  $\mathbb{1}$  has a preimage in  $\mathcal{C}$  by  $F$ , the functor  $F$  is full. Now, for  $F_*$  to be full, the map

$$\begin{aligned} F_{*|\iota_A, \iota_B}: \text{Nat}(\iota_A, \iota_B) &\longrightarrow \text{Nat}(F \circ \iota_A, F \circ \iota_B) \\ \alpha &\longmapsto \text{id}_F \star \alpha \end{aligned}$$

would need to be surjective. However, as we will show next, we have

$$\begin{aligned} \text{Nat}(\iota_A, \iota_B) &= \emptyset, \\ \text{Nat}(F \circ \iota_A, F \circ \iota_B) &\cong \text{pt}, \end{aligned}$$

so this is impossible:

- *Proof of  $\text{Nat}(\iota_A, \iota_B) = \emptyset$ :* A natural transformation  $\alpha: \iota_A \Rightarrow \iota_B$  consists of a morphism

$$\alpha: \underbrace{\iota_A(\bullet)}_{=A} \rightarrow \underbrace{\iota_B(\bullet)}_{=B}$$



in  $\mathcal{C}$  making the diagram

$$\begin{array}{ccc} \iota_A(\bullet) & \xrightarrow{\iota_A(e)} & \iota_A(\bullet) \\ \alpha \downarrow & & \downarrow \alpha \\ \iota_B(\bullet) & \xrightarrow{\iota_B(e)} & \iota_B(\bullet) \end{array}$$

commute for each  $e \in \text{Hom}_{\mathcal{B}\mathbb{Z}/2}(\bullet, \bullet) \cong \mathbb{Z}/2$ . We have two cases:

1. If  $\alpha = f$ , the naturality diagram for the unique nonidentity element of  $\mathbb{Z}/2$  is given by

$$\begin{array}{ccc} A & \xrightarrow{e_A} & A \\ f \downarrow & & \downarrow f \\ B & \xrightarrow{e_B} & B. \end{array}$$

However,  $e_B \circ f = f$  and  $f \circ e_A = g$ , so this diagram does not commute.

2. If  $\alpha = g$ , the naturality diagram for the unique nonidentity element of  $\mathbb{Z}/2$  is given by

$$\begin{array}{ccc} A & \xrightarrow{e_A} & A \\ g \downarrow & & \downarrow g \\ B & \xrightarrow{e_B} & B. \end{array}$$

However,  $e_B \circ g = g$  and  $g \circ e_A = f$ , so this diagram does not commute.

As a result, there are no natural transformations from  $\iota_A$  to  $\iota_B$ .

- *Proof of  $\text{Nat}(F \circ \iota_A, F \circ \iota_B) \cong \text{pt}$ :* A natural transformation

$$\beta: F \circ \iota_A \Rightarrow F \circ \iota_B$$

consists of a morphism

$$\beta: \underbrace{[F \circ \iota_A](\bullet)}_{=0} \rightarrow \underbrace{[F \circ \iota_B](\bullet)}_{=1}$$

in  $\mathbb{1}$  making the diagram

$$\begin{array}{ccc} [F \circ \iota_A](\bullet) & \xrightarrow{[F \circ \iota_A](e)} & [F \circ \iota_A](\bullet) \\ \beta \downarrow & & \downarrow \beta \\ [F \circ \iota_B](\bullet) & \xrightarrow{[F \circ \iota_B](e)} & [F \circ \iota_B](\bullet) \end{array}$$

commute for each  $e \in \text{Hom}_{\mathbb{B}\mathbb{Z}/2}(\bullet, \bullet) \cong \mathbb{Z}/2$ . Since the only morphism from 0 to 1 in  $\mathbb{1}$  is  $f_{01}$ , we must have  $\beta = f_{01}$  if such a transformation were to exist, and in fact it indeed does, as in this case the naturality diagram above becomes

$$\begin{array}{ccc} 0 & \xrightarrow{\text{id}_0} & 0 \\ f_{01} \downarrow & & \downarrow f_{01} \\ 1 & \xrightarrow{\text{id}_1} & 1 \end{array}$$

for each  $e \in \mathbb{Z}/2$ , and this diagram indeed commutes, making  $\beta$  into a natural transformation.

This finishes the proof.

### Item 3: Interaction With Postcomposition II

Taking  $\mathcal{X} = \text{pt}$ , it follows by assumption that the functor

$$F_*: \text{Fun}(\text{pt}, \mathcal{C}) \rightarrow \text{Fun}(\text{pt}, \mathcal{D})$$

is full. However, by **Item 5** of **Proposition 11.10.1.1.2**, we have isomorphisms of categories

$$\begin{aligned}\mathrm{Fun}(\mathrm{pt}, C) &\cong C, \\ \mathrm{Fun}(\mathrm{pt}, \mathcal{D}) &\cong \mathcal{D}\end{aligned}$$

and the diagram

$$\begin{array}{ccc}\mathrm{Fun}(\mathrm{pt}, C) & \xrightarrow{F_*} & \mathrm{Fun}(\mathrm{pt}, \mathcal{D}) \\ \downarrow \wr & & \downarrow \wr \\ C & \xrightarrow{F} & \mathcal{D}\end{array}$$

commutes. It then follows from **Item 1** that  $F$  is full.

Item 4: Interaction With Precomposition I

Omitted.

Item 5: Interaction With Precomposition II

See [BS10, p. 47].


Item 6: Interaction With Precomposition III

Omitted, but see [https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.precomp\\_fully\\_faithful.html](https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.precomp_fully_faithful.html) for a formalised proof.

Item 7: Interaction With Precomposition IV

We claim **Items 7a** to **7e** are equivalent:

- **Items 7a and 7b Are Equivalent:** This is true by the definition of corepresentably full morphism; see **Types of Morphisms in Bicat-**  
**egories, Definition 14.2.2.1.1.**
- **Items 7a, 7c and 7d Are Equivalent:** See ??, ?? of ??.
- **Items 7a and 7e Are Equivalent:** See [Adá+01, Item (b) of Remark 4.3].

This finishes the proof. 

**QUESTION 11.6.2.1.4 ► BETTER CHARACTERISATIONS OF FUNCTORS WITH FULL PRECOMPOSITION**

**Item 7** of **Proposition 11.6.2.1.2** gives a characterisation of the functors  $F$  for which  $F^*$  is full, but the characterisations given there are really messy. Are there better ones?  
This question also appears as [MO 468121b].

### 11.6.3 Fully Faithful Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.6.3.1.1 ► FULLY FAITHFUL FUNCTORS**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **fully faithful** if  $F$  is full and faithful, i.e. if, for each  $A, B \in \text{Obj}(\mathcal{C})$ , the action on morphisms

$$F_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of  $F$  at  $(A, B)$  is bijective.

**PROPOSITION 11.6.3.1.2 ► PROPERTIES OF FULLY FAITHFUL FUNCTORS**

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  and  $G: \mathcal{D} \rightarrow \mathcal{E}$  be functors.

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor  $F$  is fully faithful.
- (b) We have a pullback square

$$\begin{array}{ccc} \text{Arr}(\mathcal{C}) & \xrightarrow{\text{Arr}(F)} & \text{Arr}(\mathcal{D}) \\ \text{src} \times \text{tgt} \downarrow & \lrcorner & \downarrow \text{src} \times \text{tgt} \\ \mathcal{C} \times \mathcal{C} & \xrightarrow{F \times F} & \mathcal{D} \times \mathcal{D} \end{array}$$

in **Cats**.

2. *Interaction With Composition.* If  $F$  and  $G$  are fully faithful, then so is  $G \circ F$ .

3. *Conservativity.* If  $F$  is fully faithful, then  $F$  is conservative.
4. *Essential Injectivity.* If  $F$  is fully faithful, then  $F$  is essentially injective.
5. *Interaction With Co/Limits.* If  $F$  is fully faithful, then  $F$  reflects co/limits.
6. *Interaction With Postcomposition.* The following conditions are equivalent:

- (a) The functor  $F: C \rightarrow \mathcal{D}$  is fully faithful.
- (b) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is fully faithful.

- (c) The functor  $F: C \rightarrow \mathcal{D}$  is a representably fully faithful morphism in  $\text{Cats}_2$  in the sense of [Types of Morphisms in Bicat-egories](#), [Definition 14.1.3.1.1](#).

7. *Interaction With Precomposition I.* If  $F$  is fully faithful, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

**can fail** to be fully faithful.

8. *Interaction With Precomposition II.* If the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is fully faithful, then  $F$  **can fail** to be fully faithful (and in fact it can also fail to be either full or faithful).

9. *Interaction With Precomposition III.* If  $F$  is essentially surjective and full, then the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is fully faithful.

10. *Interaction With Precomposition IV.* The following conditions are equivalent:

(a) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is fully faithful.

(b) The precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \text{Sets}) \rightarrow \text{Fun}(C, \text{Sets})$$

is fully faithful.

(c) The functor

$$\text{Lan}_F: \text{Fun}(C, \text{Sets}) \rightarrow \text{Fun}(\mathcal{D}, \text{Sets})$$

is fully faithful.

(d) The functor  $F$  is a corepresentably fully faithful morphism in  $\text{Cats}_2$  in the sense of [Types of Morphisms in Bicategories](#), [Definition 14.2.3.1.1](#).

(e) The functor  $F$  is absolutely dense.

(f) The components

$$\eta_G: G \Longrightarrow \text{Ran}_F(G \circ F)$$

of the unit

$$\eta: \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})} \Longrightarrow \text{Ran}_F \circ F^*$$

of the adjunction  $F^* \dashv \text{Ran}_F$  are all isomorphisms.

(g) The components

$$\epsilon_G: \text{Lan}_F(G \circ F) \Longrightarrow G$$

of the counit

$$\epsilon: \text{Lan}_F \circ F^* \Longrightarrow \text{id}_{\text{Fun}(\mathcal{D}, \mathcal{X})}$$

of the adjunction  $\text{Lan}_F \dashv F^*$  are all isomorphisms.

(h) The natural transformation

$$\alpha: \text{Lan}_{h_F}(h^F) \Longrightarrow h$$

with components

$$\alpha_{B',B}: \int^{A \in C} h_{F_A}^{B'} \times h_B^{F_A} \rightarrow h_B^{B'}$$

given by

$$\alpha_{B',B}([( \phi, \psi )]) = \psi \circ \phi$$

is a natural isomorphism.

(i) For each  $B \in \text{Obj}(\mathcal{D})$ , there exist:

- An object  $A_B$  of  $C$ ;
- A morphism  $s_B: B \rightarrow F(A_B)$  of  $\mathcal{D}$ ;
- A morphism  $r_B: F(A_B) \rightarrow B$  of  $\mathcal{D}$ ;

satisfying the following conditions:

- i. The triple  $(F(A_B), r_B, s_B)$  is a retract of  $B$ , i.e. we have  $r_B \circ s_B = \text{id}_B$ .
- ii. For each morphism  $f: B' \rightarrow B$  of  $\mathcal{D}$ , we have

$$[(A_B, s_{B'}, f \circ r_{B'})] = [(A_B, s_B \circ f, r_B)]$$

$$\text{in } \int^{A \in C} h_{F_A}^{B'} \times h_B^{F_A}.$$

#### PROOF 11.6.3.1.3 ► PROOF OF PROPOSITION 11.6.3.1.2

Item 1: Characterisations

Omitted.

Item 2: Interaction With Composition

Since the map

$$(G \circ F)_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_D(G_{F_A}, G_{F_B}),$$

defined as the composition

$$\text{Hom}_C(A, B) \xrightarrow{F_{A,B}} \text{Hom}_D(F_A, F_B) \xrightarrow{G_{F(A), F(B)}} \text{Hom}_D(G_{F_A}, G_{F_B}),$$

is a composition of bijective functions, it follows from ?? that it is also bijective. Therefore  $G \circ F$  is fully faithful.

Item 3: Conservativity

This is a repetition of Item 2 of Proposition 11.6.4.1.2, and is proved there.

Item 4: Essential Injectivity

Omitted.

Item 5: Interaction With Co/Limits

Omitted.

Item 6: Interaction With Postcomposition

This follows from Item 2 of Proposition 11.6.1.1.2 and ?? of Proposition 11.6.2.1.2.

Item 7: Interaction With Precomposition I

See [MSE 733161] for an example of a fully faithful functor whose precomposition with which fails to be full.

Item 8: Interaction With Precomposition II

See [MSE 749304, Item 3].

Item 9: Interaction With Precomposition III

Omitted, but see [https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.precomp\\_fully\\_faithful.html](https://unimath.github.io/doc/UniMath/d4de26f//UniMath.CategoryTheory.precomp_fully_faithful.html) for a formalised proof.

Item 10: Interaction With Precomposition IV

We claim Items 10a to 10i are equivalent:



- *Items 10a and 10d Are Equivalent:* This is true by the definition of corepresentably fully faithful morphism; see [Types of Morphisms in Bicategories](#), [Definition 14.2.3.1.1](#).
- *Items 10a, 10f and 10g Are Equivalent:* See ??, ?? of ??.
- *Items 10a to 10c Are Equivalent:* This follows from [[Low15](#), Proposition A.1.5].
- *Items 10a, 10e, 10h and 10i Are Equivalent:* See [[Fre09](#), Theorem 4.1] and [[Adá+01](#), Theorem 1.1].

This finishes the proof.



## 11.6.4 Conservative Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

### DEFINITION 11.6.4.1.1 ► CONSERVATIVE FUNCTORS

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **conservative** if it satisfies the following condition:<sup>1</sup>

- (★) For each  $f \in \text{Mor}(\mathcal{C})$ , if  $F(f)$  is an isomorphism in  $\mathcal{D}$ , then  $f$  is an isomorphism in  $\mathcal{C}$ .

<sup>1</sup>*Slogan:* A functor  $F$  is **conservative** if it reflects isomorphisms.

### PROPOSITION 11.6.4.1.2 ► PROPERTIES OF CONSERVATIVE FUNCTORS

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.

1. *Characterisations.* The following conditions are equivalent:
  - (a) The functor  $F$  is conservative.
  - (b) For each  $f \in \text{Mor}(\mathcal{C})$ , the morphism  $F(f)$  is an isomorphism in  $\mathcal{D}$  iff  $f$  is an isomorphism in  $\mathcal{C}$ .
2. *Interaction With Fully Faithfulness.* Every fully faithful functor is conservative.

3. *Interaction With Precomposition.* The following conditions are equivalent:

(a) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is conservative.

(b) The equivalent conditions of **Item 5** of **Proposition 11.6.1.1.2** are satisfied.

#### PROOF 11.6.4.1.3 ► PROOF OF PROPOSITION 11.6.4.1.2

##### Item 1: Characterisations

This follows from **Item 1** of **Proposition 11.5.1.1.8**.


##### Item 2: Interaction With Fully Faithfulness

Let  $F : \mathcal{C} \rightarrow \mathcal{D}$  be a fully faithful functor, let  $f : A \rightarrow B$  be a morphism of  $\mathcal{C}$ , and suppose that  $F_f$  is an isomorphism. We have

$$\begin{aligned} F(\text{id}_B) &= \text{id}_{F(B)} \\ &= F(f) \circ F(f)^{-1} \\ &= F(f \circ f^{-1}). \end{aligned}$$

Similarly,  $F(\text{id}_A) = F(f^{-1} \circ f)$ . But since  $F$  is fully faithful, we must have

$$\begin{aligned} f \circ f^{-1} &= \text{id}_B, \\ f^{-1} \circ f &= \text{id}_A, \end{aligned}$$

showing  $f$  to be an isomorphism. Thus  $F$  is conservative. 

#### QUESTION 11.6.4.1.4 ► CHARACTERISATIONS OF FUNCTORS WITH CONSERVATIVE PRE-/POSTCOMPOSITION

Is there a characterisation of functors  $F : \mathcal{C} \rightarrow \mathcal{D}$  satisfying the following condition:

(★) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is conservative?

This question also appears as [MO 468121a].

## 11.6.5 Essentially Injective Functors

Let  $C$  and  $\mathcal{D}$  be categories.

### DEFINITION 11.6.5.1.1 ► ESSENTIALLY INJECTIVE FUNCTORS

A functor  $F : C \rightarrow \mathcal{D}$  is **essentially injective** if it satisfies the following condition:

(★) For each  $A, B \in \text{Obj}(C)$ , if  $F(A) \cong F(B)$ , then  $A \cong B$ .

### QUESTION 11.6.5.1.2 ► CHARACTERISATIONS OF FUNCTORS WITH ESSENTIALLY INJECTIVE PRE/POSTCOMPOSITION

Is there a characterisation of functors  $F : C \rightarrow \mathcal{D}$  such that:

1. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is essentially injective, i.e. if  $\phi \circ F \cong \psi \circ F$ , then  $\phi \cong \psi$  for all functors  $\phi$  and  $\psi$ ?

2. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_* : \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is essentially injective, i.e. if  $F \circ \phi \cong F \circ \psi$ , then  $\phi \cong \psi$ ?

This question also appears as [MO 468121a].

## 11.6.6 Essentially Surjective Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

### DEFINITION 11.6.6.1.1 ► ESSENTIALLY SURJECTIVE FUNCTORS

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **essentially surjective**<sup>1</sup> if it satisfies the following condition:

- (★) For each  $D \in \text{Obj}(\mathcal{D})$ , there exists some object  $A$  of  $\mathcal{C}$  such that  $F(A) \cong D$ .

<sup>1</sup>*Further Terminology:* Also called an **eso** functor, meaning *essentially surjective on objects*.

### QUESTION 11.6.6.1.2 ► CHARACTERISATIONS OF FUNCTORS WITH ESSENTIALLY SURJECTIVE PRE/POSTCOMPOSITION

Is there a characterisation of functors  $F: \mathcal{C} \rightarrow \mathcal{D}$  such that:

1. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is essentially surjective?

2. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is essentially surjective?

This question also appears as [MO 468121a].

## 11.6.7 Equivalences of Categories

### DEFINITION 11.6.7.1.1 ► EQUIVALENCES OF CATEGORIES

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

1. An **equivalence of categories** between  $\mathcal{C}$  and  $\mathcal{D}$  consists of a pair of functors

$$\begin{aligned} F: \mathcal{C} &\rightarrow \mathcal{D}, \\ G: \mathcal{D} &\rightarrow \mathcal{C} \end{aligned}$$

together with natural isomorphisms

$$\begin{aligned} \eta: \text{id}_{\mathcal{C}} &\xrightarrow{\sim} G \circ F, \\ \epsilon: F \circ G &\xrightarrow{\sim} \text{id}_{\mathcal{D}}. \end{aligned}$$

2. An **adjoint equivalence of categories** between  $\mathcal{C}$  and  $\mathcal{D}$  is an equivalence  $(F, G, \eta, \epsilon)$  between  $\mathcal{C}$  and  $\mathcal{D}$  which is also an adjunction.

### PROPOSITION 11.6.7.1.2 ► PROPERTIES OF EQUIVALENCES OF CATEGORIES

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.

1. *Characterisations.* If  $\mathcal{C}$  and  $\mathcal{D}$  are small<sup>1</sup>, then the following conditions are equivalent:<sup>2</sup>

- (a) The functor  $F$  is an equivalence of categories.
- (b) The functor  $F$  is fully faithful and essentially surjective.
- (c) The induced functor

$$\uparrow F\text{Sk}(\mathcal{C}): \text{Sk}(\mathcal{C}) \rightarrow \text{Sk}(\mathcal{D})$$

is an *isomorphism* of categories.

- (d) For each  $X \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(\mathcal{C}, X)$$

is an equivalence of categories.

(e) For each  $X \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(X, C) \rightarrow \text{Fun}(X, D)$$

is an equivalence of categories.

2. *Two-Out-of-Three.* Let

$$\begin{array}{ccc} C & \xrightarrow{G \circ F} & \mathcal{E} \\ & \searrow F \quad \nearrow G & \\ & D & \end{array}$$

be a diagram in  $\text{Cats}$ . If two out of the three functors among  $F$ ,  $G$ , and  $G \circ F$  are equivalences of categories, then so is the third.

3. *Stability Under Composition.* Let

$$C \xrightleftharpoons[F]{F} D \xrightleftharpoons[G']{F'} \mathcal{E}$$

be a diagram in  $\text{Cats}$ . If  $(F, G)$  and  $(F', G')$  are equivalences of categories, then so is their composite  $(F' \circ F, G' \circ G)$ .

4. *Equivalences vs. Adjoint Equivalences.* Every equivalence of categories can be promoted to an adjoint equivalence.<sup>3</sup>

5. *Interaction With Groupoids.* If  $C$  and  $D$  are groupoids, then the following conditions are equivalent:

(a) The functor  $F$  is an equivalence of groupoids.

(b) The following conditions are satisfied:

i. The functor  $F$  induces a bijection

$$\pi_0(F): \pi_0(C) \rightarrow \pi_0(D)$$

of sets.

ii. For each  $A \in \text{Obj}(C)$ , the induced map

$$F_{x,x}: \text{Aut}_C(A) \rightarrow \text{Aut}_D(F_A)$$

is an isomorphism of groups.

<sup>1</sup>Otherwise there will be size issues. One can also work with large categories and universes, or require  $F$  to be *constructively* essentially surjective; see [MSE 1465107].

<sup>2</sup>In ZFC, the equivalence between **Item 1a** and **Item 1b** is equivalent to the axiom of choice; see [MO 119454].

In Univalent Foundations, this is true without requiring neither the axiom of choice nor the law of excluded middle.

<sup>3</sup>More precisely, we can promote an equivalence of categories  $(F, G, \eta, \epsilon)$  to adjoint equivalences  $(F, G, \eta', \epsilon)$  and  $(F, G, \eta, \epsilon')$ .

#### PROOF 11.6.7.1.3 ► PROOF OF PROPOSITION 11.6.7.1.2

##### Item 1: Characterisations

We claim that **Items 1a** to **1e** are indeed equivalent:

1. **Item 1a**  $\implies$  **Item 1b**: Omitted.
2. **Item 1b**  $\implies$  **Item 1a**: Since  $F$  is essentially surjective and  $\mathcal{C}$  and  $\mathcal{D}$  are small, we can choose, using the axiom of choice, for each  $B \in \text{Obj}(\mathcal{D})$ , an object  $j_B$  of  $\mathcal{C}$  and an isomorphism  $i_B: B \rightarrow F_{j_B}$  of  $\mathcal{D}$ .  
  
Since  $F$  is fully faithful, we can extend the assignment  $B \mapsto j_B$  to a *unique* functor  $j: \mathcal{D} \rightarrow \mathcal{C}$  such that the isomorphisms  $i_B: B \rightarrow F_{j_B}$  assemble into a natural isomorphism  $\eta: \text{id}_{\mathcal{D}} \xrightarrow{\sim} F \circ j$ , with a similar natural isomorphism  $\epsilon: \text{id}_{\mathcal{C}} \xrightarrow{\sim} j \circ F$ . Hence  $F$  is an equivalence.
3. **Item 1a**  $\implies$  **Item 1c**: This follows from **Item 4** of **Proposition 11.1.3.1.3**.
4. **Item 1c**  $\implies$  **Item 1a**: Omitted.
5. **Items 1a, 1d and 1e Are Equivalent**: This follows from ??.

This finishes the proof of **Item 1**.

##### Item 2: Two-Out-of-Three

Omitted.

Item 3: Stability Under Composition

Omitted.

Item 4: Equivalences vs. Adjoint Equivalences

See [Rie16, Proposition 4.4.5].

Item 5: Interaction With Groupoids

See [nLa25, Proposition 4.4].



## 11.6.8 Isomorphisms of Categories

### DEFINITION 11.6.8.1.1 ► ISOMORPHISMS OF CATEGORIES

An **isomorphism of categories** is a pair of functors

$$F: \mathcal{C} \rightarrow \mathcal{D},$$

$$G: \mathcal{D} \rightarrow \mathcal{C}$$

such that we have

$$G \circ F = \text{id}_{\mathcal{C}},$$

$$F \circ G = \text{id}_{\mathcal{D}}.$$

### EXAMPLE 11.6.8.1.2 ► EQUIVALENT BUT NON-ISOMORPHIC CATEGORIES

Categories can be equivalent but non-isomorphic. For example, the category consisting of two isomorphic objects is equivalent to  $\text{pt}$ , but not isomorphic to it.

### PROPOSITION 11.6.8.1.3 ► PROPERTIES OF ISOMORPHISMS OF CATEGORIES

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.

1. *Characterisations.* If  $\mathcal{C}$  and  $\mathcal{D}$  are small, then the following conditions are equivalent:
  - (a) The functor  $F$  is an isomorphism of categories.



(b) The functor  $F$  is fully faithful and bijective on objects.

(c) For each  $X \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(C, X)$$

is an isomorphism of categories.

(d) For each  $X \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(X, C) \rightarrow \text{Fun}(X, \mathcal{D})$$


is an isomorphism of categories.

#### PROOF 11.6.8.1.4 ► PROOF OF PROPOSITION 11.6.8.1.3

##### Item 1: Characterisations

We claim that **Items 1a to 1d** are indeed equivalent:

1. **Items 1a and 1b Are Equivalent:** Omitted, but similar to **Item 1** of **Proposition 11.6.7.1.2**.
2. **Items 1a, 1c and 1d Are Equivalent:** This follows from ??.

This finishes the proof. 

## 11.7 More Conditions on Functors

### 11.7.1 Dominant Functors

Let  $C$  and  $\mathcal{D}$  be categories.

#### DEFINITION 11.7.1.1.1 ► DOMINANT FUNCTORS

A functor  $F: C \rightarrow \mathcal{D}$  is **dominant** if every object of  $\mathcal{D}$  is a retract of some object in  $\text{Im}(F)$ , i.e.:

(★) For each  $B \in \text{Obj}(\mathcal{D})$ , there exist:

- An object  $A$  of  $\mathcal{C}$ ;
- A morphism  $r: F(A) \rightarrow B$  of  $\mathcal{D}$ ;
- A morphism  $s: B \rightarrow F(A)$  of  $\mathcal{D}$ ;

such that we have

$$r \circ s = \text{id}_B,$$

$$\begin{array}{ccc} B & \xrightarrow{s} & F(A) \\ & \searrow \text{id}_B & \downarrow r \\ & & B. \end{array}$$

#### PROPOSITION 11.7.1.1.2 ► PROPERTIES OF DOMINANT FUNCTORS

Let  $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$  be functors and let  $I: \mathcal{X} \rightarrow \mathcal{C}$  be a functor.

1. *Interaction With Right Whiskering.* If  $I$  is full and dominant, then the map

$$- \star \text{id}_I: \text{Nat}(F, G) \rightarrow \text{Nat}(F \circ I, G \circ I)$$

is a bijection.

2. *Interaction With Adjunctions.* Let  $(F, G): \mathcal{C} \rightleftarrows \mathcal{D}$  be an adjunction.

- (a) If  $F$  is dominant, then  $G$  is faithful.
- (b) The following conditions are equivalent:
  - i. The functor  $G$  is full.
  - ii. The restriction

$$\upharpoonright G\text{Im}_F: \text{Im}(F) \rightarrow \mathcal{C}$$

of  $G$  to  $\text{Im}(F)$  is full.

**PROOF 11.7.1.1.3 ► PROOF OF PROPOSITION 11.7.1.1.2**

Item 1: Interaction With Right Whiskering

See [DFH75, Proposition 1.4].

Item 2: Interaction With Adjunctions

See [DFH75, Proposition 1.7].

**QUESTION 11.7.1.1.4 ► CHARACTERISATIONS OF FUNCTORS WITH DOMINANT PRE/POST-COMPOSITION**

Is there a characterisation of functors  $F: \mathcal{C} \rightarrow \mathcal{D}$  such that:

1. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is dominant?

2. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is dominant?

This question also appears as [MO 468121a].

**11.7.2 Monomorphisms of Categories**

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.7.2.1.1 ► MONOMORPHISMS OF CATEGORIES**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is a **monomorphism of categories** if it is a monomorphism in  $\text{Cats}$  (see ??, ??).

**PROPOSITION 11.7.2.1.2 ► PROPERTIES OF MONOMORPHISMS OF CATEGORIES**

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.


1. *Characterisations.* The following conditions are equivalent:
  - (a) The functor  $F$  is a monomorphism of categories.
  - (b) The functor  $F$  is injective on objects and morphisms, i.e.  $F$  is injective on objects and the map

$$F: \text{Mor}(\mathcal{C}) \rightarrow \text{Mor}(\mathcal{D})$$

is injective.

**PROOF 11.7.2.1.3 ► PROOF OF PROPOSITION 11.7.2.1.2**

Item 1: Characterisations

Omitted. 

**QUESTION 11.7.2.1.4 ► CHARACTERISATIONS OF FUNCTORS WITH MONIC PRE/POSTCOMPOSITION**

Is there a characterisation of functors  $F: \mathcal{C} \rightarrow \mathcal{D}$  such that:

1. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is a monomorphism of categories?

2. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is a monomorphism of categories?

This question also appears as [\[MO 468121a\]](#).

### 11.7.3 Epimorphisms of Categories

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

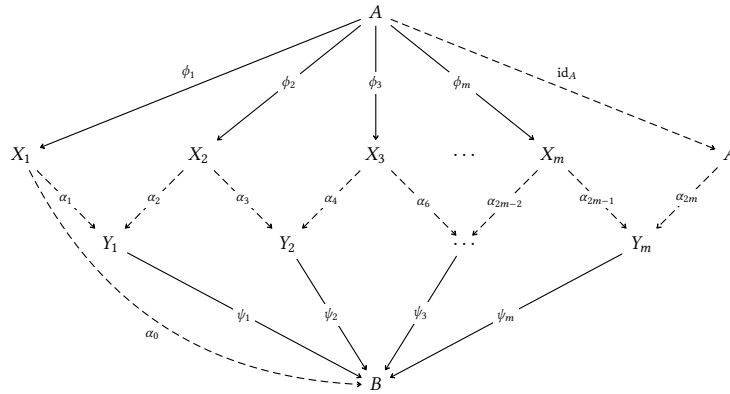
#### DEFINITION 11.7.3.1.1 ► EPIMORPHISMS OF CATEGORIES

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is a **epimorphism of categories** if it is a epimorphism in  $\mathbf{Cats}$  (see ??, ??).

#### PROPOSITION 11.7.3.1.2 ► PROPERTIES OF EPIMORPHISMS OF CATEGORIES

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.

1. *Characterisations.* The following conditions are equivalent:<sup>1</sup>
  - (a) The functor  $F$  is a epimorphism of categories.
  - (b) For each morphism  $f: A \rightarrow B$  of  $\mathcal{D}$ , we have a diagram



in  $\mathcal{D}$  satisfying the following conditions:

- i. We have  $f = \alpha_0 \circ \phi_1$ .
  - ii. We have  $f = \psi_m \circ \alpha_{2m}$ .
  - iii. For each  $0 \leq i \leq 2m$ , we have  $\alpha_i \in \text{Mor}(\text{Im}(F))$ .
2. *Surjectivity on Objects.* If  $F$  is an epimorphism of categories, then  $F$  is surjective on objects.


<sup>1</sup>Further Terminology: This statement is known as **Isbell's zigzag theorem**.

**PROOF 11.7.3.1.3 ► PROOF OF PROPOSITION 11.7.3.1.2**

Item 1: Characterisations

See [Isb68].

Item 2: Surjectivity on Objects

Omitted. 

**QUESTION 11.7.3.1.4 ► CHARACTERISATIONS OF FUNCTORS WITH EPIC PRE/POSTCOMPOSITION**

Is there a characterisation of functors  $F: \mathcal{C} \rightarrow \mathcal{D}$  such that:

1. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is an epimorphism of categories?

2. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is an epimorphism of categories?

This question also appears as [MO 468121a].

**11.7.4 Pseudomonic Functors**

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.7.4.1.1 ► PSEUDOMONIC FUNCTORS**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **pseudomonic** if it satisfies the following conditions:

1. For all diagrams of the form

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D},$$

if we have

$$\mathrm{id}_F \star \alpha = \mathrm{id}_F \star \beta,$$

then  $\alpha = \beta$ .

2. For each  $\mathcal{X} \in \mathrm{Obj}(\mathrm{Cats})$  and each natural isomorphism

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C}$$

such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams, i.e. such that we have

$$\beta = \mathrm{id}_F \star \alpha.$$

**PROPOSITION 11.7.4.1.2 ► PROPERTIES OF PSEUDOMONIC FUNCTORS**

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor  $F$  is pseudomononic.
- (b) The functor  $F$  satisfies the following conditions:
- i. The functor  $F$  is faithful, i.e. for each  $A, B \in \text{Obj}(C)$ , the action on morphisms

$$F_{A,B}: \text{Hom}_C(A, B) \rightarrow \text{Hom}_{\mathcal{D}}(F_A, F_B)$$

of  $F$  at  $(A, B)$  is injective.

- ii. For each  $A, B \in \text{Obj}(C)$ , the restriction

$$F_{A,B}^{\text{iso}}: \text{Iso}_C(A, B) \rightarrow \text{Iso}_{\mathcal{D}}(F_A, F_B)$$

of the action on morphisms of  $F$  at  $(A, B)$  to isomorphisms is surjective.

- (c) We have an isocomma square of the form

$$C \stackrel{\text{eq.}}{\cong} C \times_{\mathcal{D}} C, \quad \begin{array}{ccc} C & \xrightarrow{\text{id}_C} & C \\ \text{id}_C \downarrow & \nearrow \text{dashed} & \downarrow F \\ C & \xrightarrow{F} & \mathcal{D} \end{array}$$

in  $\text{Cats}_2$  up to equivalence.

- (d) We have an isocomma square of the form

$$C \stackrel{\text{eq.}}{\cong} C \times_{\text{Arr}(\mathcal{D})} \mathcal{D}, \quad \begin{array}{ccc} C & \hookrightarrow & \text{Arr}(C) \\ F \downarrow & \nearrow \text{dashed} & \downarrow \text{Arr}(F) \\ \mathcal{D} & \hookrightarrow & \text{Arr}(\mathcal{D}) \end{array}$$

in  $\text{Cats}_2$  up to equivalence.

- (e) For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition<sup>1</sup> functor

$$F_*: \text{Fun}(\mathcal{X}, C) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is pseudomononic.



2. *Conservativity*. If  $F$  is pseudomononic, then  $F$  is conservative.
3. *Essential Injectivity*. If  $F$  is pseudomononic, then  $F$  is essentially injective.

---

<sup>1</sup>Asking the precomposition functors

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

to be pseudomononic leads to pseudoepic functors; see [Item 1b](#) of [Item 1](#) of [Proposition 11.7.5.1.2](#).

#### PROOF 11.7.4.1.3 ► PROOF OF PROPOSITION 11.7.4.1.2


Item 1: Characterisations

Omitted.

Item 2: Conservativity

Omitted.

Item 3: Essential Injectivity

Omitted. 

## 11.7.5 Pseudoepic Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

#### DEFINITION 11.7.5.1.1 ► PSEUDOEPIC FUNCTORS

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **pseudoepic** if it satisfies the following conditions:

1. For all diagrams of the form

$$\mathcal{C} \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \downarrow \downarrow \downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{X},$$

if we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then  $\alpha = \beta$ .

2. For each  $X \in \text{Obj}(C)$  and each 2-isomorphism

$$\beta: \phi \circ F \xRightarrow{\sim} \psi \circ F, \quad C \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} X$$

of  $C$ , there exists a 2-isomorphism

$$\alpha: \phi \xRightarrow{\sim} \psi, \quad \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

of  $C$  such that we have an equality

$$C \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X = C \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} X$$

of pasting diagrams in  $C$ , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

#### PROPOSITION 11.7.5.1.2 ► PROPERTIES OF PSEUDOEPIC FUNCTORS

Let  $F: C \rightarrow \mathcal{D}$  be a functor.

1. *Characterisations.* The following conditions are equivalent:

- (a) The functor  $F$  is pseudoepic.
- (b) For each  $X \in \text{Obj}(\text{Cats})$ , the functor

$$F^*: \text{Fun}(\mathcal{D}, X) \rightarrow \text{Fun}(C, X)$$

given by precomposition by  $F$  is pseudomonic.

(c) We have an isococcomma square of the form

$$\mathcal{D} \stackrel{\text{eq.}}{\cong} \mathcal{D} \amalg_C \mathcal{D}, \quad \begin{array}{ccc} \mathcal{D} & \xleftarrow{\text{id}_{\mathcal{D}}} & \mathcal{D} \\ \text{id}_{\mathcal{D}} \uparrow & \nearrow \text{dashed} & \uparrow F \\ \mathcal{D} & \xleftarrow{F} & C \end{array}$$

in  $\text{Cats}_2$  up to equivalence.

2. *Dominance.* If  $F$  is pseudoepic, then  $F$  is dominant ([Definition 11.7.1.1.1](#)).

#### PROOF 11.7.5.1.3 ► PROOF OF PROPOSITION 11.7.5.1.2


##### Item 1: Characterisations

Omitted.

##### Item 2: Dominance

If  $F$  is pseudoepic, then

$$F^* : \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(C, \mathcal{X})$$

is pseudomonic for all  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , and thus in particular faithful. By [Item 5g](#) of [Item 5](#) of [Proposition 11.6.1.1.2](#), this is equivalent to requiring  $F$  to be dominant. 

#### QUESTION 11.7.5.1.4 ► CHARACTERISATIONS OF PSEUDOEPIC FUNCTORS

Is there a nice characterisation of the pseudoepic functors, similarly to the characterisation of pseudomonic functors given in [Item 1b](#) of [Item 1](#) of [Proposition 11.7.4.1.2](#)?

This question also appears as [\[MO 321971\]](#).

**QUESTION 11.7.5.1.5 ► MUST A PSEUDOMONIC AND PSEUDOEPIC FUNCTOR BE AN EQUIVALENCE OF CATEGORIES**

A pseudomonic and pseudoepic functor is dominant, faithful, essentially injective, and full on isomorphisms. Is it necessarily an equivalence of categories? If not, how bad can this fail, i.e. how far can a pseudomonic and pseudoepic functor be from an equivalence of categories? This question also appears as [MO 468334].

**QUESTION 11.7.5.1.6 ► CHARACTERISATIONS OF FUNCTORS WITH PSEUDOEPIC PRE-/POSTCOMPOSITION**

Is there a characterisation of functors  $F: \mathcal{C} \rightarrow \mathcal{D}$  such that:

1. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the precomposition functor

$$F^*: \text{Fun}(\mathcal{D}, \mathcal{X}) \rightarrow \text{Fun}(\mathcal{C}, \mathcal{X})$$

is pseudoepic?

2. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$ , the postcomposition functor

$$F_*: \text{Fun}(\mathcal{X}, \mathcal{C}) \rightarrow \text{Fun}(\mathcal{X}, \mathcal{D})$$

is pseudoepic?

This question also appears as [MO 468121a].

## 11.8 Even More Conditions on Functors

### 11.8.1 Injective on Objects Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.8.1.1.1 ► INJECTIVE ON OBJECTS FUNCTORS**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **injective on objects** if the action on objects

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D})$$

of  $F$  is injective.


**PROPOSITION 11.8.1.1.2 ► PROPERTIES OF INJECTIVE ON OBJECTS FUNCTORS**

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.

1. *Characterisations.* The following conditions are equivalent:
  - (a) The functor  $F$  is injective on objects.
  - (b) The functor  $F$  is an isocofibration in  $\mathbf{Cats}_2$ .

**PROOF 11.8.1.1.3 ► PROOF OF PROPOSITION 11.8.1.1.2**

Item 1: Characterisations

Omitted. 

## 11.8.2 Surjective on Objects Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.8.2.1.1 ► SURJECTIVE ON OBJECTS FUNCTORS**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **surjective on objects** if the action on objects

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D})$$

of  $F$  is surjective.

## 11.8.3 Bijective on Objects Functors

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.8.3.1.1 ► BIJECTIVE ON OBJECTS FUNCTORS**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **bijective on objects**<sup>1</sup> if the action on objects

$$F: \text{Obj}(\mathcal{C}) \rightarrow \text{Obj}(\mathcal{D})$$

of  $F$  is a bijection.

<sup>1</sup>*Further Terminology:* Also called a **bo** functor.

### 11.8.4 Functors Representably Faithful on Cores

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

#### DEFINITION 11.8.4.1.1 ► FUNCTORS REPRESENTABLY FAITHFUL ON CORES

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **representably faithful on cores** if, for each  $X \in \text{Obj}(\text{Cats})$ , the postcomposition by  $F$  functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is faithful.

#### REMARK 11.8.4.1.2 ► UNWINDING DEFINITION 11.8.4.1.1

In detail, a functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **representably faithful on cores** if, given a diagram of the form

$$\begin{array}{ccc} & \phi & \\ \alpha \downarrow & \xrightarrow{\quad} & C \xrightarrow{F} \mathcal{D} \\ & \beta \downarrow & \\ & \psi & \end{array}$$

if  $\alpha$  and  $\beta$  are natural isomorphisms and we have

$$\text{id}_F \star \alpha = \text{id}_F \star \beta,$$

then  $\alpha = \beta$ .

#### QUESTION 11.8.4.1.3 ► CHARACTERISATION OF FUNCTORS REPRESENTABLY FAITHFUL ON CORES

Is there a characterisation of functors representably faithful on cores?

### 11.8.5 Functors Representably Full on Cores

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.8.5.1** *Functors Representably Full on Cores*

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **representably full on cores** if, for each  $X \in \text{Obj}(\text{Cats})$ , the postcomposition by  $F$  functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is full.

**REMARK 11.8.5.1.2 ► UNWINDING DEFINITION 11.8.5.1.1**

In detail, a functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **representably full on cores** if, for each  $X \in \text{Obj}(\text{Cats})$  and each natural isomorphism

$$\beta: F \circ \phi \xrightarrow{\sim} F \circ \psi, \quad X \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C}$$

such that we have an equality

$$X \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = X \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in  $\text{Cats}_2$ , i.e. such that we have

$$\beta = \text{id}_F \star \alpha.$$

**QUESTION 11.8.5.1.3 ► CHARACTERISATION OF FUNCTORS REPRESENTABLY FULL ON CORES**

Is there a characterisation of functors representably full on cores?  
This question also appears as [MO 468121a].



## 11.8.6 Functors Representably Fully Faithful on Cores

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

### DEFINITION 11.8.6.1.1 ► FUNCTORS REPRESENTABLY FULLY FAITHFUL ON CORES

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **representably fully faithful on cores** if, for each  $X \in \text{Obj}(\text{Cats})$ , the postcomposition by  $F$  functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is fully faithful.

### REMARK 11.8.6.1.2 ► UNWINDING DEFINITION 11.8.6.1.1

In detail, a functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **representably fully faithful on cores** if it satisfies the conditions in [Remarks 11.8.4.1.2](#) and [11.8.5.1.2](#), i.e.:

1. For all diagrams of the form

$$\begin{array}{ccc} & \xrightarrow{\phi} & \\ \alpha \downarrow & & \downarrow \beta \\ X & \xrightarrow{\quad} & C \xrightarrow{F} \mathcal{D} \\ & \xleftarrow{\psi} & \end{array}$$

with  $\alpha$  and  $\beta$  natural isomorphisms, if we have  $\text{id}_F \star \alpha = \text{id}_F \star \beta$ , then  $\alpha = \beta$ .

2. For each  $X \in \text{Obj}(\text{Cats})$  and each natural isomorphism

$$\beta: F \circ \phi \xRightarrow{\sim} F \circ \psi, \quad \begin{array}{ccc} & \xrightarrow{F \circ \phi} & \\ \beta \downarrow & & \downarrow \\ X & \xrightarrow{\quad} & \mathcal{D} \\ & \xleftarrow{F \circ \psi} & \end{array}$$

of  $C$ , there exists a natural isomorphism

$$\alpha: \phi \xRightarrow{\sim} \psi, \quad \begin{array}{ccc} & \xrightarrow{\phi} & \\ \alpha \downarrow & & \downarrow \\ X & \xrightarrow{\quad} & C \\ & \xleftarrow{\psi} & \end{array}$$

of  $C$  such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} C \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in  $\mathbf{Cats}_2$ , i.e. such that we have

$$\beta = \text{id}_F \star \alpha.$$

**QUESTION 11.8.6.1.3 ► CHARACTERISATION OF FUNCTORS REPRESENTABLY FULLY FAITHFUL ON CORES**

Is there a characterisation of functors representably fully faithful on cores?

## 11.8.7 Functors Corepresentably Faithful on Cores

Let  $C$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.8.7.1.1 ► FUNCTORS COREPRESENTABLY FAITHFUL ON CORES**

A functor  $F: C \rightarrow \mathcal{D}$  is **corepresentably faithful on cores** if, for each  $X \in \text{Obj}(\mathbf{Cats})$ , the postcomposition by  $F$  functor

$$F_*: \text{Core}(\text{Fun}(X, C)) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is faithful.

**REMARK 11.8.7.1.2 ► UNWINDING DEFINITION 11.8.7.1.1**

In detail, a functor  $F: C \rightarrow \mathcal{D}$  is **corepresentably faithful on cores** if, given a diagram of the form

$$C \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \beta \\ \xrightarrow{\psi} \end{array} X,$$

if  $\alpha$  and  $\beta$  are natural isomorphisms and we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then  $\alpha = \beta$ .

**QUESTION 11.8.7.1.3 ► CHARACTERISATION OF FUNCTORS COREPRESENTABLY FAITHFUL ON CORES**

Is there a characterisation of functors corepresentably faithful on cores?

## 11.8.8 Functors Corepresentably Full on Cores

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.8.8.1.1 ► FUNCTORS COREPRESENTABLY FULL ON CORES**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **corepresentably full on cores** if, for each  $X \in \text{Obj}(\text{Cats})$ , the postcomposition by  $F$  functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is full.

**REMARK 11.8.8.1.2 ► UNWINDING DEFINITION 11.8.8.1.1**

In detail, a functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **corepresentably full on cores** if, for each  $X \in \text{Obj}(\text{Cats})$  and each natural isomorphism

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad \mathcal{C} \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} X,$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} X$$

such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{C} \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in  $\mathbf{Cats}_2$ , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

**QUESTION 11.8.8.1.3 ► CHARACTERISATION OF FUNCTORS COREPRESENTABLY FULL ON CORES**

Is there a characterisation of functors corepresentably full on cores?  
This question also appears as [MO 468121a].

## 11.8.9 Functors Corepresentably Fully Faithful on Cores

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories.

**DEFINITION 11.8.9.1.1 ► FUNCTORS COREPRESENTABLY FULLY FAITHFUL ON CORES**

A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **corepresentably fully faithful on cores** if, for each  $X \in \text{Obj}(\mathbf{Cats})$ , the postcomposition by  $F$  functor

$$F_*: \text{Core}(\text{Fun}(X, \mathcal{C})) \rightarrow \text{Core}(\text{Fun}(X, \mathcal{D}))$$

is fully faithful.

**REMARK 11.8.9.1.2 ► UNWINDING DEFINITION 11.8.9.1.1**

In detail, a functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is **corepresentably fully faithful on cores** if it satisfies the conditions in [Remarks 11.8.7.1.2](#) and [11.8.8.1.2](#), i.e.:

1. For all diagrams of the form

$$C \xrightarrow{F} \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \Downarrow \beta \\ \xrightarrow{\psi} \end{array} \mathcal{X},$$

if  $\alpha$  and  $\beta$  are natural isomorphisms and we have

$$\alpha \star \text{id}_F = \beta \star \text{id}_F,$$

then  $\alpha = \beta$ .

2. For each  $\mathcal{X} \in \text{Obj}(\text{Cats})$  and each natural isomorphism

$$\beta: \phi \circ F \xrightarrow{\sim} \psi \circ F, \quad C \begin{array}{c} \xrightarrow{\phi \circ F} \\ \beta \Downarrow \\ \xrightarrow{\psi \circ F} \end{array} \mathcal{X},$$

there exists a natural isomorphism

$$\alpha: \phi \xrightarrow{\sim} \psi, \quad \mathcal{D} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{X}$$

such that we have an equality

$$\mathcal{X} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} C \xrightarrow{F} \mathcal{D} = \mathcal{X} \begin{array}{c} \xrightarrow{F \circ \phi} \\ \beta \Downarrow \\ \xrightarrow{F \circ \psi} \end{array} \mathcal{D}$$

of pasting diagrams in  $\text{Cats}_2$ , i.e. such that we have

$$\beta = \alpha \star \text{id}_F.$$

**QUESTION 11.8.9.1.3 ► CHARACTERISATION OF FUNCTORS COREPRESENTABLY FULLY FAITHFUL ON CORES**

Is there a characterisation of functors corepresentably fully faithful on cores?

## 11.9 Natural Transformations

### 11.9.1 Transformations

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories and let  $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$  be functors.

**DEFINITION 11.9.1.1.1 ► TRANSFORMATIONS**

A **transformation**<sup>1</sup>  $\alpha: F \Rightarrow G$  **from**  $F$  **to**  $G$  is a collection

$$\{\alpha_A: F(A) \rightarrow G(A)\}_{A \in \text{Obj}(\mathcal{C})}$$

of morphisms of  $\mathcal{D}$ .

<sup>1</sup>*Further Terminology:* Also called an **unnatural transformation** for emphasis.

**NOTATION 11.9.1.1.2 ► THE SET OF TRANSFORMATIONS BETWEEN TWO FUNCTORS**


We write  $\text{Trans}(F, G)$  for the set of transformations from  $F$  to  $G$ .

**REMARK 11.9.1.1.3 ► THE SET OF TRANSFORMATIONS AS A PRODUCT**

We have an isomorphism

$$\text{Trans}(F, G) \cong \prod_{A \in \mathcal{C}} \text{Hom}_{\mathcal{D}}(F_A, G_A).$$

**PROOF 11.9.1.1.4 ► PROOF OF REMARK 11.9.1.1.3**

Omitted. 

### 11.9.2 Natural Transformations

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories and  $F, G: \mathcal{C} \rightrightarrows \mathcal{D}$  be functors.

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A **natural transformation**  $\alpha: F \Rightarrow G$  **from**  $F$  **to**  $G$  is a transformation

$$\{\alpha_A: F(A) \rightarrow G(A)\}_{A \in \text{Obj}(C)}$$

from  $F$  to  $G$  such that, for each morphism  $f: A \rightarrow B$  of  $C$ , the diagram

$$\begin{array}{ccc} F(A) & \xrightarrow{F(f)} & F(B) \\ \alpha_A \downarrow & & \downarrow \alpha_B \\ G(A) & \xrightarrow{G(f)} & G(B) \end{array}$$

commutes.

**REMARK 11.9.2.1.2 ► FURTHER TERMINOLOGY AND NOTATION FOR NATURAL TRANSFORMATIONS**

Let  $\alpha: F \Rightarrow G$  be a natural transformation.

1. For each  $A \in \text{Obj}(C)$ , the morphism  $\alpha_A: F_A \rightarrow G_A$  is called the **component of  $\alpha$  at  $A$** .
2. We denote natural transformations such as  $\alpha$  in diagrams as

$$C \begin{array}{c} \xrightarrow{F} \\ \alpha \downarrow \\ \xrightarrow{G} \end{array} \mathcal{D}.$$

**NOTATION 11.9.2.1.3 ► THE SET OF NATURAL TRANSFORMATIONS BETWEEN TWO FUNCTORS**

We write  $\text{Nat}(F, G)$  for the set of natural transformations from  $F$  to  $G$ .

**DEFINITION 11.9.2.1.4 ► EQUALITY OF NATURAL TRANSFORMATIONS**

Two natural transformations  $\alpha, \beta: F \Rightarrow G$  are **equal** if we have

$$\alpha_A = \beta_A$$



for each  $A \in \text{Obj}(C)$ .

### 11.9.3 Examples of Natural Transformations

#### EXAMPLE 11.9.3.1.1 ► IDENTITY NATURAL TRANSFORMATIONS

The **identity natural transformation**  $\text{id}_F: F \Rightarrow F$  of  $F$  is the natural transformation consisting of the collection

$$\{(\text{id}_F)_A: F(A) \rightarrow F(A)\}_{A \in \text{Obj}(C)}$$

defined by

$$(\text{id}_F)_A \stackrel{\text{def}}{=} \text{id}_{F(A)}$$

for each  $A \in \text{Obj}(C)$ .

#### PROOF 11.9.3.1.2 ► PROOF OF EXAMPLE 11.9.3.1.1

The naturality condition for  $\text{id}_F$  is the requirement that, for each morphism  $f: A \rightarrow B$  of  $C$ , the diagram

$$\begin{array}{ccc} F(A) & \xrightarrow{F(f)} & F(B) \\ \text{id}_{F(A)} \downarrow & & \downarrow \text{id}_{F(B)} \\ F(A) & \xrightarrow{F(f)} & F(B) \end{array}$$

commutes. This follows from unitality of the composition of  $\mathcal{D}$ , as we have

$$\begin{aligned} F(f) \circ \text{id}_{F(A)} &= F(f) \\ &= \text{id}_{F(B)} \circ F(f), \end{aligned}$$

where we have applied unitality twice. 

**EXAMPLE 11.9.3.1.3 ► NATURAL TRANSFORMATIONS BETWEEN MORPHISMS OF MONOIDS**

Let  $A$  and  $B$  be monoids and let  $f, g: A \rightrightarrows B$  be morphisms of monoids. Applying the delooping construction of ??, we obtain functors  $Bf, Bg: BA \rightrightarrows BB$ . We then have

$$\text{Nat}(Bf, Bg) \cong \left\{ b \in B \left| \begin{array}{l} \text{for each } a \in A, \text{ we} \\ \text{have } bf(a) = g(a)b \end{array} \right. \right\}.$$

**PROOF 11.9.3.1.4 ► PROOF OF EXAMPLE 11.9.3.1.3**

Unwinding the definitions in this case, we see that a transformation  $\alpha$  from  $Bf$  to  $Bg$  consists of a collection


$$\{\alpha_{\bullet}: \bullet \rightarrow \bullet\}_{\bullet \in \text{Obj}(BA)}$$

of morphisms of  $BB$  indexed by  $\text{Obj}(BA)$ . Since  $\text{Obj}(BA) = \text{pt}$  and the morphisms of  $BB$  are precisely the elements of  $B$ , it follows that  $\alpha$  corresponds precisely to the data of an element  $b \in B$ . Now, a transformation  $[b]: Bf \Rightarrow Bg$  is natural precisely if, for each  $a \in \text{Hom}_{BA}(\bullet, \bullet) \stackrel{\text{def}}{=} A$ , the diagram

$$\begin{array}{ccc} Bf(\bullet) & \xrightarrow{Bf(a)} & Bf(\bullet) \\ [b]_{\bullet} \downarrow & & \downarrow [b]_{\bullet} \\ Bg(\bullet) & \xrightarrow{Bg(a)} & Bg(\bullet) \end{array}$$

commutes. Unwinding the definitions, we see that this diagram is given by

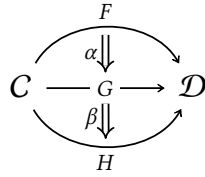
$$\begin{array}{ccc} \bullet & \xrightarrow{f(a)} & \bullet \\ b \downarrow & & \downarrow b \\ \bullet & \xrightarrow{g(a)} & \bullet \end{array}$$

and hence corresponds precisely to the condition  $g(a)b = bf(a)$ . 

### 11.9.4 Vertical Composition of Natural Transformations

#### DEFINITION 11.9.4.1.1 ► VERTICAL COMPOSITION OF NATURAL TRANSFORMATIONS

The **vertical composition** of two natural transformations  $\alpha: F \Rightarrow G$  and  $\beta: G \Rightarrow H$  as in the diagram



is the natural transformation  $\beta \circ \alpha: F \Rightarrow H$  consisting of the collection

$$\{(\beta \circ \alpha)_A: F(A) \rightarrow H(A)\}_{A \in \text{Obj}(C)}$$

with

$$(\beta \circ \alpha)_A \stackrel{\text{def}}{=} \beta_A \circ \alpha_A$$

for each  $A \in \text{Obj}(C)$ .

**PROOF 11.9.4.1.2 ► PROOF OF DEFINITION 11.9.4.1.1**

The naturality condition for  $\beta \circ \alpha$  is the requirement that the boundary of the diagram

$$\begin{array}{ccc}
 F(A) & \xrightarrow{F(f)} & F(B) \\
 \alpha_A \downarrow & (1) & \downarrow \alpha_B \\
 G(A) & \xrightarrow{G(f)} & G(B) \\
 \beta_A \downarrow & (2) & \downarrow \beta_B \\
 H(A) & \xrightarrow{H(f)} & H(B)
 \end{array}$$

commutes. Since

- Subdiagram (1) commutes by the naturality of  $\alpha$ .
- Subdiagram (2) commutes by the naturality of  $\beta$ .

so does the boundary diagram. Hence  $\beta \circ \alpha$  is a natural transformation.


**PROPOSITION 11.9.4.1.3 ► PROPERTIES OF VERTICAL COMPOSITION OF NATURAL TRANSFORMATIONS**

Let  $\mathcal{C}$ ,  $\mathcal{D}$ , and  $\mathcal{E}$  be categories.

1. *Functionality.* The assignment  $(\beta, \alpha) \mapsto \beta \circ \alpha$  defines a function

$$\circ_{F,G,H}: \text{Nat}(G, H) \times \text{Nat}(F, G) \rightarrow \text{Nat}(F, H).$$

2. *Associativity.* Let  $F, G, H, K: C \rightrightarrows \mathcal{D}$  be functors. The diagram

$$\begin{array}{ccc}
 & \text{Nat}(H, K) \times (\text{Nat}(G, H) \times \text{Nat}(F, G)) & \\
 \alpha_{\text{Nat}(H, K), \text{Nat}(G, H), \text{Nat}(F, G)}^{\text{Sets}} \nearrow & & \searrow \text{id}_{\text{Nat}(H, K)} \times \circ_{F, G, H} \\
 (\text{Nat}(H, K) \times \text{Nat}(G, H)) \times \text{Nat}(F, G) & & \text{Nat}(H, K) \times \text{Nat}(F, H) \\
 \downarrow \circ_{G, H, K} \times \text{id}_{\text{Nat}(F, G)} & & \downarrow \circ_{F, H, K} \\
 \text{Nat}(G, K) \times \text{Nat}(F, G) & \xrightarrow{\circ_{F, G, K}} & \text{Nat}(F, K)
 \end{array}$$

commutes, i.e. given natural transformations

$$F \xRightarrow{\alpha} G \xRightarrow{\beta} H \xRightarrow{\gamma} K,$$

we have

$$(\gamma \circ \beta) \circ \alpha = \gamma \circ (\beta \circ \alpha).$$

3. *Unitality.* Let  $F, G: C \rightrightarrows \mathcal{D}$  be functors.

(a) *Left Unitality.* The diagram

$$\begin{array}{ccc}
 \text{pt} \times \text{Nat}(F, G) & & \\
 \downarrow [\text{id}_G] \times \text{id}_{\text{Nat}(F, G)} & \searrow \lambda_{\text{Nat}(F, G)}^{\text{Sets}} & \\
 \text{Nat}(G, G) \times \text{Nat}(F, G) & \xrightarrow{\circ_{F, G, G}} & \text{Nat}(F, G)
 \end{array}$$

commutes, i.e. given a natural transformation  $\alpha: F \Rightarrow G$ , we have

$$\text{id}_G \circ \alpha = \alpha.$$

(b) *Right Unitality*. The diagram

$$\begin{array}{ccc}
 \text{Nat}(F, G) \times \text{pt} & & \\
 \downarrow \text{id}_{\text{Nat}(F, G)} \times [\text{id}_F] & \searrow \rho_{\text{Nat}(F, G)}^{\text{Sets}} & \\
 \text{Nat}(F, G) \times \text{Nat}(F, F) & \xrightarrow{\circ_{F, F, G}^C} & \text{Nat}(F, G)
 \end{array}$$

commutes, i.e. given a natural transformation  $\alpha: F \Rightarrow G$ , we have

$$\alpha \circ \text{id}_F = \alpha.$$

4. *Middle Four Exchange*. Let  $F_1, F_2, F_3: \mathcal{C} \rightarrow \mathcal{D}$  and  $G_1, G_2, G_3: \mathcal{D} \rightarrow \mathcal{E}$  be functors. The diagram

$$\begin{array}{ccc}
 (\text{Nat}(G_2, G_3) \times \text{Nat}(G_1, G_2)) \times (\text{Nat}(F_2, F_3) \times \text{Nat}(F_1, F_2)) & \xleftarrow{\mu_1} & (\text{Nat}(G_2, G_3) \times \text{Nat}(F_2, F_3)) \times (\text{Nat}(G_1, G_2) \times \text{Nat}(F_1, F_2)) \\
 \downarrow \circ_{G_1, G_2, G_3} \times \circ_{F_1, F_2, F_3} & & \downarrow \star_{F_2, F_3, G_2, G_3} \times \star_{F_1, F_2, G_1, G_2} \\
 \text{Nat}(G_1, G_3) \times \text{Nat}(F_1, F_3) & & \text{Nat}(G_2 \circ F_2, G_3 \circ F_3) \times \text{Nat}(G_1 \circ F_1, G_2 \circ F_2) \\
 \searrow \star_{F_1, F_3, G_1, G_3} & & \swarrow \circ_{G_1 \circ F_1, G_2 \circ F_2, G_3 \circ F_3} \\
 & \text{Nat}(G_1 \circ F_1, G_3 \circ F_3) &
 \end{array}$$

commutes, i.e. given a diagram

$$\begin{array}{ccccc}
 & F_1 & & G_1 & \\
 & \curvearrowright & & \curvearrowright & \\
 C & \xrightarrow{F_2} & \mathcal{D} & \xrightarrow{G_2} & \mathcal{E} \\
 & \curvearrowleft & & \curvearrowleft & \\
 & F_3 & & G_3 &
 \end{array}$$

in  $\text{Cats}_2$ , we have

$$(\beta' \star \alpha') \circ (\beta \star \alpha) = (\beta' \circ \beta) \star (\alpha' \circ \alpha).$$

**PROOF 11.9.4.1.4 ► PROOF OF PROPOSITION 11.9.4.1.3****Item 1: Functionality**

Omitted.

**Item 2: Associativity**

Indeed, we have

$$\begin{aligned}
 ((\gamma \circ \beta) \circ \alpha)_A &\stackrel{\text{def}}{=} (\gamma \circ \beta)_A \circ \alpha_A \\
 &\stackrel{\text{def}}{=} (\gamma_A \circ \beta_A) \circ \alpha_A \\
 &= \gamma_A \circ (\beta_A \circ \alpha_A) \\
 &\stackrel{\text{def}}{=} \gamma_A \circ (\beta \circ \alpha)_A \\
 &\stackrel{\text{def}}{=} (\gamma \circ (\beta \circ \alpha))_A
 \end{aligned}$$

for each  $A \in \text{Obj}(C)$ , showing the desired equality.

**Item 3: Unitality**

We have

$$\begin{aligned}
 (\text{id}_G \circ \alpha)_A &= \text{id}_G \circ \alpha_A \\
 &= \alpha_A, \\
 (\alpha \circ \text{id}_F)_A &= \alpha_A \circ \text{id}_F \\
 &= \alpha_A
 \end{aligned}$$

for each  $A \in \text{Obj}(C)$ , showing the desired equality.

**Item 4: Middle Four Exchange**

This is proved in **Item 4** of **Proposition 11.9.5.1.4**. 

**11.9.5 Horizontal Composition of Natural Transformations**

## DEFINITION 11.9.5.1.1 ► HORIZONTAL COMPOSITION OF NATURAL TRANSFORMATIONS

The **horizontal composition**<sup>1,2</sup> of two natural transformations  $\alpha: F \Rightarrow G$  and  $\beta: H \Rightarrow K$  as in the diagram

$$\begin{array}{ccc} C & \xrightarrow{F} & \mathcal{D} \\ \alpha \Downarrow & & \beta \Downarrow \\ C & \xrightarrow{G} & \mathcal{D} \end{array} \quad \begin{array}{ccc} \mathcal{D} & \xrightarrow{H} & \mathcal{E} \\ \beta \Downarrow & & \beta \Downarrow \\ \mathcal{D} & \xrightarrow{K} & \mathcal{E} \end{array}$$

of  $\alpha$  and  $\beta$  is the natural transformation

$$\beta \star \alpha: (H \circ F) \Rightarrow (K \circ G),$$

as in the diagram

$$\begin{array}{ccc} C & \xrightarrow{H \circ F} & \mathcal{E} \\ \beta \star \alpha \Downarrow & & \\ C & \xrightarrow{K \circ G} & \mathcal{E} \end{array}$$

consisting of the collection

$$\{(\beta \star \alpha)_A: H(F(A)) \rightarrow K(G(A))\}_{A \in \text{Obj}(\mathcal{C})},$$

of morphisms of  $\mathcal{E}$  with

$$\begin{array}{ccc} H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\ \beta_{F(A)} \downarrow & & \downarrow \beta_{G(A)} \\ K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)). \end{array}$$

$$\begin{aligned} (\beta \star \alpha)_A &\stackrel{\text{def}}{=} \beta_{G(A)} \circ H(\alpha_A) \\ &= K(\alpha_A) \circ \beta_{F(A)}, \end{aligned}$$

<sup>1</sup>*Further Terminology:* Also called the **Godement product** of  $\alpha$  and  $\beta$ .

<sup>2</sup>Horizontal composition forms a map

$$\star_{(F,H),(G,K)}: \text{Nat}(H, K) \times \text{Nat}(F, G) \rightarrow \text{Nat}(H \circ F, K \circ G).$$



**PROOF 11.9.5.1.2 ► PROOF OF DEFINITION 11.9.5.1.1**

First, we claim that we indeed have

$$\beta_{G(A)} \circ H(\alpha_A) = K(\alpha_A) \circ \beta_{F(A)}, \quad \begin{array}{ccc} H(F(A)) & \xrightarrow{H(\alpha_A)} & H(G(A)) \\ \beta_{F(A)} \downarrow & & \downarrow \beta_{G(A)} \\ K(F(A)) & \xrightarrow{K(\alpha_A)} & K(G(A)). \end{array}$$

This is, however, simply the naturality square for  $\beta$  applied to the morphism  $\alpha_A: F(A) \rightarrow G(A)$ . Next, we check the naturality condition for  $\beta \star \alpha$ , which is the requirement that the boundary of the diagram

$$\begin{array}{ccc} H(F(A)) & \xrightarrow{H(F(f))} & H(F(B)) \\ \downarrow H(\alpha_A) & (1) & \downarrow H(\alpha_B) \\ H(G(A)) & \xrightarrow{H(G(f))} & H(G(B)) \\ \downarrow \beta_{G(A)} & (2) & \downarrow \beta_{G(B)} \\ K(G(A)) & \xrightarrow{K(G(f))} & K(G(B)) \end{array}$$

commutes. Since

- Subdiagram (1) commutes by the naturality of  $\alpha$ .
- Subdiagram (2) commutes by the naturality of  $\beta$ .

so does the boundary diagram. Hence  $\beta \circ \alpha$  is a natural transformation.<sup>1</sup>



<sup>1</sup>Reference: [Bor94, Proposition 1.3.4].

**DEFINITION 11.9.5.1.3 ► WHISKERING OF FUNCTORS WITH NATURAL TRANSFORMATIONS**

Let

$$\mathcal{X} \xrightarrow{F} \mathcal{C} \begin{array}{c} \xrightarrow{\phi} \\ \alpha \Downarrow \\ \xrightarrow{\psi} \end{array} \mathcal{D} \xrightarrow{G} \mathcal{Y}$$

be a diagram in  $\mathbf{Cats}_2$ .

1. The **left whiskering of  $\alpha$  with  $G$**  is the natural transformation<sup>1</sup>

$$\mathrm{id}_G \star \alpha: G \circ \phi \Longrightarrow G \circ \psi.$$

2. The **right whiskering of  $\alpha$  with  $F$**  is the natural transformation<sup>2</sup>

$$\alpha \star \mathrm{id}_F: \phi \circ F \Longrightarrow \psi \circ F.$$

<sup>1</sup>*Further Notation:* Also written  $G\alpha$  or  $G \star \alpha$ , although we won't use either of these notations in this work.

<sup>2</sup>*Further Notation:* Also written  $\alpha F$  or  $\alpha \star F$ , although we won't use either of these notations in this work.

**PROPOSITION 11.9.5.1.4 ► PROPERTIES OF HORIZONTAL COMPOSITION OF NATURAL TRANSFORMATIONS**

Let  $\mathcal{C}$ ,  $\mathcal{D}$ , and  $\mathcal{E}$  be categories.

1. *Functionality.* The assignment  $(\beta, \alpha) \mapsto \beta \star \alpha$  defines a function

$$\star_{(F,G),(H,K)}: \mathrm{Nat}(H, K) \times \mathrm{Nat}(F, G) \rightarrow \mathrm{Nat}(H \circ F, K \circ G).$$

2. *Associativity.* Let

$$\mathcal{C} \begin{array}{c} \xrightarrow{F_1} \\ \xrightarrow{G_1} \end{array} \mathcal{D} \begin{array}{c} \xrightarrow{F_2} \\ \xrightarrow{G_2} \end{array} \mathcal{E} \begin{array}{c} \xrightarrow{F_3} \\ \xrightarrow{G_3} \end{array} \mathcal{F}$$

be a diagram in  $\mathbf{Cats}_2$ . The diagram

$$\begin{array}{ccc}
 \text{Nat}(F_3, G_3) \times \text{Nat}(F_2, G_2) \times \text{Nat}(F_1, G_1) & \xrightarrow{\star(F_2, G_2), (F_3, G_3) \times \text{id}} & \text{Nat}(F_3 \circ F_2, G_3 \circ G_2) \times \text{Nat}(F_1, G_1) \\
 \downarrow \text{id} \times \star(F_1, G_1), (F_2, G_2) & & \downarrow \star(F_3 \circ F_2), (G_3 \circ G_2, F_1, G_1) \\
 \text{Nat}(F_3, G_3) \times \text{Nat}(F_2 \circ F_1, G_2 \circ G_1) & \xrightarrow{\star(F_2 \circ F_1), (G_2 \circ G_1, F_3, G_3)} & \text{Nat}(F_3 \circ F_2 \circ F_1, G_3 \circ G_2 \circ G_1)
 \end{array}$$

commutes, i.e. given natural transformations

$$\begin{array}{ccccc}
 C & \xrightarrow{F_1} & \mathcal{D} & \xrightarrow{F_2} & \mathcal{E} & \xrightarrow{F_3} & \mathcal{F} \\
 \alpha \downarrow & & \beta \downarrow & & \gamma \downarrow & & \\
 C & \xrightarrow{G_1} & \mathcal{D} & \xrightarrow{G_2} & \mathcal{E} & \xrightarrow{G_3} & \mathcal{F}
 \end{array}$$

we have

$$(\gamma \star \beta) \star \alpha = \gamma \star (\beta \star \alpha).$$

3. *Interaction With Identities.* Let  $F: C \rightarrow \mathcal{D}$  and  $G: \mathcal{D} \rightarrow \mathcal{E}$  be functors. The diagram

$$\begin{array}{ccc}
 \text{pt} \times \text{pt} & \xrightarrow{[\text{id}_G] \times [\text{id}_F]} & \text{Nat}(G, G) \times \text{Nat}(F, F) \\
 \uparrow \wr & & \downarrow \star(F, F), (G, G) \\
 \text{pt} & \xrightarrow{[\text{id}_{G \circ F}]} & \text{Nat}(G \circ F, G \circ F)
 \end{array}$$

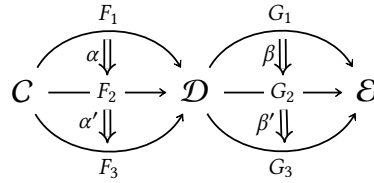
commutes, i.e. we have

$$\text{id}_G \star \text{id}_F = \text{id}_{G \circ F}.$$

4. *Middle Four Exchange.* Let  $F_1, F_2, F_3: C \rightarrow \mathcal{D}$  and  $G_1, G_2, G_3: \mathcal{D} \rightarrow \mathcal{E}$  be functors. The diagram

$$\begin{array}{ccc}
 (\text{Nat}(G_2, G_3) \times \text{Nat}(G_1, G_2)) \times (\text{Nat}(F_2, F_3) \times \text{Nat}(F_1, F_2)) & \xleftarrow{\mu_4} & (\text{Nat}(G_2, G_3) \times \text{Nat}(F_2, F_3)) \times (\text{Nat}(G_1, G_2) \times \text{Nat}(F_1, F_2)) \\
 \downarrow \circ_{G_1, G_2, G_3} \times \circ_{F_1, F_2, F_3} & & \downarrow \star_{F_2, F_3, G_2, G_3} \times \star_{F_1, F_2, G_1, G_2} \\
 \text{Nat}(G_1, G_3) \times \text{Nat}(F_1, F_3) & & \text{Nat}(G_2 \circ F_2, G_3 \circ F_3) \times \text{Nat}(G_1 \circ F_1, G_2 \circ F_2) \\
 \searrow \star_{F_1, F_3, G_1, G_3} & & \swarrow \circ_{G_1 \circ F_1, G_2 \circ F_2, G_3 \circ F_3} \\
 & \text{Nat}(G_1 \circ F_1, G_3 \circ F_3) &
 \end{array}$$

commutes, i.e. given a diagram



in  $\mathbf{Cats}_2$ , we have

$$(\beta' \star \alpha') \circ (\beta \star \alpha) = (\beta' \circ \beta) \star (\alpha' \circ \alpha).$$

#### PROOF 11.9.5.1.5 ► PROOF OF PROPOSITION 11.9.5.1.4

Item 1: Functionality

Omitted.

Item 2: Associativity

Omitted.

Item 3: Interaction With Identities

We have

$$\begin{aligned} (\mathrm{id}_G \star \mathrm{id}_F)_A &\stackrel{\mathrm{def}}{=} (\mathrm{id}_G)_{F_A} \circ G_{(\mathrm{id}_F)_A} \\ &\stackrel{\mathrm{def}}{=} \mathrm{id}_{G_{F_A}} \circ G_{\mathrm{id}_{F_A}} \\ &= \mathrm{id}_{G_{F_A}} \circ \mathrm{id}_{G_{F_A}} \\ &= \mathrm{id}_{G_{F_A}} \\ &\stackrel{\mathrm{def}}{=} (\mathrm{id}_{G \circ F})_A \end{aligned}$$

for each  $A \in \mathrm{Obj}(C)$ , showing the desired equality.

Item 4: Middle Four Exchange

Let  $A \in \text{Obj}(C)$  and consider the diagram

$$\begin{array}{ccccc}
 & & G_1(F_3(A)) & & \\
 & \nearrow^{G_1(\alpha'_A)} & & \searrow_{\beta_{F_3(A)}} & \\
 G_1(F_1(A)) & \xrightarrow{G_1(\alpha_A)} & G_1(F_2(A)) & (1) & G_2(F_3(A)) \xrightarrow{\beta'_{F_3(A)}} G_3(F_3(A)). \\
 & \searrow_{\beta_{F_2(A)}} & & \nearrow_{G_2(\alpha'_A)} & \\
 & & G_2(F_2(A)) & & 
 \end{array}$$

The top composition

$$\begin{array}{ccccc}
 & & G_1(F_3(A)) & & \\
 & \nearrow^{G_1(\alpha'_A)} & & \searrow_{\beta_{F_3(A)}} & \\
 G_1(F_1(A)) & \xrightarrow{G_1(\alpha_A)} & G_1(F_2(A)) & (1) & G_2(F_3(A)) \xrightarrow{\beta'_{F_3(A)}} G_3(F_3(A)). \\
 & \searrow_{\beta_{F_2(A)}} & & \nearrow_{G_2(\alpha'_A)} & \\
 & & G_2(F_2(A)) & & 
 \end{array}$$

is given by  $((\beta' \circ \beta) \star (\alpha' \circ \alpha))_A$ , while the bottom composition

$$\begin{array}{ccccc}
 & & G_1(F_3(A)) & & \\
 & \nearrow^{G_1(\alpha'_A)} & & \searrow_{\beta_{F_3(A)}} & \\
 G_1(F_1(A)) & \xrightarrow{G_1(\alpha_A)} & G_1(F_2(A)) & (1) & G_2(F_3(A)) \xrightarrow{\beta'_{F_3(A)}} G_3(F_3(A)). \\
 & \searrow_{\beta_{F_2(A)}} & & \nearrow_{G_2(\alpha'_A)} & \\
 & & G_2(F_2(A)) & & 
 \end{array}$$

is given by  $((\beta' \star \alpha') \circ (\beta \star \alpha))_A$ . Now, Subdiagram (1) corresponds to the naturality condition

$$\begin{array}{ccc}
 G_1(F_2(A)) & \xrightarrow{G_1(\alpha'_A)} & G_1(F_3(A)) \\
 \beta_{F_2(A)} \downarrow & & \downarrow \beta_{F_3(A)} \\
 G_2(F_2(A)) & \xrightarrow{G_2(\alpha'_A)} & G_2(F_3(A))
 \end{array}$$


$G_2(\alpha'_A) \circ \beta_{F_2(A)} = \beta_{F_3(A)} \circ G_1(\alpha'_A),$

for  $\beta: G_1 \Rightarrow G_2$  at  $\alpha'_A: F_2(A) \rightarrow F_3(A)$ , and thus commutes. Thus we have

$$((\beta' \circ \beta) \star (\alpha' \circ \alpha))_A = ((\beta' \star \alpha') \circ (\beta \star \alpha))_A$$

for each  $A \in \text{Obj}(C)$  and therefore

$$(\beta' \star \alpha') \circ (\beta \star \alpha) = (\beta' \circ \beta) \star (\alpha' \circ \alpha).$$

This finishes the proof. 

## 11.9.6 Properties of Natural Transformations

### PROPOSITION 11.9.6.1.1 ► NATURAL TRANSFORMATIONS AS CATEGORICAL HOMOTOPIES

Let  $F, G: C \Rightarrow D$  be functors. The following data are equivalent:<sup>1</sup>

1. A natural transformation  $\alpha: F \Rightarrow G$ .

2. A functor  $[\alpha]: C \rightarrow \mathcal{D}^{\mathbb{1}}$  filling the diagram

$$\begin{array}{ccc}
 & & \mathcal{D} \\
 & \nearrow F & \uparrow \text{ev}_0 \\
 C & \xrightarrow{[\alpha]} & \mathcal{D}^{\mathbb{1}} \\
 & \searrow G & \downarrow \text{ev}_1 \\
 & & \mathcal{D}
 \end{array}$$

3. A functor  $[\alpha]: C \times \mathbb{1} \rightarrow \mathcal{D}$  filling the diagram

$$\begin{array}{ccc}
 C & & \\
 \uparrow \text{ev}_0 & \searrow F & \\
 C \times \mathbb{1} & \xrightarrow{[\alpha]} & \mathcal{D} \\
 \downarrow \text{ev}_1 & \nearrow G & \\
 C & & 
 \end{array}$$

<sup>1</sup>Taken from [M0 64365].

#### PROOF 11.9.6.1.2 ► PROOF OF PROPOSITION 11.9.6.1.1

From Item 1 to Item 2 and Back

We may identify  $\mathcal{D}^{\mathbb{1}}$  with  $\text{Arr}(\mathcal{D})$ . Given a natural transformation

$\alpha: F \Rightarrow G$ , we have a functor

$$[\alpha]: C \longrightarrow \mathcal{D}^{\mathbb{I}}$$

$$A \longmapsto \alpha_A$$

$$(f: A \rightarrow B) \longmapsto \left( \begin{array}{ccc} F_A & \xrightarrow{F_f} & F_B \\ \alpha_A \downarrow & & \downarrow \alpha_B \\ G_A & \xrightarrow{G_f} & G_B \end{array} \right)$$

making the diagram in [Item 2](#) commute. Conversely, every such functor gives rise to a natural transformation from  $F$  to  $G$ , and these constructions are inverse to each other.

From Item 2 to Item 3 and Back

This follows from [Item 3](#) of [Proposition 11.10.1.1.2](#). 

## 11.9.7 Natural Isomorphisms

Let  $C$  and  $\mathcal{D}$  be categories and let  $F, G: C \Rightarrow \mathcal{D}$  be functors.

### DEFINITION 11.9.7.1.1 ► NATURAL ISOMORPHISMS

A natural transformation  $\alpha: F \Rightarrow G$  is a **natural isomorphism** if there exists a natural transformation  $\alpha^{-1}: G \Rightarrow F$  such that

$$\alpha^{-1} \circ \alpha = \text{id}_F,$$

$$\alpha \circ \alpha^{-1} = \text{id}_G.$$

### PROPOSITION 11.9.7.1.2 ► PROPERTIES OF NATURAL ISOMORPHISMS

Let  $\alpha: F \Rightarrow G$  be a natural transformation.

1. *Characterisations.* The following conditions are equivalent:
  - (a) The natural transformation  $\alpha$  is a natural isomorphism.



(b) For each  $A \in \text{Obj}(C)$ , the morphism  $\alpha_A: F_A \rightarrow G_A$  is an isomorphism.

2. *Componentwise Inverses of Natural Transformations Assemble Into Natural Transformations.* Let  $\alpha^{-1}: G \Rightarrow F$  be a transformation such that, for each  $A \in \text{Obj}(C)$ , we have

$$\begin{aligned}\alpha_A^{-1} \circ \alpha_A &= \text{id}_{F(A)}, \\ \alpha_A \circ \alpha_A^{-1} &= \text{id}_{G(A)}.\end{aligned}$$

Then  $\alpha^{-1}$  is a natural transformation.

#### PROOF 11.9.7.1.3 ► PROOF OF PROPOSITION 11.9.7.1.2

##### Item 1: Characterisations

The implication **Item 1a**  $\Rightarrow$  **Item 1b** is clear, whereas the implication **Item 1b**  $\Rightarrow$  **Item 1a** follows from **Item 2**.

##### Item 2: Componentwise Inverses of Natural Transformations Assemble

The naturality condition for  $\alpha^{-1}$  corresponds to the commutativity of the diagram

$$\begin{array}{ccc} G(A) & \xrightarrow{G(f)} & G(B) \\ \alpha_A^{-1} \downarrow & & \downarrow \alpha_B^{-1} \\ F(A) & \xrightarrow{F(f)} & F(B) \end{array}$$

for each  $A, B \in \text{Obj}(C)$  and each  $f \in \text{Hom}_C(A, B)$ . Considering the diagram


$$\begin{array}{ccc}
 G(A) & \xrightarrow{G(f)} & G(B) \\
 \alpha_A^{-1} \downarrow & (1) & \downarrow \alpha_B^{-1} \\
 F(A) & \xrightarrow{F(f)} & F(B) \\
 \alpha_A \downarrow & (2) & \downarrow \alpha_B \\
 G(A) & \xrightarrow{G(f)} & G(B),
 \end{array}$$

where the boundary diagram as well as Subdiagram (2) commute, we have

$$\begin{aligned}
 G(f) &= G(f) \circ \text{id}_{G(A)} \\
 &= G(f) \circ \alpha_A \circ \alpha_A^{-1} \\
 &= \alpha_B \circ F(f) \circ \alpha_A^{-1}.
 \end{aligned}$$

Postcomposing both sides with  $\alpha_B^{-1}$ , we get

$$\begin{aligned}
 \alpha_B^{-1} \circ G(f) &= \alpha_B^{-1} \circ \alpha_B \circ F(f) \circ \alpha_A^{-1} \\
 &= \text{id}_{F(B)} \circ F(f) \circ \alpha_A^{-1} \\
 &= F(f) \circ \alpha_A^{-1},
 \end{aligned}$$

which is the naturality condition we wanted to show. Thus  $\alpha^{-1}$  is a natural transformation. 

## 11.10 Categories of Categories

### 11.10.1 Functor Categories

Let  $C$  be a category and  $\mathcal{D}$  be a small category.

## DEFINITION 11.10.1.1.1 ► FUNCTOR CATEGORIES

The **category of functors from  $C$  to  $\mathcal{D}$** <sup>1</sup> is the category  $\text{Fun}(C, \mathcal{D})$ <sup>2</sup> where

- *Objects.* The objects of  $\text{Fun}(C, \mathcal{D})$  are functors from  $C$  to  $\mathcal{D}$ .
- *Morphisms.* For each  $F, G \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$ , we have

$$\text{Hom}_{\text{Fun}(C, \mathcal{D})}(F, G) \stackrel{\text{def}}{=} \text{Nat}(F, G).$$

- *Identities.* For each  $F \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$ , the unit map

$$\mathbb{1}_F^{\text{Fun}(C, \mathcal{D})} : \text{pt} \rightarrow \text{Nat}(F, F)$$

of  $\text{Fun}(C, \mathcal{D})$  at  $F$  is given by

$$\text{id}_F^{\text{Fun}(C, \mathcal{D})} \stackrel{\text{def}}{=} \text{id}_F,$$

where  $\text{id}_F : F \Rightarrow F$  is the identity natural transformation of  $F$  of [Example 11.9.3.1.1](#).

- *Composition.* For each  $F, G, H \in \text{Obj}(\text{Fun}(C, \mathcal{D}))$ , the composition map

$$\circ_{F, G, H}^{\text{Fun}(C, \mathcal{D})} : \text{Nat}(G, H) \times \text{Nat}(F, G) \rightarrow \text{Nat}(F, H)$$

of  $\text{Fun}(C, \mathcal{D})$  at  $(F, G, H)$  is given by

$$\beta \circ_{F, G, H}^{\text{Fun}(C, \mathcal{D})} \alpha \stackrel{\text{def}}{=} \beta \circ \alpha,$$

where  $\beta \circ \alpha$  is the vertical composition of  $\alpha$  and  $\beta$  of [Item 1](#) of [Proposition 11.9.4.1.3](#).

<sup>1</sup>*Further Terminology:* Also called the **functor category**  $\text{Fun}(C, \mathcal{D})$ .

<sup>2</sup>*Further Notation:* Also written  $\mathcal{D}^C$  and  $[C, \mathcal{D}]$ .

**PROPOSITION 11.10.1.1.2 ► PROPERTIES OF FUNCTOR CATEGORIES**

Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories and let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a functor.

1. *Functoriality.* The assignments  $\mathcal{C}, \mathcal{D}, (\mathcal{C}, \mathcal{D}) \mapsto \text{Fun}(\mathcal{C}, \mathcal{D})$  define functors

$$\begin{aligned} \text{Fun}(\mathcal{C}, -): \quad \text{Cats} &\rightarrow \text{Cats}, \\ \text{Fun}(-, \mathcal{D}): \quad \text{Cats}^{\text{op}} &\rightarrow \text{Cats}, \\ \text{Fun}(-, -): \text{Cats}^{\text{op}} \times \text{Cats} &\rightarrow \text{Cats}. \end{aligned}$$

2. *2-Functoriality.* The assignments  $\mathcal{C}, \mathcal{D}, (\mathcal{C}, \mathcal{D}) \mapsto \text{Fun}(\mathcal{C}, \mathcal{D})$  define 2-functors

$$\begin{aligned} \text{Fun}(\mathcal{C}, -): \quad \text{Cats}_2 &\rightarrow \text{Cats}_2, \\ \text{Fun}(-, \mathcal{D}): \quad \text{Cats}_2^{\text{op}} &\rightarrow \text{Cats}_2, \\ \text{Fun}(-, -): \text{Cats}_2^{\text{op}} \times \text{Cats}_2 &\rightarrow \text{Cats}_2. \end{aligned}$$

3. *Adjointness.* We have adjunctions

$$\begin{aligned} (\mathcal{C} \times - \dashv \text{Fun}(\mathcal{C}, -)): \quad \text{Cats} &\overset{\mathcal{C} \times -}{\underset{\text{Fun}(\mathcal{C}, -)}{\rightleftarrows}} \text{Cats}, \\ (- \times \mathcal{D} \dashv \text{Fun}(\mathcal{D}, -)): \quad \text{Cats} &\overset{- \times \mathcal{D}}{\underset{\text{Fun}(\mathcal{D}, -)}{\rightleftarrows}} \text{Cats}, \end{aligned}$$

witnessed by bijections of sets

$$\begin{aligned} \text{Hom}_{\text{Cats}}(\mathcal{C} \times \mathcal{D}, \mathcal{E}) &\cong \text{Hom}_{\text{Cats}}(\mathcal{D}, \text{Fun}(\mathcal{C}, \mathcal{E})), \\ \text{Hom}_{\text{Cats}}(\mathcal{C} \times \mathcal{D}, \mathcal{E}) &\cong \text{Hom}_{\text{Cats}}(\mathcal{C}, \text{Fun}(\mathcal{D}, \mathcal{E})), \end{aligned}$$

natural in  $\mathcal{C}, \mathcal{D}, \mathcal{E} \in \text{Obj}(\text{Cats})$ .

4. *2-Adjointness.* We have 2-adjunctions

$$\begin{aligned} (\mathcal{C} \times - \dashv \text{Fun}(\mathcal{C}, -)): \quad \text{Cats}_2 &\overset{\mathcal{C} \times -}{\underset{\text{Fun}(\mathcal{C}, -)}{\rightleftarrows_2}} \text{Cats}_2, \\ (- \times \mathcal{D} \dashv \text{Fun}(\mathcal{D}, -)): \quad \text{Cats}_2 &\overset{- \times \mathcal{D}}{\underset{\text{Fun}(\mathcal{D}, -)}{\rightleftarrows_2}} \text{Cats}_2, \end{aligned}$$

witnessed by isomorphisms of categories

$$\begin{aligned}\mathrm{Fun}(C \times \mathcal{D}, \mathcal{E}) &\cong \mathrm{Fun}(\mathcal{D}, \mathrm{Fun}(C, \mathcal{E})), \\ \mathrm{Fun}(C \times \mathcal{D}, \mathcal{E}) &\cong \mathrm{Fun}(C, \mathrm{Fun}(\mathcal{D}, \mathcal{E})),\end{aligned}$$

natural in  $C, \mathcal{D}, \mathcal{E} \in \mathrm{Obj}(\mathrm{Cats}_2)$ .

5. *Interaction With Punctual Categories.* We have a canonical isomorphism of categories

$$\mathrm{Fun}(\mathrm{pt}, C) \cong C,$$

natural in  $C \in \mathrm{Obj}(\mathrm{Cats})$ .

6. *Objectwise Computation of Co/Limits.* Let

$$D: \mathcal{I} \rightarrow \mathrm{Fun}(C, \mathcal{D})$$

be a diagram in  $\mathrm{Fun}(C, \mathcal{D})$ . We have isomorphisms

$$\begin{aligned}\lim(D)_A &\cong \lim_{i \in \mathcal{I}}(D_i(A)), \\ \mathrm{colim}(D)_A &\cong \mathrm{colim}_{i \in \mathcal{I}}(D_i(A)),\end{aligned}$$

naturally in  $A \in \mathrm{Obj}(C)$ .

7. *Interaction With Co/Completeness.* If  $\mathcal{E}$  is co/complete, then so is  $\mathrm{Fun}(C, \mathcal{E})$ .

8. *Monomorphisms and Epimorphisms.* Let  $\alpha: F \Rightarrow G$  be a morphism of  $\mathrm{Fun}(C, \mathcal{D})$ . The following conditions are equivalent:

- (a) The natural transformation

$$\alpha: F \Rightarrow G$$

is a monomorphism (resp. epimorphism) in  $\mathrm{Fun}(C, \mathcal{D})$ .

- (b) For each  $A \in \mathrm{Obj}(C)$ , the morphism

$$\alpha_A: F_A \rightarrow G_A$$

is a monomorphism (resp. epimorphism) in  $\mathcal{D}$ .

**PROOF 11.10.1.1.3 ► PROOF OF PROPOSITION 11.10.1.1.2**

Item 1: Functoriality

Omitted.

Item 2: 2-Functoriality

Omitted.

Item 3: Adjointness

Omitted.

Item 4: 2-Adjointness

Omitted.

Item 5: Interaction With Punctual Categories

Omitted.


Item 6: Objectwise Computation of Co/Limits

Omitted.

Item 7: Interaction With Co/Completeness

This follows from ??.

Item 8: Monomorphisms and Epimorphisms

Omitted. **11.10.2 The Category of Categories and Functors****DEFINITION 11.10.2.1.1 ► THE CATEGORY OF CATEGORIES AND FUNCTORS**

The **category of (small) categories and functors** is the category  $\mathbf{Cats}$  where

- *Objects.* The objects of  $\mathbf{Cats}$  are small categories.
- *Morphisms.* For each  $C, \mathcal{D} \in \mathbf{Obj}(\mathbf{Cats})$ , we have

$$\mathbf{Hom}_{\mathbf{Cats}}(C, \mathcal{D}) \stackrel{\text{def}}{=} \mathbf{Obj}(\mathbf{Fun}(C, \mathcal{D})).$$

- *Identities.* For each  $C \in \mathbf{Obj}(\mathbf{Cats})$ , the unit map

$$\mathbb{1}_C^{\mathbf{Cats}}: \mathbf{pt} \rightarrow \mathbf{Hom}_{\mathbf{Cats}}(C, C)$$

of  $\mathbf{Cats}$  at  $C$  is defined by

$$\mathrm{id}_C^{\mathbf{Cats}} \stackrel{\mathrm{def}}{=} \mathrm{id}_C,$$

where  $\mathrm{id}_C: C \rightarrow C$  is the identity functor of  $C$  of [Example 11.5.1.1.4](#).

- *Composition.* For each  $C, \mathcal{D}, \mathcal{E} \in \mathrm{Obj}(\mathbf{Cats})$ , the composition map

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\mathbf{Cats}}: \mathrm{Hom}_{\mathbf{Cats}}(\mathcal{D}, \mathcal{E}) \times \mathrm{Hom}_{\mathbf{Cats}}(C, \mathcal{D}) \rightarrow \mathrm{Hom}_{\mathbf{Cats}}(C, \mathcal{E})$$

of  $\mathbf{Cats}$  at  $(C, \mathcal{D}, \mathcal{E})$  is given by

$$G \circ_{C, \mathcal{D}, \mathcal{E}}^{\mathbf{Cats}} F \stackrel{\mathrm{def}}{=} G \circ F,$$

where  $G \circ F: C \rightarrow \mathcal{E}$  is the composition of  $F$  and  $G$  of [Definition 11.5.1.1.6](#).

#### PROPOSITION 11.10.2.1.2 ► PROPERTIES OF THE CATEGORY $\mathbf{Cats}$

Let  $C$  be a category.

1. *Co/Completeness.* The category  $\mathbf{Cats}$  is complete and cocomplete.
2. *Cartesian Monoidal Structure.* The quadruple  $(\mathbf{Cats}, \times, \mathrm{pt}, \mathrm{Fun})$  is a Cartesian closed monoidal category.

#### PROOF 11.10.2.1.3 ► PROOF OF PROPOSITION 11.10.2.1.2

Item 1: Co/Completeness

Omitted.

Item 2: Cartesian Monoidal Structure

Omitted.



**11.10.3 The 2-Category of Categories, Functors, and Natural Transformations**



**DEFINITION 11.10.3.1.1 ► THE 2-CATEGORY OF CATEGORIES**

The **2-category of (small) categories, functors, and natural transformations** is the 2-category  $\mathbf{Cats}_2$  where

- *Objects.* The objects of  $\mathbf{Cats}_2$  are small categories.
- *Hom-Categories.* For each  $C, \mathcal{D} \in \mathbf{Obj}(\mathbf{Cats}_2)$ , we have

$$\mathrm{Hom}_{\mathbf{Cats}_2}(C, \mathcal{D}) \stackrel{\mathrm{def}}{=} \mathrm{Fun}(C, \mathcal{D}).$$

- *Identities.* For each  $C \in \mathbf{Obj}(\mathbf{Cats}_2)$ , the unit functor

$$\mathbb{1}_C^{\mathbf{Cats}_2} : \mathbf{pt} \rightarrow \mathrm{Fun}(C, C)$$

of  $\mathbf{Cats}_2$  at  $C$  is the functor picking the identity functor  $\mathrm{id}_C : C \rightarrow C$  of  $C$ .

- *Composition.* For each  $C, \mathcal{D}, \mathcal{E} \in \mathbf{Obj}(\mathbf{Cats}_2)$ , the composition bifunctor

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\mathbf{Cats}_2} : \mathrm{Hom}_{\mathbf{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \mathrm{Hom}_{\mathbf{Cats}_2}(C, \mathcal{D}) \rightarrow \mathrm{Hom}_{\mathbf{Cats}_2}(C, \mathcal{E})$$

of  $\mathbf{Cats}_2$  at  $(C, \mathcal{D}, \mathcal{E})$  is the functor where

- *Action on Objects.* For each object  $(G, F) \in \mathbf{Obj}(\mathrm{Hom}_{\mathbf{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \mathrm{Hom}_{\mathbf{Cats}_2}(C, \mathcal{D}))$ , we have

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\mathbf{Cats}_2}(G, F) \stackrel{\mathrm{def}}{=} G \circ F.$$

- *Action on Morphisms.* For each morphism  $(\beta, \alpha) : (K, H) \Rightarrow (G, F)$  of  $\mathrm{Hom}_{\mathbf{Cats}_2}(\mathcal{D}, \mathcal{E}) \times \mathrm{Hom}_{\mathbf{Cats}_2}(C, \mathcal{D})$ , we have

$$\circ_{C, \mathcal{D}, \mathcal{E}}^{\mathbf{Cats}_2}(\beta, \alpha) \stackrel{\mathrm{def}}{=} \beta \star \alpha,$$

where  $\beta \star \alpha$  is the horizontal composition of  $\alpha$  and  $\beta$  of

**Definition 11.9.5.1.1.**


**PROPOSITION 11.10.3.1.2** ► PROPERTIES OF THE 2-CATEGORY  $\mathbf{Cats}_2$ 

Let  $\mathcal{C}$  be a category.

1. *2-Categorical Co/Completeness.* The 2-category  $\mathbf{Cats}_2$  is complete and cocomplete as a 2-category, having all 2-categorical and bi-categorical co/limits.

**PROOF 11.10.3.1.3** ► PROOF OF PROPOSITION 11.10.3.1.2

Item 1: Co/Completeness

Omitted. 

**11.10.4 The Category of Groupoids****DEFINITION 11.10.4.1.1** ► THE CATEGORY OF SMALL GROUPOIDS

The **category of (small) groupoids** is the full subcategory  $\mathbf{Grpd}$  of  $\mathbf{Cats}$  spanned by the groupoids.

**11.10.5 The 2-Category of Groupoids****DEFINITION 11.10.5.1.1** ► THE 2-CATEGORY OF SMALL GROUPOIDS

The **2-category of (small) groupoids** is the full sub-2-category  $\mathbf{Grpd}_2$  of  $\mathbf{Cats}_2$  spanned by the groupoids.

# Appendices

## A Other Chapters

### Preliminaries

1. [Introduction](#)
2. [A Guide to the Literature](#)

### Sets

3. [Sets](#)
4. [Constructions With Sets](#)
5. [Monoidal Structures on the Category of Sets](#)
6. [Pointed Sets](#)
7. [Tensor Products of Pointed Sets](#)

### Relations

8. [Relations](#)
9. [Constructions With Relations](#)

10. [Conditions on Relations](#)

### Categories

11. [Categories](#)
12. [Presheaves and the Yoneda Lemma](#)

### Monoidal Categories

13. [Constructions With Monoidal Categories](#)

### Bicategories

14. [Types of Morphisms in Bicat-egories](#)

### Extra Part

15. [Notes](#)

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