

# **Category theory notes**

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# 1 Basic category theory

## 1.1 Categories

### 1.1.1 What is a category?

There are lots of different sorts of mathematical structures, each of which is good for different things. Groups are good for talking about symmetries, for instance, and rings are good for talking about function fields.

Categories are just another type of mathematical structure, but they have a different, more abstract feel to them than groups or rings. One reason for this is that they are inherently meta-mathematical: they are good for talking about other mathematical objects and the relationships between them.

For this reason, category theory has developed a reputation for being abstract and difficult to learn, which is mostly undeserved. Categories are nothing special; they are mathematical objects, just like groups or vector spaces. They are simply good for different things.

Unfortunately, there are many different conventions regarding how to typeset category theory. I will do my best to stick to the conventions used at the nLab ([20]).

**Definition 1** (category). A category  $C$  consists of the following pieces of data.

- A collection<sup>1</sup>  $\text{Obj}(C)$  of *objects*.
- For every two objects  $A, B \in \text{Obj}(C)$ , a collection  $\text{Hom}(A, B)$  of *morphisms* with the following properties.

1. For any  $f \in \text{Hom}(A, B)$  and  $g \in \text{Hom}(B, C)$ , there is an associated morphism

$$g \circ f \in \text{Hom}(A, C),$$

called the *composition* of  $f$  and  $g$ .

2. This composition is associative:  $(f \circ g) \circ h = f \circ (g \circ h)$ .
3. For every  $A \in \text{Obj}(C)$ , there is at least one morphism  $\text{id}_A$ , called the *identity morphism* which functions as both a left and right identity with respect to the composition of morphisms, i.e.

$$f \circ \text{id}_A = f \quad \text{and} \quad \text{id}_A \circ g = g.$$

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<sup>1</sup>There is a reason we say that there is a *collection*, rather than a *set*, of objects (and morphisms): it may be that there may be ‘too many’ objects (or morphisms) to be contained in a set. For example, there is no set of all sets, but we will see that there is a category of sets. We will for the most part sidestep foundational questions of size, but in some cases it will be unavoidable. In particular, categories whose objects and/or morphisms are small enough to be contained in a set will play an especially important role.

If ever it is potentially unclear which category we are talking about, we will add a subscript to  $\text{Hom}$ , writing for example  $\text{Hom}_C(A, B)$  instead of  $\text{Hom}(A, B)$ .

*Notation 2.* Following Aluffi ([10]), we will use a sans serif font to denote categories. For example  $\mathbf{C}$ ,  $\mathbf{Set}$ .

One often thinks of the objects in a category as ‘generalized sets,’ and of morphisms as ‘generalized functions.’ It is therefore often useful to use functional notation  $f: A \rightarrow B$  to describe morphisms. For example, the following two notations are equivalent:

$$f \in \text{Hom}(A, B) \iff f: A \rightarrow B.$$

Here is something to be aware of: the identity morphism  $\text{id}_A: A \rightarrow A$  is often simply denoted by  $A$ . This is actually a good notation, and we will use it freely in later chapters. However, we will avoid it in earlier chapters since it is potentially confusing whether we are talking about  $A$  the object or  $A$  the morphism.

### 1.1.2 Some examples of categories

The idea of a category is very abstract, but not abstruse. The easiest way to convince oneself of this is to see some examples. The most common type of category is given by ‘mathematical structures and structure-preserving maps between them,’ so many of our examples will be in this vein.

**Example 3** (The category of sets). The prototypical category is  $\mathbf{Set}$ , the category whose objects are sets and whose morphisms are functions.

In order to check that  $\mathbf{Set}$  is indeed a category, we need to check that the axioms are satisfied. In fact, everything is more or less clear by definition.

Our category  $\mathbf{Set}$  first needs a collection of objects. Although there is no set of all sets, there certainly is a collection of all sets. Therefore, we are free to choose

$$\text{Obj}(\mathbf{Set}) = [\text{all sets}].$$

The next thing  $\mathbf{Set}$  needs is, for each pair of objects (i.e. sets)  $A$  and  $B$ , a collection of morphisms  $\text{Hom}_{\mathbf{Set}}(A, B)$  between them. The morphisms between the objects in  $\mathbf{Set}$  will consist of all set-functions between. That is,

$$\text{Hom}_{\mathbf{Set}}(A, B) = \{f: A \rightarrow B \mid f \text{ is a function}\}.$$

Next one has to check that functions satisfy the necessary axioms. Given a function  $f: A \rightarrow B$  and a function  $g: B \rightarrow C$ , we can compose them to get a function  $g \circ f: A \rightarrow C$ . Thus, functions can indeed be composed in the necessary way.

The composition of morphisms is associative, since composition of functions is.

Furthermore, every set  $A$  has an identity function

$$\text{id}_A: A \rightarrow A; \quad a \mapsto a.$$

which maps every element to itself.

Thus,  $\mathbf{Set}$  is a category! That’s all there is to it!

**Example 4** (category with one object). There is an important category called  $\mathbf{1}$ , which has one object and one morphism.

- The set of objects  $\text{Obj}(\mathbf{1})$  is the singleton  $\{*\}$ .
- The only morphism is the identity morphism  $\text{id}_*: * \rightarrow *$ .

Here is a picture of the category  $\mathbf{1}$ .



Categories capture the essence of ‘things and composable maps between them.’ There are many mathematical structures which naturally come with a notion of map between them, usually called homomorphisms. These structure preserving maps are almost always composable, which means it is often natural to imagine such objects as living in their own categories.

**Example 5.** If you know what the following mathematical objects are, it is nearly effortless to check that they are categories.<sup>2</sup>

- $\text{Grp}$ , whose objects are groups and whose morphisms are group homomorphisms.
- $\text{Ab}$ , whose objects are abelian groups and whose morphisms are group homomorphisms.
- $\text{Ring}$ , whose objects are rings and whose morphisms are ring homomorphisms.
- $R\text{-Mod}$ , whose objects are modules over a ring  $R$  and whose morphisms are module homomorphisms.
- $\text{Vect}_k$ , whose objects are vector spaces over a field  $k$  and whose morphisms are linear maps.
- $\text{FinVect}_k$ , whose objects are finite-dimensional vector spaces over a field  $k$  and whose morphisms are linear maps.
- $k\text{-Alg}$ , whose objects are algebras over a field  $k$  and whose morphisms are algebra homomorphisms.

**Example 6.** In addition to algebraic structures, categories help to talk about geometrical structures. The following are also categories.

- $\text{Top}$ , whose objects are topological spaces and whose morphisms are continuous maps.
- $\text{Met}$ , whose objects are metric spaces and whose morphisms are metric maps.
- $\text{Man}^p$ , whose objects are manifolds of class  $C^p$  and whose morphisms are  $p$ -times differentiable functions.
- $\text{SmoothMfd}$ , whose objects are  $C^\infty$  manifolds and whose morphisms are smooth functions.

**Example 7.** Here is a slightly whimsical example of a category, which is different in nature to the other categories we’ve looked at before. This category is important when studying group representations.

Let  $G$  be a group. We are going to create a category  $G$  which behaves like this group.

- Our category  $G$  has only one object, called  $*$ .

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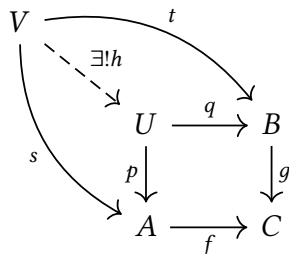
<sup>2</sup>Look at the definition. It *really* is trivial.

- The set  $\text{Hom}_G(*, *)$  is equal to the underlying set of the group  $G$ , and for  $f, g \in \text{Hom}_G(*, *)$ , the compositions  $f \circ g = f \cdot g$ , where  $\cdot$  is the group operation in  $G$ . The identity  $e \in G$  is the identity morphism  $\text{id}_*$  on  $*$ .

$$\begin{array}{c}
 g \\
 \downarrow \\
 f \circ \text{id}_* \\
 \downarrow \\
 g \circ f
 \end{array}$$

## Commutative diagrams

It is often helpful to visualize objects and morphisms in categories as graphs<sup>3</sup> with the objects as vertices and the morphisms as edges. This makes it possible to reason about categories using graph-like diagrams. Scroll to almost any later page in this document, and you will likely see a diagram or two which resembles this one (copied directly from [Definition 122](#)).



Category theorists frequently employ these diagrams, called *commutative diagrams*,<sup>4</sup> to make the ideas behind a proof more clear. Many results in category theory are most easily proved by drawing such a diagram, and then pointing at edges and vertices while repeating the phrase ‘and then this goes here’ and furrowing one’s brow. This sort of proof is called a ‘diagram chase,’ and category theorists are very fond of them.

### 1.1.3 Building new categories from existing ones

One of the first things one learns about when talking about a mathematical structure is how to use existing ones to create new ones. For example, one can take the product of two groups to create a third, or take the quotient of a vector space by a subspace. Categories are no exception. In this section, we will learn how to create new categories out of old categories.

#### The opposite category

The first way of doing this we’ll examine creates out of any category its *opposite category*, where all the morphisms go the other way.

**Definition 8** (opposite category). Let  $C$  be a category. Its opposite category  $C^{\text{op}}$  is the category defined in the following way.

<sup>3</sup>Strictly speaking, they are *multidigraphs*, i.e. directed graphs which are allowed to have more than one edge between any given pair of vertices.

<sup>4</sup>We will define later when a diagram does or does not commute. Annoyingly, even diagrams which don’t commute are called commutative diagrams.

- The objects of  $C^{\text{op}}$  are the same as the objects of  $C$ :

$$\text{Obj}(C^{\text{op}}) = \text{Obj}(C).$$

- The morphisms  $A \rightarrow B$  in  $C^{\text{op}}$  are defined to be the morphisms  $B \rightarrow A$  in  $C$ :

$$\text{Hom}_{C^{\text{op}}}(A, B) = \text{Hom}_C(B, A).$$

That is to say, the opposite category is the category one gets by formally reversing all the arrows in a category. If  $f \in \text{Hom}_C(A, B)$ , i.e.  $f: A \rightarrow B$ , then in  $C^{\text{op}}$ ,  $f: B \rightarrow A$ .

This may seem like an uninteresting definition, but having it around will make life a lot easier when it comes to defining functors ([Section 1.2](#)).

## Product categories

One can take the Cartesian product of two sets by creating ordered pairs. One can also take the product of two categories, which works in basically the same way.

**Definition 9** (product category). Let  $C$  and  $D$  be categories. The product category  $C \times D$  is the following category.

- The objects  $\text{Obj}(C \times D)$  consist of all ordered pairs  $(C, D)$ , where  $C \in \text{Obj}(C)$  and  $D \in \text{Obj}(D)$ .
- For any two objects  $(C, D)$ , and  $(C', D') \in \text{Obj}(C \times D)$ , the morphisms  $\text{Hom}_{C \times D}((C, D), (C', D'))$  are ordered pairs  $(f, g)$ , where  $f \in \text{Hom}_C(C, C')$  and  $g \in \text{Hom}_D(D, D')$ .
- Composition is taken componentwise, so that

$$(f_1, g_1) \circ (f_2, g_2) = (f_1 \circ f_2, g_1 \circ g_2).$$

- The identity morphisms are given in the obvious way:

$$\text{id}_{(C, D)} = (\text{id}_C, \text{id}_D).$$

Product categories are best pictured in the following way. The object  $(C, D) \in \text{Obj}(C \times D)$  is two objects right next to each other.

$$\begin{array}{c} C \\ D \end{array}$$

A morphism  $(f, g): (C, D) \rightarrow (C', D')$  is two morphisms next to each other:

$$\begin{array}{ccc} C & \xrightarrow{f} & C' \\ D & \xrightarrow{g} & D' \end{array}$$



## Subcategories

Many mathematical objects have a notion of ‘sub-object.’ For example, groups can have subgroups, and vector spaces can have vector subspaces. Categories also have this notion. As with groups and vector spaces, the definition of a ‘subcategory’ is more or less obvious, but it is helpful to know exactly what one has to check to show that a subcollection of objects and morphisms from a category forms a subcategory.

**Definition 10** (subcategory). Let  $C$  be a category. A category  $S$  is a subcategory of  $C$  if the following conditions hold.

- The objects  $\text{Obj}(S)$  of  $S$  are a subcollection of the objects of  $C$ .
- For  $S, T \in \text{Obj}(S)$ , the morphisms  $\text{Hom}_S(S, T)$  are a subcollection of the morphisms  $\text{Hom}_C(S, T)$  which satisfy the following.
  - For every  $S \in \text{Obj}(S)$ , the identity  $\text{id}_S \in \text{Hom}_S(S, S)$ .
  - For all  $f \in \text{Hom}_S(S, T)$  and  $g \in \text{Hom}_S(T, U)$ , the composite  $g \circ f \in \text{Hom}_S(S, U)$ .

If  $S$  is a subcategory of  $C$ , we will write  $S \subseteq C$ .

One particularly important kind of subcategory occurs when one takes a subset of all objects in a subcategory, but keeps all morphisms between them. This is known as a *full subcategory*.

**Definition 11** (full subcategory). Let  $C$  be a category,  $S \subseteq C$  a subcategory. We say that  $S$  is full in  $C$  if for every  $S, T \in \text{Obj}(S)$ ,  $\text{Hom}_S(S, T) = \text{Hom}_C(S, T)$ . That is, if there are no morphisms in  $\text{Hom}_C(S, T)$  that are not in  $\text{Hom}_S(S, T)$ .

**Example 12.** Recall that  $\text{Vect}_k$  is the category of vector spaces over a field  $k$ , and  $\text{FinVect}_k$  is the category of finite dimensional vector spaces.

It is not difficult to see that  $\text{FinVect}_k \subset \text{Vect}_k$ : all finite dimensional vector spaces are vector spaces, and all linear maps between finite-dimensional vector spaces are maps between vector spaces. In fact, since for  $V$  and  $W$  finite-dimensional, one does not gain any maps by moving from  $\text{Hom}_{\text{FinVect}_k}(V, W)$  to  $\text{Hom}_{\text{Vect}_k}(V, W)$ ,  $\text{FinVect}_k$  is even a *full* subcategory of  $\text{Vect}_k$ .

### 1.1.4 Properties of morphisms

Category theory has many essences, one of which is as a major generalization of set theory. It is often possible to upgrade statements about functions between sets to statements about morphisms between objects in an arbitrary category. However, this is not as simple as it may sound: nowhere in the axioms in the definition of a category does it say that the objects of a category have to *be* sets, so we cannot talk about their elements.

In a sense, it’s a miracle that this works at all. We are generalizing definitions from set theory, which are almost always given in terms of elements because elements are the only structure sets have, without ever mentioning the elements of the objects we’re talking about. We therefore have to find definitions which we can give purely in terms objects and morphisms between them.

## Isomorphism

The concept of an isomorphism exists for many mathematical entities. Two groups can be isomorphic, as can two sets or graphs. It turns out that the concept of isomorphism is best understood as a categorical one.

**Definition 13** (isomorphism). Let  $C$  be a category,  $A, B \in \text{Obj}(C)$ . A morphism  $f \in \text{Hom}(A, B)$  is said to be an isomorphism if there exists a morphism  $g \in \text{Hom}(B, A)$  such that

$$g \circ f = \text{id}_A, \quad \text{and} \quad f \circ g = \text{id}_B.$$

$$\text{id}_A \hookrightarrow A \xrightleftharpoons[g]{f} B \rhookrightarrow \text{id}_B$$

We usually denote such a  $g$  by  $f^{-1}$ .

If we have an isomorphism  $f: A \rightarrow B$ , we say that  $A$  and  $B$  are isomorphic, and write  $A \simeq B$ . This is not an abuse of notation; it is easy to check that isomorphism is an equivalence relation.

## Monomorphisms

Monomorphicity is an attempt to define a property analogous to injectivity which can be used in any category. The regular definition of injectivity, i.e.

$$f(a) = f(b) \implies a = b$$

will not do, because the objects in a category do not in general have elements. Therefore, we have to use a different property of injective functions: that they are left-cancellable. That is, if  $f$  is injective, then

$$f \circ g_1 = f \circ g_2 \implies g_1 = g_2$$

for any functions  $g_1$  and  $g_2$ .

**Definition 14** (monomorphism). Let  $C$  be a category,  $A, B \in \text{Obj}(C)$ . A morphism  $f: A \rightarrow B$  is said to be a monomorphism (or simply *mono*) if for any  $Z \in \text{Obj}(C)$  and any  $g_1, g_2: Z \rightarrow A$ ,  $f \circ g_1 = f \circ g_2$  implies  $g_1 = g_2$ .

$$Z \xrightarrow[g_2]{g_1} A \xrightarrow{f} B$$

*Note 15.* When we wish to notationally distinguish monomorphisms, we will denote them by hooked arrows: if  $f: A \rightarrow B$  is mono, we will write

$$A \hookrightarrow^f B.$$

This turns out to work due to the following theorem.

**Theorem 16.** In  $\text{Set}$ , a morphism is a monomorphism if and only if it is injective.

*Proof.* Suppose  $f: A \rightarrow B$  is a monomorphism. Then for any set  $Z$  and any maps  $g_1, g_2: Z \rightarrow A$ ,  $f \circ g_1 = f \circ g_2$  implies  $g_1 = g_2$ . In particular, take  $Z$  to be the singleton  $Z = \{*\}$  and call  $g_1(*) = a_1$  and  $g_2(*) = a_2$ . Then  $(f \circ g_1)(*) = f(a_1)$  and  $(f \circ g_2)(*) = f(a_2)$ , so

$$f(a_1) = f(a_2) \implies a_1 = a_2.$$

But this is exactly the definition of injectivity.

Now suppose that  $f$  is injective. Then for any  $Z$  and  $g_1, g_2$  as above,

$$(f \circ g_1)(z) = (f \circ g_2)(z) \implies g_1(z) = g_2(z) \quad \text{for all } z \in Z.$$

But this means that  $g_1 = g_2$ , so  $f$  is mono. □

**Example 17.** In  $\text{Vect}_k$ , a morphism  $L: V \rightarrow W$  is mono if and only if it is injective. That injectivity implies monomorphicity is obvious because any linear map is in particular a set function. To see that any linear monomorphism is injective, consider  $k$  as a vector space over itself. Then for any maps  $A, B: k \rightarrow V$ , we have

$$L \circ A = L \circ B \implies A = B.$$

In particular, for any  $a, b \in V$ , let  $A(1) = a$  and  $B(1) = b$ . Then

$$\begin{aligned} L(a) &= L(b) \\ L(A(1)) &= L(B(1)) \\ (L \circ A)(1) &= (L \circ B)(1) \\ L \circ A &= L \circ B \\ A &= B \\ A(1) &= B(1) \\ a &= b. \end{aligned}$$

## Epimorphisms

The notion of a surjection can also be generalized. Pleasingly, it is more clear that epimorphisms are dual to monomorphisms than that surjectivity is dual to injectivity.

**Definition 18** (epimorphism). Let  $C$  be a category,  $A, B \in \text{Obj}(C)$ . A morphism  $f: A \rightarrow B$  is said to be a epimorphism if for all  $Z \in \text{Obj}(C)$  and all  $g_1, g_2: B \rightarrow Z$ ,  $g_1 \circ f = g_2 \circ f$  implies  $g_1 = g_2$ .

$$A \xrightarrow{f} B \xrightarrow[g_2]{g_1} Z.$$

*Notation 19.* We will denote epimorphisms by two-headed arrows. That is, if  $f: A \rightarrow B$  is epi, we will write

$$A \xrightarrow{f} \twoheadrightarrow B$$

**Theorem 20.** In  $\text{Set}$ , a morphism  $f$  is an epimorphism if and only if it is a surjection.

*Proof.* Suppose  $f: A \rightarrow B$  is an epimorphism. Then for any set  $Z$  and maps  $g_1, g_2: B \rightarrow Z$ , there  $g_1 \circ f = g_2 \circ f$  implies  $g_1 = g_2$ . In particular, this is true if  $Z = \{0, 1\}$ , and  $g_1$  and  $g_2$  are as follows.

$$g_1: b \mapsto 0 \quad \text{for all } b; \quad g_2: b \mapsto \begin{cases} 0, & b \in \text{im}(f) \\ 1, & b \notin \text{im}(f). \end{cases}$$

But then  $g_1 \circ f = g_2 \circ f$ , so  $g_1 = g_2$  since  $f$  is epi. Hence,  $\text{im}(f) = B$ , so  $f$  is surjective.

If  $f$  is surjective, then there exists a right inverse  $f^{-1}$  such that  $f^{-1} \circ f = \text{id}_A$ . Then

$$g_1 \circ f = g_2 \circ f \implies g_1 \circ f \circ f^{-1} = g_2 \circ f \circ f^{-1} \implies g_1 = g_2.$$

□

**Example 21.** In  $\text{Vect}_k$ , epimorphisms are surjective linear maps.

*Note 22.* In  $\text{Set}$ , we have the following correspondences.

- Isomorphism  $\iff$  Bijective
- Bijective  $\iff$  Injective & Surjective
- Injective & Surjective  $\iff$  Mono & Epi

Thus in  $\text{Set}$  a morphism is an isomorphism if and only if it is a monomorphism and an epimorphism. A very common mistake is to assume that this holds true in any category. This is wrong! A morphism can be monic and epic without being an isomorphism.

This occurs, for example, in the category  $\text{Top}$ , whose objects are topological spaces and whose morphisms are continuous maps. This is because of the following chain of reasoning.

- In order for a continuous map  $f$  to be monic, it is certainly sufficient that it be injective, since the injectivity of a function implies that for any other functions  $\alpha$  and  $\beta$ ,

$$f \circ \alpha = f \circ \beta \implies \alpha = \beta.$$

This certainly remains true if  $\alpha$  and  $\beta$  are taken from the subset of set-functions which are continuous. Thus in  $\text{Top}$ ,

$$\text{injective} \implies \text{monic}.$$

- Exactly analogous reasoning shows that in  $\text{Top}$ ,

$$\text{surjective} \implies \text{epic}.$$

- Thus, any continuous map which is bijective is both mono and epic in  $\text{Top}$ . However, there are continuous, bijective maps which are not isomorphisms! Take, for example, the map

$$[0, 2\pi) \rightarrow S^1 \subset \mathbb{R}^2; \quad x \mapsto (\cos x, \sin x).$$

This is clearly continuous and bijective, hence both a monomorphism and an epimorphism in  $\text{Top}$ . However, it has no inverse in  $\text{Top}$ : its inverse function is discontinuous at  $(1, 0) \in S^1$ , so it is not a morphism  $S^1 \rightarrow [0, 2\pi)$ .

## Smallness and local smallness

Set theory has some foundational annoyances. Among the most famous of these is Russel's paradox, which demonstrates that that not every collection of sets is small enough to be a set itself. Category theory has its own foundational issues, which for the most part we will avoid. However, there are a few important situations in which foundational questions of size play an unavoidably important role.

Recall that in our definition of a category, we said that objects and morphisms of a category need not fit inside a set; we only need them to form a 'collection.' We were cagy about what exactly we meant by this. The more precise statement is that they must form a *class*, although we will not have to worry about what a class is.

Using classes instead of sets works perfectly well. However, sets are better behaved than classes, and it is useful to have a special name for categories whose objects and/or morphisms *really* do fit into a set.

**Definition 23** (small, locally small, hom-set). A category  $C$  can have the following properties.

- We say that  $C$  is locally small if for all  $A, B \in \text{Obj}(C)$ ,  $\text{Hom}_C(A, B)$  is a set.
- We say that  $C$  is small if  $\text{Obj}(C)$  is a set and for all objects  $A, B \in \text{Obj}(C)$ ,  $\text{Hom}_C(A, B)$  is a set.

If we are working with a category which is locally small, so that  $\text{Hom}_C(A, B)$  is always a set, we call  $\text{Hom}_C(A, B)$  the hom-set. (Actually, terminology is often abused, and  $\text{Hom}_C(A, B)$  is called a hom-set even if it is not a set.)

**Example 24.** The category  $\text{Set}$  is locally small but not small.

## 1.2 Functors

Category theory is as fantastically useful as it is because of the ubiquity of the notion of a structure preserving map. Many interesting examples of categories arise by considering as objects some class of mathematical entities, and as morphisms the structure-preserving maps between them.

Categories are themselves mathematical objects, so it would be hypocritical not to look for the correct notion of a structure preserving map between them. This is called a functor.

**Definition 25** (functor). Let  $C$  and  $D$  be categories. A functor  $\mathcal{F}$  from  $C$  to  $D$  is the following.

- It assigns to each object  $X \in \text{Obj}(C)$  an object  $\mathcal{F}(X) \in \text{Obj}(D)$ .
- It assigns each morphism  $f \in \text{Hom}_C(X, Y)$  to a morphism  $\mathcal{F}(f) \in \text{Hom}(\mathcal{F}(X), \mathcal{F}(Y))$  in such a way that the following conditions are satisfied.
  - It maps identities to identities, i.e.

$$\mathcal{F}(\text{id}_X) = \text{id}_{\mathcal{F}(X)} \quad \text{for all } X \in \text{Obj}(C).$$

- It respects composition:

$$\mathcal{F}(g \circ f) = \mathcal{F}(g) \circ \mathcal{F}(f).$$

*Notation 26.* We will typeset functors with calligraphic letters, and notate them with squiggly arrows. For example, if  $C$  and  $D$  are categories and  $\mathcal{F}$  is a functor from  $C$  to  $D$ , then we would write

$$\mathcal{F}: C \rightsquigarrow D.$$

Later, when we confront the idea that functors are really just morphisms in the category of categories, we will stop using the squiggly-arrow notation and denote functors with straight arrows. For now, however, it will be helpful to keep morphisms straight from functors.

### 1.2.1 Examples

**Example 27.** Let  $1$  be the category with one object  $*$  (Example 4). Let  $C$  be any category. Then for each  $X \in \text{Obj}(C)$ , we have the functor

$$\mathcal{F}_X: 1 \rightsquigarrow C; \quad \mathcal{F}(*) = X, \quad \mathcal{F}(\text{id}_*) = \text{id}_X.$$

There is a special name for functors whose domain is a product category.

**Definition 28** (bifunctor). A bifunctor is a functor whose domain is a product category (Definition 9).

**Example 29.** The Cartesian product of sets is a bifunctor

$$\times: \text{Set} \times \text{Set} \rightarrow \text{Set},$$

which sends an object (i.e. a pair of sets)  $(A, B)$  to its Cartesian product  $A \times B$ , and sends a morphism

$$(f, g): (A, B) \rightarrow (C, D)$$

to a morphism

$$f \times g: A \times B \rightarrow C \times D; \quad (a, b) \mapsto (f(a), g(b)).$$

Checking that this respects composition and sends identities to identities is not at all tricky.

**Example 30.** Let  $G$  be a group, and  $V$  a vector space over some field  $k$ . A *representation*  $\rho$  of  $G$  on  $V$  assigns to each  $g \in G$  a linear transformation  $\rho(g): V \rightarrow V$  such that

$$\rho(gh) = \rho(g) \cdot \rho(h).$$

Let  $G$  be a group. Recall Example 7, in which we constructed from a group  $G$  a category  $G$  with one object  $*$ , whose morphisms  $\text{Hom}_G(*, *)$  were given by the elements of  $G$ .

Then functors  $\rho: G \rightsquigarrow \text{Vect}_k$  are  $k$ -linear representations of  $G$ !

To see this, let us unwrap the definition. The functor  $\rho$  assigns to  $* \in \text{Obj}(G)$  an object  $\rho(*) = V \in \text{Obj}(\text{Vect})$ , and to each morphism  $g: * \rightarrow *$  a morphism  $\rho(g): V \rightarrow V$ . Furthermore,  $\rho$  must respect composition in the sense that

$$\rho(g \cdot h) = \rho(g) \cdot \rho(h).$$

But this means precisely that  $\rho$  is a representation of  $G$ .

**Example 31.** Recall that  $\text{Grp}$  is the category of groups. Denote by  $\text{CRing}$  the category of commutative rings.

The following are functors  $\text{CRing} \rightsquigarrow \text{Grp}$ .

- $\text{GL}_n$ , which assigns to each commutative ring  $K$  the group of all  $n \times n$  invertible matrices with entries in  $K$ , and to each commutative ring homomorphism  $f: K \rightarrow K'$  a map

$$\text{GL}_n(f): \text{GL}_n(K) \rightarrow \text{GL}_n(K'); \quad \begin{pmatrix} a_{11} & \cdots & a_{nn} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \mapsto \begin{pmatrix} f(a_{11}) & \cdots & f(a_{nn}) \\ \vdots & \ddots & \vdots \\ f(a_{n1}) & \cdots & f(a_{nn}) \end{pmatrix}.$$

- $(\cdot)^*$ , which maps each commutative ring  $K$  to its group of units  $K^*$ , and each morphism  $K \rightarrow K'$  to its restriction to  $K^*$ .

## 1.2.2 Properties of functors

### Full, faithful, and essentially surjective

**Definition 32** (full, faithful). Let  $\mathcal{C}$  and  $\mathcal{D}$  be locally small categories (Definition 23), and let  $\mathcal{F}: \mathcal{C} \rightsquigarrow \mathcal{D}$ . Then  $\mathcal{F}$  induces a family of set-functions

$$\mathcal{F}_{X,Y}: \text{Hom}_{\mathcal{C}}(X, Y) \rightarrow \text{Hom}_{\mathcal{D}}(\mathcal{F}(X), \mathcal{F}(Y)).$$

We say that  $\mathcal{F}$  is

- full if  $\mathcal{F}_{X,Y}$  is surjective for all  $X, Y \in \text{Obj}(\mathcal{C})$
- faithful if  $\mathcal{F}_{X,Y}$  is injective for all  $X, Y \in \text{Obj}(\mathcal{C})$ ,
- fully faithful if  $\mathcal{F}$  is full and faithful.

*Note 33.* Fullness and faithfulness are *not* the functorial analogs of surjectivity and injectivity. A functor between small categories can be full (resp. faithful) without being surjective (resp. injective) on objects. Instead, we have the following result.

**Lemma 34.** A fully faithful functor is injective on objects up to isomorphism. That is, if  $\mathcal{F}: \mathcal{C} \rightsquigarrow \mathcal{D}$  is a fully faithful functor and  $\mathcal{F}(A) \simeq \mathcal{F}(B)$ , then  $A \simeq B$ .

*Proof.* Let  $\mathcal{F}: \mathcal{C} \rightsquigarrow \mathcal{D}$  be a fully faithful functor, and suppose that  $\mathcal{F}(A) \simeq \mathcal{F}(B)$ . Then there exist  $f': \mathcal{F}(A) \rightarrow \mathcal{F}(B)$  and  $g': \mathcal{F}(B) \rightarrow \mathcal{F}(A)$  such that  $f' \circ g' = \text{id}_{\mathcal{F}(B)}$  and  $g' \circ f' = \text{id}_{\mathcal{F}(A)}$ . Because the function  $\mathcal{F}_{A,B}$  is bijective it is invertible, so there is a unique morphism  $f \in \text{Hom}_{\mathcal{C}}(A, B)$  such that  $\mathcal{F}(f) = f'$ , and similarly there is a unique  $g \in \text{Hom}_{\mathcal{C}}(B, A)$  such that  $\mathcal{F}(g) = g'$ .

Now,

$$\text{id}_{\mathcal{F}(A)} = g' \circ f' = \mathcal{F}(g) \circ \mathcal{F}(f) = \mathcal{F}(g \circ f),$$

and since  $\mathcal{F}$  is injective, we must have  $g \circ f = \text{id}_A$ . Identical logic shows that we must also have  $f \circ g = \text{id}_B$ . Thus  $A \simeq B$ .  $\square$

It now makes sense to define a different functorial version of surjectivity.

**Definition 35** (essentially surjective). A functor  $\mathcal{F}: \mathcal{C} \rightsquigarrow \mathcal{D}$  is essentially surjective if for every  $A' \in \text{Obj}(\mathcal{D})$ , there exists  $A \in \text{Obj}(\mathcal{C})$  such that  $A' \simeq \mathcal{F}(A)$ .

## Covariance and contravariance

What we have called simply a *functor*, many people would call a *covariant functor*. These people would say that there is a second kind of functor, called a *contravariant functor*, which flips arrows around. That is, applying a contravariant functor  $\mathcal{F}$  to a morphism  $f: A \rightarrow B$ , one would find a morphism

$$\mathcal{F}(f): \mathcal{F}(B) \rightarrow \mathcal{F}(A).$$

In order to respect compositions, these people say, a contravariant functor must obey the modified composition rule

$$\mathcal{F}(g \circ f) = \mathcal{F}(f) \circ \mathcal{F}(g).$$

We are choosing not to use the notion of a contravariant functor, and for a good reason: we don't need it! Recall the so-called opposite category ([Definition 8](#)). Roughly speaking, the opposite to a category is a category in which arrows go the other way.

A contravariant functor  $\mathcal{F}: \mathcal{C} \rightsquigarrow \mathcal{D}$ , then, can be thought of as a *covariant* (i.e. ordinary) functor  $\mathcal{F}: \mathcal{C}^{\text{op}} \rightsquigarrow \mathcal{D}$ . This turns out to be much simpler and more convenient than dealing with two kinds of functors all the time.

**Definition 36** (contravariant functor). A contravariant functor  $\mathcal{F}: \mathcal{C} \rightsquigarrow \mathcal{D}$  is simply a (covariant) functor  $\mathcal{F}\mathcal{C}^{\text{op}} \rightsquigarrow \mathcal{D}$ .

## 1.3 Natural transformations

Saunders Mac Lane, one of the fathers of category theory, used to say that he invented categories so he could talk about functors, and he invented functors so he could talk about natural transformations. Indeed, arguably the first paper ever published on category theory, published by Eilenberg and Mac Lane in 1945 and titled “General Theory of Natural Equivalences.” [\[23\]](#), was about natural transformations.

Natural transformation can be viewed in several ways. At their most abstract, they provide a notion of ‘morphisms between functors,’ and indeed we will later define a category whose objects are functors between two categories and whose morphisms are natural transformations. More concretely, however, they often provide a rigorous definition of canonicalness.

For example, one often hears the statement “For any two sets  $A$  and  $B$ ,  $A \times B$  is isomorphic to  $B \times A$ .” This is certainly true, but not very meaningful; any two sets with the same number of elements are canonical. What one is trying to say is that  $A \times B$  and  $B \times A$  are *canonically* isomorphic. The question is: what exactly is meant by ‘canonical’?

This is a surprisingly elusive question. Between any two sets  $A$  and  $B$ , there is an obvious map

$$\text{swap}_{A,B}: A \times B \rightarrow B \times A; \quad (a, b) \mapsto (b, a).$$

However, between two different pairs of sets, there is a different swap function. How is one to say that these are really the same functions?



One way is to say that this swap function must commute with functional evaluation. Notice that for *any* functions  $f: A \rightarrow C$  and  $g: B \rightarrow D$ , the following diagram commutes.

$$\begin{array}{ccc}
 A \times B & \xrightarrow{(f,g)} & C \times D \\
 \downarrow \text{swap}_{A,B} & & \downarrow \text{swap}_{C,D} \\
 B \times A & \xrightarrow{(g,f)} & D \times C
 \end{array}$$

$(a, b) \mapsto (f(a), g(b))$   
 $\downarrow \qquad \qquad \downarrow$   
 $(b, a) \mapsto (g(b), f(a))$

That is to say, it doesn't matter whether you use first embed<sup>5</sup>  $A \times B$  into  $C \times D$  and then use the swap isomorphism, or whether you do the swap first and then use embed  $B \times A$  into  $D \times C$ ; you get the same map either way. Furthermore, this is true for *any* embeddings  $f$  and  $g$ .

As we have seen (in [Example 29](#)), the cartesian product of sets is a functor from the product category ([Definition 9](#))  $\text{Set} \times \text{Set}$  to  $\text{Set}$  which maps  $(A, B)$  to  $A \times B$ . There is another functor  $\text{Set} \times \text{Set} \rightsquigarrow \text{Set}$  which sends  $(A, B)$  to  $B \times A$ . The above discussion means that there is a natural isomorphism, called swap, between them.

This example makes clear a common theme of natural transformations: they formalize the idea of 'the same function' between different objects. They allow us to make precise statements like 'swap<sub>A,B</sub> and swap<sub>C,D</sub> are somehow the same, despite the fact that they cannot be equal as functions.'

## Definitions and elementary examples

**Definition 37** (natural transformation). let  $\mathcal{C}$  and  $\mathcal{D}$  be categories, and let  $\mathcal{F}$  and  $\mathcal{G}$  be functors from  $\mathcal{C}$  to  $\mathcal{D}$ . A natural transformation  $\eta$  between  $\mathcal{F}$  and  $\mathcal{G}$  consists of

- for each object  $A \in \text{Obj}(\mathcal{C})$  a morphism  $\eta_A: \mathcal{F}(A) \rightarrow \mathcal{G}(A)$ , such that
- for all  $A, B \in \text{Obj}(\mathcal{C})$ , for each morphism  $f \in \text{Hom}(A, B)$ , the diagram

$$\begin{array}{ccc}
 \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B) \\
 \eta_A \downarrow & & \downarrow \eta_B \\
 \mathcal{G}(A) & \xrightarrow{\mathcal{G}(f)} & \mathcal{G}(B)
 \end{array}$$

commutes.

**Definition 38** (natural isomorphism). A natural isomorphism  $\eta: \mathcal{F} \Rightarrow \mathcal{G}$  is a natural transformation such that each  $\eta_A$  is an isomorphism.

*Notation 39.* We will use double-shafted arrows to denote natural transformations: if  $\mathcal{F}$  and  $\mathcal{G}$  are functors and  $\eta$  is a natural transformation from  $\mathcal{F}$  to  $\mathcal{G}$ , we will write

$$\eta: \mathcal{F} \Rightarrow \mathcal{G}.$$

<sup>5</sup>The word embedding here is meant to be evocative rather than literal;  $f$  and  $g$  don't have to be injective.

**Lemma 40.** Given a natural isomorphism  $\eta: \mathcal{F} \Rightarrow \mathcal{G}$ , we can construct an inverse natural isomorphism  $\eta^{-1}: \mathcal{G} \Rightarrow \mathcal{F}$ .

*Proof.* The natural transformation gives us for any two objects  $A$  and  $B$  and morphism  $f: A \rightarrow B$  a naturality square

$$\begin{array}{ccc} \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B) \\ \eta_A \downarrow & & \downarrow \eta_B \\ \mathcal{G}(A) & \xrightarrow{\mathcal{G}(f)} & \mathcal{G}(B) \end{array}$$

which tells us that

$$\eta_B \circ \mathcal{F}(f) = \mathcal{G}(f) \circ \eta_A.$$

Since  $\eta$  is a natural isomorphism, its components  $\eta_A$  are isomorphisms, so they have inverses  $\eta_A^{-1}$ . Acting on the above equation with  $\eta_A^{-1}$  from the right and  $\eta_B^{-1}$  from the left, we find

$$\mathcal{F}(f) \circ \eta_A^{-1} = \eta_B^{-1} \circ \mathcal{G}(f),$$

i.e. the following diagram commutes.

$$\begin{array}{ccc} \mathcal{G}(A) & \xrightarrow{\mathcal{G}(f)} & \mathcal{G}(B) \\ \eta_A^{-1} \downarrow & & \downarrow \eta_B^{-1} \\ \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B) \end{array}$$

But this is just the naturality square for a natural isomorphism  $\eta^{-1}$  with components  $(\eta^{-1})_A = \eta_A^{-1}$ . □

**Example 41** (the determinant). Recall the functors  $\mathrm{GL}_n$  and  $(\cdot)^*$  from [Example 31](#).

Denote by  $\det_K M$  the determinant of a matrix  $M$  with its entries in a commutative ring  $K$ . Then the determinant is a map

$$\det_K: \mathrm{GL}_n(K) \rightarrow K^*.$$

Because the determinant is defined by the same formula for each  $K$ , the action of  $f$  commutes with  $\det_K$ : it doesn't matter whether we map the entries of  $M$  with  $f$  first and then take the determinant, or take the determinant first and then feed the result to  $f$ .

That is to say, the following diagram commutes.

$$\begin{array}{ccc} \mathrm{GL}_n(K) & \xrightarrow{\det_K} & K^* \\ \mathrm{GL}_n(f) \downarrow & & \downarrow f^* \\ \mathrm{GL}_n(K') & \xrightarrow{\det_{K'}} & K'^* \end{array}$$

This means that  $\det$  is a natural transformation  $\mathrm{GL}_n \Rightarrow (\cdot)^*$ .

**Example 42** (intertwiners and scattering theory). Let  $G$  be a group,  $\mathcal{G}$  the category which mimics it, and let  $\rho$  and  $\rho': \mathcal{G} \rightsquigarrow \mathbf{Vect}$  be representations (recall [Example 30](#)). Let  $\rho(*) = V$  and  $\rho'(*) = W$ .

A natural transformation  $\eta: \rho \Rightarrow \rho'$  is called an *intertwiner*. So what is an intertwiner?

The natural transformation  $\eta$  has only one component,  $\eta_*: V \rightarrow W$ , which is subject to the condition that for any  $g \in \text{Hom}_G(*, *)$ , the diagram below commutes.

$$\begin{array}{ccc} V & \xrightarrow{\rho(g)} & V \\ \eta_* \downarrow & & \downarrow \eta_* \\ W & \xrightarrow{\rho'(g)} & W \end{array}$$

That is, an intertwiner is a linear map  $V \rightarrow W$  such that for all  $g$ ,

$$\eta_* \circ \rho(g) = \rho'(g) \circ \eta_*.$$

Intertwiners are extremely important in high-energy physics.

In scattering theory one models the state of the world as  $T \rightarrow -\infty$  as a composite system of several incoming free particles, and as  $T \rightarrow +\infty$  a composite system of outgoing free particles. Therefore, the Hilbert space of the incoming particles is

$$\mathcal{H}_{\text{in}} = \mathcal{H}_{1,\text{in}} \otimes \cdots \otimes \mathcal{H}_{m,\text{in}}$$

and that of the outgoing particles is

$$\mathcal{H}_{\text{out}} = \mathcal{H}_{1,\text{out}} \otimes \cdots \otimes \mathcal{H}_{n,\text{out}}.$$

In relativistic quantum mechanics, the Hilbert space of a free particle alone in the world is the representation space of some irreducible representation of the Poincaré group. The action of the Poincaré group on this representation space implements Poincaré transformations on the particle. For a system of several particles, the Poincaré group acts on the incoming and outgoing Hilbert spaces via the tensor product representation.

Scattering theory finds a map  $U: \mathcal{H}_{\text{in}} \rightarrow \mathcal{H}_{\text{out}}$ , which interpolates between incoming states and outgoing states. However, not any linear map will do; since we demand that our laws be Poincaré-invariant, we want our transformation to be Poincaré-equivariant. Therefore, we want scattering theory to produce for us a map  $U: \mathcal{H}_{\text{in}} \rightarrow \mathcal{H}_{\text{out}}$  such that the diagram

$$\begin{array}{ccc} \mathcal{H}_{\text{in}} & \xrightarrow{\rho_{\text{in}}(g)} & \mathcal{H}_{\text{in}} \\ U \downarrow & & \downarrow U \\ \mathcal{H}_{\text{out}} & \xrightarrow{\rho_{\text{out}}(g)} & \mathcal{H}_{\text{out}} \end{array}$$

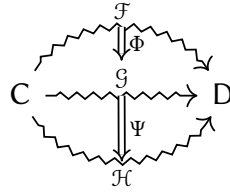
commutes.

That is, scattering theory produces intertwiners between the incoming and outgoing representations  $\rho_{\text{in}}$  and  $\rho_{\text{out}}$  of the Poincaré group.

## Vertical composition

We mentioned earlier that one could define a category whose objects were functors and whose morphisms were natural transformations. We are now going to make good on that threat. In order to do so, we need only specify how to compose natural transformations. The correct notion is known as *vertical composition*.

**Lemma 43.** Let  $C$  and  $D$  be categories,  $\mathcal{F}, \mathcal{G}, \mathcal{H}$  be functors, and  $\Phi$  and  $\Psi$  be natural transformations as follows.



This induces a natural transformation  $\mathcal{F} \Rightarrow \mathcal{H}$ .

*Proof.* For each object  $A \in \text{Obj}(C)$ , the composition  $\Psi_A \circ \Phi_A$  exists and maps  $\mathcal{F}(A) \rightarrow \mathcal{H}(A)$ . Let's write

$$\Psi_A \circ \Phi_A = (\Psi \circ \Phi)_A.$$

We have to show that these are the components of a natural transformation, i.e. that they make the following diagram commute for all  $A, B \in \text{Obj}(C)$ , all  $f : A \rightarrow B$ .

$$\begin{array}{ccc} \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B) \\ (\Psi \circ \Phi)_A \downarrow & & \downarrow (\Psi \circ \Phi)_B \\ \mathcal{H}(A) & \xrightarrow{\mathcal{H}(f)} & \mathcal{H}(B) \end{array}$$

We can do this by adding a middle row.

$$\begin{array}{ccc} \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B) \\ \Phi_A \downarrow & & \downarrow \Phi_B \\ \mathcal{G}(A) & \xrightarrow{\mathcal{G}(f)} & \mathcal{G}(B) \\ \Psi_A \downarrow & & \downarrow \Psi_B \\ \mathcal{H}(A) & \xrightarrow{\mathcal{H}(f)} & \mathcal{H}(B) \end{array}$$

The top and bottom squares are the naturality squares for  $\Phi$  and  $\Psi$  respectively. The outside square is the one we want to commute, and it manifestly does because each of the inside squares does.  $\square$

**Definition 44** (vertical composition). The above composition  $\Psi \circ \Phi$  is called vertical composition.

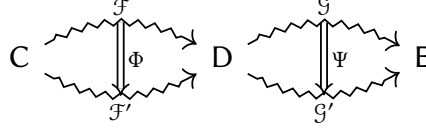
We can now define, for any categories  $C$  and  $D$ , a category whose objects are functors  $C \rightsquigarrow D$  and whose morphisms are natural transformations.

**Definition 45** (functor category). Let  $C$  and  $D$  be categories. The functor category  $\text{Func}(C, D)$  (sometimes  $D^C$  or  $[C, D]$ ) is the category whose objects are functors  $C \rightsquigarrow D$ , and whose morphisms are natural transformations between them. The composition is given by vertical composition.

## Horizontal composition

We can also compose natural transformations in a not so obvious way.

**Lemma 46.** *Consider the following arrangement of categories, functors, and natural transformations.*



*This induces a natural transformation  $G \circ F \Rightarrow G' \circ F'$ .*

*Proof.* By definition,  $\Phi$  and  $\Psi$  make the diagrams

$$\begin{array}{ccc} \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B) \\ \Phi_A \downarrow & & \downarrow \Phi_B \\ \mathcal{F}'(A) & \xrightarrow{\mathcal{F}'(f)} & \mathcal{F}'(B) \end{array} \quad \text{and} \quad \begin{array}{ccc} \mathcal{G}(A) & \xrightarrow{\mathcal{G}(f)} & \mathcal{G}(B) \\ \Psi_A \downarrow & & \downarrow \Psi_B \\ \mathcal{G}'(A) & \xrightarrow{\mathcal{G}'(f)} & \mathcal{G}'(B) \end{array}$$

commute. Since functors respect composition they take commutative diagrams to commutative diagrams, so if we map everything in the first diagram to E with  $\mathcal{G}$  to get another commutative diagram in E.

$$\begin{array}{ccc} (\mathcal{G} \circ \mathcal{F})(A) & \xrightarrow{(\mathcal{G} \circ \mathcal{F})(f)} & (\mathcal{G} \circ \mathcal{F})(B) \\ \mathcal{G}(\Phi_A) \downarrow & & \downarrow \mathcal{G}(\Phi_B) \\ (\mathcal{G} \circ \mathcal{F}')(A) & \xrightarrow{(\mathcal{G} \circ \mathcal{F}')(f)} & (\mathcal{G} \circ \mathcal{F}')(B) \end{array}$$

Since  $\mathcal{F}'(f): \mathcal{F}'(A) \rightarrow \mathcal{F}'(B)$  is a morphism in D and  $\Psi$  is a natural transformation, the following diagram commutes.

$$\begin{array}{ccc} (\mathcal{G} \circ \mathcal{F}')(A) & \xrightarrow{(\mathcal{G} \circ \mathcal{F}')(f)} & (\mathcal{G} \circ \mathcal{F}')(B) \\ \Psi_{\mathcal{F}'(A)} \downarrow & & \downarrow \Psi_{\mathcal{F}'(B)} \\ (\mathcal{G}' \circ \mathcal{F}')(A) & \xrightarrow{(\mathcal{G}' \circ \mathcal{F}')(f)} & (\mathcal{G}' \circ \mathcal{F}')(B) \end{array}$$

Sticking these two diagrams on top of each other gives a new commutative diagram.

$$\begin{array}{ccc} (\mathcal{G} \circ \mathcal{F})(A) & \xrightarrow{(\mathcal{G} \circ \mathcal{F})(f)} & (\mathcal{G} \circ \mathcal{F})(B) \\ \mathcal{G}(\Phi_A) \downarrow & & \downarrow \mathcal{G}(\Phi_B) \\ (\mathcal{G} \circ \mathcal{F}')(A) & \xrightarrow{(\mathcal{G} \circ \mathcal{F}')(f)} & (\mathcal{G} \circ \mathcal{F}')(B) \\ \Psi_{\mathcal{F}'(A)} \downarrow & & \downarrow \Psi_{\mathcal{F}'(B)} \\ (\mathcal{G}' \circ \mathcal{F}')(A) & \xrightarrow{(\mathcal{G}' \circ \mathcal{F}')(f)} & (\mathcal{G}' \circ \mathcal{F}')(B) \end{array}$$

The outside rectangle is nothing else but the commuting square for a natural transformation

$$(\Psi * \Phi): \mathcal{G} \circ \mathcal{F} \Rightarrow \mathcal{G}' \circ \mathcal{F}'$$

with components  $(\Psi * \Phi)_A = \Psi_{\mathcal{F}(A)} \circ \mathcal{G}(\Phi_A)$ .  $\square$

**Definition 47** (horizontal composition). The natural transformation  $\Psi * \Phi$  defined above is called the horizontal composition of  $\Phi$  and  $\Psi$ .

One might worry the above definition of the horizontal composition is lopsided. Why did we apply the functor  $\mathcal{G}$  to the first square rather than  $\mathcal{G}'$ ? It becomes less so if we notice the following. The first step in our construction of  $\Psi * \Phi$  was to apply the functor  $\mathcal{G}$  to the commutative diagram

$$\begin{array}{ccc} \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B) \\ \Phi_A \downarrow & & \downarrow \Phi_B \\ \mathcal{F}'(A) & \xrightarrow{\mathcal{F}'(f)} & \mathcal{F}'(B) \end{array} .$$

We could instead have applied the functor  $\mathcal{G}'$ , giving us the following.

$$\begin{array}{ccc} (\mathcal{G}' \circ \mathcal{F})(A) & \xrightarrow{(\mathcal{G}' \circ \mathcal{F})(f)} & (\mathcal{G}' \circ \mathcal{F})(B) \\ \mathcal{G}'(\Phi_A) \downarrow & & \downarrow \mathcal{G}'(\Phi_B) \\ (\mathcal{G}' \circ \mathcal{F}')(A) & \xrightarrow{(\mathcal{G}' \circ \mathcal{F}')(f)} & (\mathcal{G}' \circ \mathcal{F}')(B) \end{array}$$

Then we could have glued to it the bottom of the following commuting square.

$$\begin{array}{ccc} (\mathcal{G} \circ \mathcal{F})(A) & \xrightarrow{(\mathcal{G} \circ \mathcal{F})(f)} & (\mathcal{G} \circ \mathcal{F})(B) \\ \Psi_{\mathcal{F}(A)} \downarrow & & \downarrow \Psi_{\mathcal{F}(B)} \\ (\mathcal{G}' \circ \mathcal{F})(A) & \xrightarrow{(\mathcal{G}' \circ \mathcal{F})(f)} & (\mathcal{G}' \circ \mathcal{F})(B) \end{array}$$

If you do this you get *another* natural transformation  $\mathcal{G} \circ \mathcal{F} \Rightarrow \mathcal{G}' \circ \mathcal{F}'$ , with components  $\mathcal{G}'(\Phi_A) \circ \Psi_{\mathcal{F}(A)}$ . Why did we use the first definition rather than this one?

It turns out that  $\Psi_{\mathcal{F}(A)} \circ \mathcal{G}(\Phi_A)$  and  $\mathcal{G}'(\Phi_A) \circ \Psi_{\mathcal{F}(A)}$  are equal. To see this, pick any  $A \in \text{Obj}(\mathcal{A})$ . From the morphism

$$\Phi_A: \mathcal{F}(A) \rightarrow \mathcal{F}'(A),$$

the natural transformation  $\Psi$  gives us a commuting square

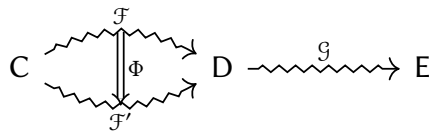
$$\begin{array}{ccc} (\mathcal{G} \circ \mathcal{F})(A) & \xrightarrow{\mathcal{G}(\Phi_A)} & (\mathcal{G} \circ \mathcal{F}')(A) \\ \Psi_{\mathcal{F}(A)} \downarrow & & \downarrow \Psi_{\mathcal{F}'(A)} \\ (\mathcal{G}' \circ \mathcal{F})(A) & \xrightarrow{\mathcal{G}'(\Phi_A)} & (\mathcal{G}' \circ \mathcal{F}')(A) \end{array} ;$$

the two ways of going from top left to bottom right are nothing else but  $\Psi_{\mathcal{F}(A)} \circ \mathcal{G}(\Phi_A)$  and  $\mathcal{G}'(\Phi_A) \circ \Psi_{\mathcal{F}(A)}$ .

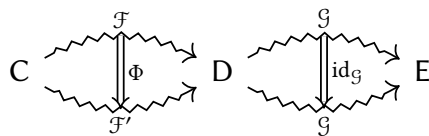
## Whiskering

We will mainly be interested in a special case of horizontal composition, in which one of the natural transformations is the identity natural transformation:

**Example 48** (whiskering). Consider the following assemblage of categories, functors, and natural transformations.



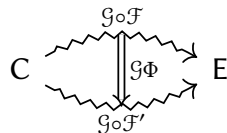
The horizontal composition allows us to  $\Phi$  to a natural transformation  $\mathcal{G} \circ \mathcal{F}$  to  $\mathcal{G} \circ \mathcal{F}'$  as follows. First, augment the diagram as follows.



We can then take the horizontal composition of  $\Phi$  and  $\text{id}_G$  to get a natural transformation from  $\mathcal{G} \circ \mathcal{F}$  to  $\mathcal{G} \circ \mathcal{F}'$  with components

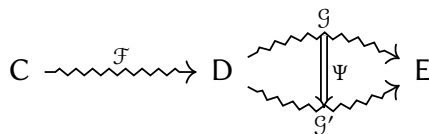
$$(\text{id}_G * \Phi)_A = \mathcal{G}(\Phi_A).$$

This natural transformation is called the *right whiskering* of  $\Phi$  with  $\mathcal{G}$ , and is denoted  $\mathcal{G}\Phi$ . That is to say,  $(\mathcal{G}\Phi)_A = \mathcal{G}(\Phi_A)$ .



The reason for the name is clear: we removed a whisker from the RHS of our diagram.

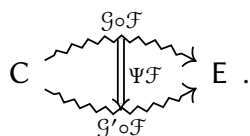
We can also remove a whisker from the LHS. Given this:



we can build a natural transformation (denoted  $\Psi\mathcal{F}$ ) with components

$$(\Psi\mathcal{F})_A = \Psi_{\mathcal{F}(A)},$$

making this:



This is called the *left whiskering* of  $\Psi$  with  $\mathcal{F}$

We would like to be able to express when two categories are the ‘same.’ The correct notion of sameness is provided by the following definition.

## Categorical equivalence

**Definition 49** (categorical equivalence). Let  $C$  and  $D$  be categories. We say that  $C$  and  $D$  are equivalent if there is a pair of functors

$$C \begin{array}{c} \xrightarrow{\mathcal{F}} \\ \xleftarrow{\mathcal{G}} \end{array} D$$

and natural isomorphisms  $\eta: \mathcal{F} \circ \mathcal{G} \Rightarrow \text{id}_C$  and  $\varphi: \text{id}_D \Rightarrow \mathcal{G} \circ \mathcal{F}$ .

*Note 50.* The above definition of categorical equivalence is equivalent to the following:  $C$  and  $D$  are equivalent if there is a functor  $\mathcal{F}: C \rightsquigarrow D$  which is fully faithful ([Definition 32](#)) and essentially surjective ([Definition 35](#)). That is to say, if the equivalence  $\mathcal{F}$  is ‘bijective up to isomorphism.’

**Definition 51** (essentially small category). A category  $C$  is said to be essentially small if it is equivalent to a small category ([Definition 23](#)).

## 1.4 Some special categories

### 1.4.1 Comma categories

**Definition 52** (comma category). Let  $A, B, C$  be categories,  $\mathcal{S}$  and  $\mathcal{T}$  functors as follows.

$$A \begin{array}{c} \xrightarrow{\mathcal{S}} \\ \xleftarrow{\mathcal{T}} \end{array} C \begin{array}{c} \xrightarrow{\mathcal{T}} \\ \xleftarrow{\mathcal{S}} \end{array} B$$

The comma category  $(\mathcal{S} \downarrow \mathcal{T})$  is the category whose

- objects are triples  $(\alpha, \beta, f)$  where  $\alpha \in \text{Obj}(A)$ ,  $\beta \in \text{Obj}(B)$ , and  $f \in \text{Hom}_C(\mathcal{S}(\alpha), \mathcal{T}(\beta))$ , and whose
- morphisms  $(\alpha, \beta, f) \rightarrow (\alpha', \beta', f')$  are all pairs  $(g, h)$ , where  $g: \alpha \rightarrow \alpha'$  and  $h: \beta \rightarrow \beta'$ , such that the diagram

$$\begin{array}{ccc} \mathcal{S}(\alpha) & \xrightarrow{\mathcal{S}(g)} & \mathcal{S}(\alpha') \\ f \downarrow & & \downarrow f' \\ \mathcal{T}(\beta) & \xrightarrow{\mathcal{T}(h)} & \mathcal{T}(\beta') \end{array}$$

commutes.

*Notation 53.* We will often specify the comma category  $(\mathcal{S} \downarrow \mathcal{T})$  by simply writing down the diagram

$$A \begin{array}{c} \xrightarrow{\mathcal{S}} \\ \xleftarrow{\mathcal{T}} \end{array} C \begin{array}{c} \xrightarrow{\mathcal{T}} \\ \xleftarrow{\mathcal{S}} \end{array} B .$$

Let us check in some detail that a comma category really is a category. To do so, we need to check the three properties listed in [Definition 1](#)

1. We must be able to compose morphisms, i.e. we must have the following diagram.

$$\begin{array}{ccccc} & & (g', h') \circ (g, h) & & \\ & \searrow & \curvearrowright & \searrow & \\ (\alpha, \beta, f) & \xrightarrow{(g, h)} & (\alpha', \beta', f') & \xrightarrow{(g', h')} & (\alpha'', \beta'', f'') \end{array}$$



We certainly do, since by definition, each square of the following diagram commutes,

$$\begin{array}{ccccc} \mathcal{S}(\alpha) & \xrightarrow{\mathcal{S}(g)} & \mathcal{S}(\alpha') & \xrightarrow{\mathcal{S}(g')} & \mathcal{S}(\alpha'') \\ f \downarrow & & f' \downarrow & & \downarrow f'' \\ \mathcal{T}(\alpha) & \xrightarrow{\mathcal{T}(h)} & \mathcal{T}(\alpha') & \xrightarrow{\mathcal{T}(h')} & \mathcal{T}(\alpha'') \end{array}$$

so the square formed by taking the outside rectangle

$$\begin{array}{ccc} \mathcal{S}(\alpha) & \xrightarrow{\mathcal{S}(g') \circ \mathcal{S}(g)} & \mathcal{S}(\alpha'') \\ f \downarrow & & \downarrow f'' \\ \mathcal{T}(\alpha) & \xrightarrow{\mathcal{T}(h') \circ \mathcal{T}(h)} & \mathcal{T}(\alpha'') \end{array}$$

commutes. But  $\mathcal{S}$  and  $\mathcal{T}$  are functors, so

$$\mathcal{S}(g') \circ \mathcal{S}(g) = \mathcal{S}(g' \circ g),$$

and similarly for  $\mathcal{T}(h' \circ h)$ . Thus, the composition of morphisms is given via

$$(g', h') \circ (g, h) = (g' \circ g, h' \circ h).$$

2. We can see from this definition that associativity in  $(\mathcal{S} \downarrow \mathcal{T})$  follows from associativity in the underlying categories  $A$  and  $B$ .
3. The identity morphism is the pair  $(\text{id}_{\mathcal{S}(\alpha)}, \text{id}_{\mathcal{T}(\beta)})$ . It is trivial from the definition of the composition of morphisms that this morphism functions as the identity morphism.

### 1.4.2 Slice categories

A special case of a comma category, the so-called *slice category*, occurs when  $C = A$ ,  $\mathcal{S}$  is the identity functor, and  $B = 1$ , the category with one object and one morphism ([Example 4](#)).

**Definition 54** (slice category). A slice category is a comma category

$$A \xrightarrow{\text{id}_A} A \xleftarrow{\mathcal{T}} 1.$$

Let us unpack this prescription. Taking the definition literally, the objects in our category are triples  $(\alpha, \beta, f)$ , where  $\alpha \in \text{Obj}(A)$ ,  $\beta \in \text{Obj}(1)$ , and  $f \in \text{Hom}_A(\text{id}_A(\alpha), \mathcal{T}(\beta))$ .

There's a lot of extraneous information here, and our definition can be consolidated considerably. Since the functor  $\mathcal{T}$  is given and  $1$  has only one object (call it  $*$ ), the object  $\mathcal{T}(\beta)$  (call it  $X$ ) is singled out in  $A$ . We can think of  $\mathcal{T}$  as  $\mathcal{F}_X$  ([Example 27](#)). Similarly, since the identity morphism doesn't do anything interesting, Therefore, we can collapse the following diagram considerably.

$$\begin{array}{ccc} \mathcal{F}_X(*) & \xrightarrow{\mathcal{F}_X(\text{id}_*)} & \mathcal{F}_X(*) \\ f \downarrow & & \downarrow f' \\ \text{id}_A(\alpha) & \xrightarrow{\text{id}_A(g)} & \text{id}_A(\alpha') \end{array}$$

The objects of a slice category therefore consist of pairs  $(\alpha, f)$ , where  $\alpha \in \text{Obj}(A)$  and

$$f : \alpha \rightarrow X;$$

the morphisms  $(\alpha, f) \rightarrow (\alpha', f')$  consist of maps  $g : \alpha \rightarrow \alpha'$ . This allows us to define a slice category more neatly.

Let  $A$  be a category,  $X \in \text{Obj}(A)$ . The slice category  $(A \downarrow X)$  is the category whose objects are pairs  $(\alpha, f)$ , where  $\alpha \in \text{Obj}(A)$  and  $f : \alpha \rightarrow X$ , and whose morphisms  $(\alpha, f) \rightarrow (\alpha', f')$  are maps  $g : \alpha \rightarrow \alpha'$  such that the diagram

$$\begin{array}{ccc} \alpha & \xrightarrow{g} & \alpha' \\ & \searrow f & \swarrow f' \\ & X & \end{array}$$

commutes.

One can also define a coslice category, which is what you get when you take a slice category and turn the arrows around: coslice categories are *dual* to slice categories.

**Definition 55** (coslice category). Let  $A$  be a category,  $X \in \text{Obj}(A)$ . The coslice category  $(X \downarrow A)$  is the comma category given by the diagram

$$1 \xrightarrow{\mathcal{F}_X} A \xleftarrow{\text{id}_A} A.$$

The objects are morphisms  $f : X \rightarrow \alpha$  and the morphisms are morphisms  $g : \alpha \rightarrow \alpha'$  such that the diagram

$$\begin{array}{ccc} & X & \\ f \swarrow & & \searrow f' \\ \alpha & \xrightarrow{g} & \alpha' \end{array}$$

commutes.

## 1.5 Universal properties

In linear algebra, it is aesthetically preferable to avoid introducing an arbitrary basis every time one needs to prove something, instead using properties intrinsic to the vector space itself. This is arguably true in general: the prettiest way of working with a structure is to use only the information available from the category in which the structure lives. The definition of a product (of sets, for example) is best given without making use of hand-wavy statements like “ordered pairs of an element here and an element there.”

There is a very powerful way of defining objects using only category-theoretic information, called *universal properties*.

Universal properties are ubiquitous in mathematics. The reader, whether he or she is aware of it or not has almost certainly seen and used a few examples, such as the universal properties for products and tensor algebras. They are astonishingly useful.

For instance, suppose someone approaches you on the street late at night and tells you that they're going to steal your wallet unless you can write down a map  $\mathbb{R} \rightarrow \mathbb{R} \times \mathbb{R}$ . You write down

$$x \mapsto (x, x^2).$$

Your would-be mugger scoffs, saying "That's not a map  $\mathbb{R} \rightarrow \mathbb{R} \times \mathbb{R}$ . What you have really done is write down a pair of maps  $\mathbb{R} \rightarrow \mathbb{R}$ !"

You, however, are as cool as a cucumber. You calmly tell the thief "The universal property for the Cartesian product tells us that writing down a pair of maps  $\mathbb{R} \rightarrow \mathbb{R}$  is the same as writing down a map  $\mathbb{R} \rightarrow \mathbb{R} \times \mathbb{R}$ ." Your assailant leaves, dejected.

## Initial and terminal objects

It is difficult to talk about specific objects in a category using only category-theoretic information. For example, imagine trying to explain the structure of the Klein 4-group to someone without talking about its elements.

However, not all is lost. Certain objects in a category are special, and you can talk about them without any reference to non-categorical data.

**Definition 56** (initial objects, final objects, zero objects). Let  $C$  be a category, and let  $A \in \text{Obj}(C)$ .

- $A$  is said to be an initial object if for all  $B \in \text{Obj}(C)$ ,  $\text{Hom}(A, B)$  has exactly one element, i.e. if there is exactly one arrow from  $A$  to every object in  $C$ . Initial objects are generally called  $\emptyset$ .
- $A$  is said to be a terminal object if  $\text{Hom}(B, A)$  has exactly one element for all  $B \in \text{Obj}(C)$ , i.e. if there is exactly one arrow from every object in  $C$  to  $A$ . Terminal objects are generally called  $1$ .
- $A$  is said to be a zero object if it is both initial and terminal. Zero objects are almost always called  $0$ .

The names  $\emptyset$  and  $1$  for the initial and terminal objects may seem odd, but in  $\text{Set}$  they make sense.

**Example 57.** In  $\text{Set}$ , there is exactly one map from any set  $S$  to any one-element set  $\{*\}$ . Thus  $\{*\} = 1$  is a terminal object in  $\text{Set}$ .

Furthermore, it is conventional that there is exactly one map from the empty set  $\emptyset$  to any set  $B$ . Thus the empty set  $\emptyset$  is initial in  $\text{Set}$ .

The category  $\text{Set}$  has no zero objects.

**Example 58.** The trivial group is a zero object in  $\text{Grp}$ .

You may have noticed that initial, terminal, and zero objects may not be unique. For example, in  $\text{Set}$ , any singleton is terminal. This is true; however, they are unique up to unique isomorphism.

**Theorem 59.** Let  $C$  be a category, let  $I$  and  $I'$  be two initial objects in  $C$ . Then there exists a unique isomorphism between  $I$  and  $I'$ .

*Proof.* Since  $I$  is initial, there exists exactly one morphism from  $I$  to *any* object, including  $I$  itself. By [Definition 1, Part 3](#), this morphism must be the identity morphism  $\text{id}_I$ . Similarly, the only morphism from  $I'$  to itself is the identity morphism  $\text{id}_{I'}$ .

But since  $I$  is initial, there exists a unique morphism from  $I$  to  $I'$ ; call it  $f$ . Similarly, there exists a unique morphism from  $I'$  to  $I$ ; call it  $g$ . By [Definition 1, Part 1](#), we can take the composition  $g \circ f$  to get a morphism  $I \rightarrow I$ .

But there is only one isomorphism  $I \rightarrow I$ : the identity morphism! Thus

$$g \circ f = \text{id}_I.$$

Similarly,

$$f \circ g = \text{id}_{I'}.$$

This means that, by [Definition 13](#),  $f$  and  $g$  are isomorphisms. They are clearly unique because of the uniqueness condition in the definition of an initial object. Thus, between any two initial objects there is a unique isomorphism.

$$\text{id}_I = g \circ f \circ \text{id}_I \quad \begin{array}{c} \xrightarrow{f} \\ \xleftarrow{g} \end{array} \quad I \quad \begin{array}{c} \xrightarrow{f} \\ \xleftarrow{g} \end{array} \quad I' \quad \begin{array}{c} \xrightarrow{f} \\ \xleftarrow{g} \end{array} \quad \text{id}_{I'} = f \circ g$$

□

Showing that terminal and zero objects are unique up to unique isomorphism is almost exactly the same.

## Morphisms to and from functors

We have succeeded in specifying certain objects (namely initial, terminal, and zero objects) in a category using only categorical information uniquely up to a unique isomorphism. Unfortunately, initial, terminal, and zero objects are usually not very interesting; they are often trivial examples of the structures contained in the category.

However, they give us a way of defining interesting mathematical objects: we have to cook up a category where the object in question is initial or terminal. In a sense, this is the most general definition of a universal property: an object satisfies a universal property if it is initial or terminal in some category. However, the vast majority of interesting universal properties come from objects which are initial or terminal in more complicated categories such as the following.

**Definition 60** (category of morphisms from an object to a functor). Let  $C, D$  be categories, let  $\mathcal{U}: D \rightsquigarrow C$  be a functor. Further let  $X \in \text{Obj}(C)$ . The category of morphisms  $(X \downarrow \mathcal{U})$  is the following comma category (see [Definition 52](#)):

$$1 \rightsquigarrow_{\mathcal{F}_X} C \leftarrow_{\mathcal{U}} D.$$

Just as for (co)slice categories ([Definitions 54 and 55](#)), there is some unpacking to be done. In fact, the unpacking is very similar to that of coslice categories. The LHS of the commutative

square diagram collapses because the functor  $\mathcal{F}_X$  picks out a single element  $X$ ; therefore, the objects of  $(X \downarrow \mathcal{U})$  are ordered pairs

$$(\alpha, f); \quad \alpha \in \text{Obj}(\mathcal{D}), \quad f: X \rightarrow \mathcal{U}(\alpha),$$

and the morphisms  $(\alpha, f) \rightarrow (\alpha', f')$  are morphisms  $g: \alpha \rightarrow \alpha'$  such that the diagram

$$\begin{array}{ccc} & X & \\ f \swarrow & & \searrow f' \\ \mathcal{U}(\alpha) & \xrightarrow{\mathcal{U}(g)} & \mathcal{U}(\alpha') \end{array}$$

commutes.

Just as slice categories are dual to coslice categories, we can take the dual of the previous definition.

**Definition 61** (category of morphisms from a functor to an object). Let  $\mathcal{C}, \mathcal{D}$  be categories, let  $\mathcal{U}: \mathcal{D} \rightsquigarrow \mathcal{C}$  be a functor. The category of morphisms  $(\mathcal{U} \downarrow X)$  is the comma category

$$\mathcal{D} \xrightarrow{\mathcal{U}} \mathcal{C} \xleftarrow{\mathcal{F}_X} 1.$$

The objects in this category are pairs  $(\alpha, f)$ , where  $\alpha \in \text{Obj}(\mathcal{D})$  and  $f: \mathcal{U}(\alpha) \rightarrow X$ . The morphisms  $(\alpha, f) \rightarrow (\alpha', f')$  are morphisms  $g: \alpha \rightarrow \alpha'$  such that the diagram

$$\begin{array}{ccc} \mathcal{U}(\alpha) & \xrightarrow{\mathcal{U}(g)} & \mathcal{U}(\alpha') \\ f \searrow & & \swarrow f' \\ & X & \end{array}$$

commutes.

## Initial and terminal morphisms

**Definition 62** (initial morphism). Let  $\mathcal{C}, \mathcal{D}$  be categories, let  $\mathcal{U}: \mathcal{D} \rightsquigarrow \mathcal{C}$  be a functor, and let  $X \in \text{Obj}(\mathcal{C})$ . An initial morphism (called a *universal arrow* in [17]) is an initial object in the category  $(X \downarrow \mathcal{U})$ , i.e. the comma category which has the diagram

$$1 \xrightarrow{\mathcal{F}_X} \mathcal{C} \xleftarrow{\mathcal{U}} \mathcal{D}$$

This is not by any stretch of the imagination a transparent definition, but decoding it will be good practice.

The definition tells us that an initial morphism is an object in  $(X \downarrow \mathcal{U})$ , i.e. a pair  $(I, \varphi)$  for  $I \in \text{Obj}(\mathcal{D})$  and  $\varphi: X \rightarrow \mathcal{U}(I)$ . But it is not just any object: it is an initial object. This means that for any other object  $(\alpha, f)$ , there exists a unique morphism  $(I, \varphi) \rightarrow (\alpha, f)$ . But such morphisms are simply maps  $g: I \rightarrow \alpha$  such that the diagram

$$\begin{array}{ccc} & X & \\ \varphi \swarrow & & \searrow f \\ \mathcal{U}(I) & \xrightarrow{\mathcal{U}(g)} & \mathcal{U}(\alpha) \end{array}$$

commutes.

We can express this schematically via the following diagram (which is essentially the above diagram, rotated to agree with the literature).

$$\begin{array}{ccc}
 X & \xrightarrow{\varphi} & \mathcal{U}(I) \\
 & \searrow f & \downarrow \mathcal{U}(g) \\
 & & \mathcal{U}(\alpha)
 \end{array}
 \qquad
 \begin{array}{c}
 I \\
 \downarrow \exists! g \\
 \alpha
 \end{array}$$

As always, there is a dual notion.

**Definition 63** (terminal morphism). Let  $\mathcal{C}, \mathcal{D}$  be categories, let  $\mathcal{U}: \mathcal{D} \rightsquigarrow \mathcal{C}$  be a functor, and let  $X \in \text{Obj}(\mathcal{C})$ . A terminal morphism is a terminal object in the category  $(\mathcal{U} \downarrow X)$ .

This time “terminal object” means a pair  $(I, \varphi)$  such that for any other object  $(\alpha, f)$  there is a unique morphism  $g: \alpha \rightarrow I$  such that the diagram

$$\begin{array}{ccc}
 \mathcal{U}(\alpha) & \xrightarrow{\mathcal{U}(g)} & \mathcal{U}(I) \\
 & \searrow f & \swarrow \varphi \\
 & & X
 \end{array}$$

commutes.

Again, with the diagram helpfully rotated, we have the following.

$$\begin{array}{ccc}
 \mathcal{U}(\alpha) & & \alpha \\
 \mathcal{U}(g) \downarrow & \searrow f & \downarrow \exists! g \\
 \mathcal{U}(I) & \xrightarrow{\varphi} & X \\
 & & I
 \end{array}$$

**Definition 64** (universal property). Now is the time for an admission: despite what Wikipedia may tell you, there is no hard and fast definition of a universal property. In complete generality, an object with a universal property is just an object which is initial or terminal in some category. However, quite a few interesting universal properties are given in terms of initial and terminal morphisms, and it will pay to study a few examples.

*Note 65.* One often hand-wavily says that an object  $I$  satisfies a universal property if  $(I, \varphi)$  is an initial or terminal morphism. This is actually rather annoying; one has to remember that when one states a universal property in terms of a universal morphism, one is defining not only an object  $I$  but also a morphism  $\varphi$ , which is often left implicit.

## Examples of universal properties

Generally when one sees universal properties, they are not in the form ‘an initial morphism in such-and-such a comma category.’ Often, one has to play around with them a bit to get them into that form. In fact, this is seldom useful. In this section, we give several examples of universal properties as they are commonly written down, and translate them into the form above for practice.

**Example 66** (tensor algebra). One often sees some variation of the following universal characterization of the tensor algebra, which was taken (almost) verbatim from Wikipedia. We will try to stretch it to fit our definition, following the logic through in some detail.

Let  $V$  be a vector space over a field  $k$ , and let  $A$  be an algebra over  $k$ . The tensor algebra  $T(V)$  satisfies the following universal property.

Any linear transformation  $f: V \rightarrow A$  from  $V$  to  $A$  can be uniquely extended to an algebra homomorphism  $T(V) \rightarrow A$  as indicated by the following commutative diagram.

$$\begin{array}{ccc} V & \xrightarrow{i} & T(V) \\ & \searrow f & \downarrow \tilde{f} \\ & & A \end{array}$$

As it turns out, it will take rather a lot of stretching.

Let  $\mathcal{U}: k\text{-Alg} \rightsquigarrow \text{Vect}_k$  be the forgetful functor which assigns to each algebra over a field  $k$  its underlying vector space. Pick some  $k$ -vector space  $V$ . We consider the category  $(V \downarrow \mathcal{U})$ , which is given by the following diagram.

$$1 \xrightarrow{\mathcal{F}_V} \text{Vect}_k \xleftarrow{\mathcal{U}} k\text{-Alg}$$

By [Definition 62](#), the objects of  $(V \downarrow \mathcal{U})$  are pairs  $(A, L)$ , where  $A$  is a  $k$ -algebra and  $L$  is a linear map  $V \rightarrow \mathcal{U}(A)$ . The morphisms are algebra homomorphisms  $\rho: A \rightarrow A'$  such that the diagram

$$\begin{array}{ccc} & V & \\ L \swarrow & & \searrow L' \\ \mathcal{U}(A) & \xrightarrow{\mathcal{U}(\rho)} & \mathcal{U}(A') \end{array}$$

commutes. An object  $(T(V), i)$  is initial if for any object  $(A, f)$  there exists a unique morphism  $g: T(V) \rightarrow A$  such that the diagram

$$\begin{array}{ccc} V & \xrightarrow{i} & \mathcal{U}(T(V)) \\ & \searrow L & \downarrow \mathcal{U}(g) \\ & & \mathcal{U}(A) \end{array} \qquad \begin{array}{ccc} T(V) & & \\ & \downarrow \exists! g & \\ & A & \end{array}$$

commutes.

Thus, the pair  $(i, T(V))$  is the initial object in the category  $(V \downarrow \mathcal{U})$ . We called  $T(V)$  the *tensor algebra* over  $V$ .

But what is  $i$ ? Notice that in the Wikipedia definition above, the map  $i$  is from  $V$  to  $T(V)$ , but in the diagram above, it is from  $V$  to  $\mathcal{U}(T(V))$ . What gives?

The answer is that the diagram in Wikipedia's definition does not take place in a specific category. Instead, it implicitly treats  $T(V)$  only as a vector space. But this is exactly what the functor  $\mathcal{U}$  does.

**Example 67** (tensor product). According to the excellent book [3], the tensor product satisfies the following universal property.

Let  $V_1$  and  $V_2$  be vector spaces. Then we say that a vector space  $V_3$  together with a bilinear map  $\iota: V_1 \times V_2 \rightarrow V_3$  has the *universal property* provided that for any bilinear map  $B: V_1 \times V_2 \rightarrow W$ , where  $W$  is also a vector space, there exists a unique linear map  $L: V_3 \rightarrow W$  such that  $B = L\iota$ . Here is a diagram describing this ‘factorization’ of  $B$  through  $\iota$ :

$$\begin{array}{ccc} V_1 \times V_2 & \xrightarrow{\iota} & V_3 \\ & \searrow B & \downarrow L \\ & & W \end{array}$$

It turns out that the tensor product defined in this way is neither an initial or final morphism. This is because in the category  $\text{Vect}_k$ , there is no way of making sense of a bilinear map.

**Example 68** (categorical product). Here is the universal property for a product, taken verbatim from Wikipedia ([21]).

Let  $\mathcal{C}$  be a category with some objects  $X_1$  and  $X_2$ . A product of  $X_1$  and  $X_2$  is an object  $X$  (often denoted  $X_1 \times X_2$ ) together with a pair of morphisms  $\pi_1: X \rightarrow X_1$  and  $\pi_2: X \rightarrow X_2$  such that for every object  $Y$  and pair of morphisms  $f_1: Y \rightarrow X_1$ ,  $f_2: Y \rightarrow X_2$ , there exists a unique morphism  $f: Y \rightarrow X_1 \times X_2$  such that the following diagram commutes.

$$\begin{array}{ccccc} & & Y & & \\ & \swarrow f_1 & \downarrow f & \searrow f_2 & \\ X_1 & \xleftarrow{\pi_1} & X_1 \times X_2 & \xrightarrow{\pi_2} & X_2 \end{array}$$

Consider the comma category  $(\Delta \downarrow (X_1, X_2))$  (where  $\Delta$  is the diagonal functor, see [Example 72](#)) given by the following diagram.

$$\mathcal{C} \xrightarrow{\Delta} \mathcal{C} \times \mathcal{C} \xleftarrow{\mathcal{F}_{(X_1, X_2)}} 1$$

The objects of this category are pairs  $(A, (s, t))$ , where  $A \in \text{Obj}(\mathcal{C})$  and

$$(s, t): \Delta(A) = (A, A) \rightarrow (X_1, X_2).$$

The morphisms  $(A, (s, t)) \rightarrow (B, (u, v))$  are morphisms  $r: A \rightarrow B$  such that the diagram

$$\begin{array}{ccc} (A, A) & \xrightarrow{(r, r)} & (B, B) \\ \downarrow (s, t) & & \downarrow (u, v) \\ & (X_1, X_2) & \end{array}$$

commutes.



An object  $(X_1 \times X_2, (\pi_1, \pi_2))$  is final if for any other object  $(Y, (f_1, f_2))$ , there exists a unique morphism  $f: Y \rightarrow X_1 \times X_2$  such that the diagram

$$\begin{array}{ccc}
 (Y, Y) & & Y \\
 \downarrow (f, f) & \searrow (f_1, f_2) & \downarrow \exists! f \\
 (X_1 \times X_2, X_1 \times X_2) & \xrightarrow{(\pi_1, \pi_2)} & (X_1, X_2) \\
 & & \downarrow \\
 & & X_1 \times X_2
 \end{array}$$

commutes. If we re-arrange our diagram a bit, it is not too hard to see that it is equivalent to the one given above. Thus, we can say: a product of two sets  $X_1$  and  $X_2$  is a final object in the category  $(\Delta \downarrow (X_1, X_2))$

## 2 Cartesian closed categories

### 2.1 Cartesian closed categories

This section loosely follows [24].

Cartesian closed categories are the prototype for many of the structures possessed by monoidal categories.

### 2.2 Products

We saw in [Example 68](#) the definition for a categorical product. In some categories, we can naturally take the product of any two objects; one generally says that such a category *has products*. We formalize that in the following.

**Definition 69** (category with products). Let  $C$  be a category such that for every two objects  $A, B \in \text{Obj}(C)$ , there exists an object  $A \times B$  which satisfies the universal property ([Example 68](#)). Then we say that  $C$  has products.

*Note 70.* Sometimes people call a category with products a *Cartesian category*, but others use this terminology to mean a category with all finite limits.<sup>1</sup> We will avoid it altogether.

Recall that in [Example 29](#) we showed that the Cartesian product of two sets is functorial. The same turns out to be true for the categorical product.

**Theorem 71.** *Let  $C$  be a category with products. Then the product can be extended to a bifunctor ([Definition 28](#))  $C \times C \rightarrow C$ .*

*Proof.* Let  $X, Y \in \text{Obj}(C)$ . We need to check that the assignment  $(X, Y) \mapsto \times(X, Y) \equiv X \times Y$  is functorial, i.e. that  $\times$  assigns

- to each pair  $(X, Y) \in \text{Obj}(C \times C)$  an object  $X \times Y \in \text{Obj}(C)$  and
- to each pair of morphisms  $(f, g): (X, Y) \rightarrow (X', Y')$  a morphism

$$\times(f, g) = f \times g: X \times Y \rightarrow X' \times Y'$$

such that

$$\circ \text{id}_X \times \text{id}_Y = \text{id}_{X \times Y}, \text{ and}$$

---

<sup>1</sup>We will see later that any category with both products and equalizers has all finite limits.

◦  $\times$  respects composition as follows.

$$\begin{array}{c}
 (f',g') \circ (f,g) = (f' \circ f, g' \circ g) \\
 \begin{array}{ccccc}
 & \searrow & & \searrow & \\
 (X, Y) & \xrightarrow{(f,g)} & (X', Y') & \xrightarrow{(f',g')} & (X'', Y'') \\
 & \swarrow & & \swarrow & \\
 & & & & 
 \end{array} \\
 \Downarrow \times \\
 \begin{array}{ccccc}
 X \times Y & \xrightarrow{f \times g} & X' \times Y' & \xrightarrow{f' \times g'} & X'' \times Y'' \\
 & \searrow & & \searrow & \\
 & & & & 
 \end{array} \\
 f' \times g' \circ f \times g = (f' \circ f) \times (g' \circ g)
 \end{array}$$

We know how  $\times$  assigns objects in  $C \times C$  to objects in  $C$ . We need to figure out how  $\times$  should assign to a morphism  $(f, g)$  in  $C \times C$  a morphism  $f \times g$  in  $C$ . We do this by diagram chasing.

Suppose we are given two maps  $f: X_1 \rightarrow X_2$  and  $g: Y_1 \rightarrow Y_2$ . We can view this as a morphism  $(f, g)$  in  $C \times C$ .

Recall the universal property for products: a product  $X_1 \times Y_1$  is a final object in the category  $(\Delta \downarrow (X_1, Y_1))$ . Objects in this category can be thought of as diagrams in  $C \times C$ .

$$(X_1 \times Y_1, X_1 \times Y_1) \xrightarrow{(\pi_1, \pi_2)} (X_1, Y_1) .$$

By assumption, we can take the product of both  $X_1$  and  $Y_1$ , and  $X_2$  and  $Y_2$ . This gives us two diagrams living in  $C \times C$ , which we can put next to each other.

$$(X_1 \times Y_1, X_1 \times Y_1) \xrightarrow{(\pi_1, \pi_2)} (X_1, Y_1)$$

$$(X_2 \times Y_2, X_2 \times Y_2) \xrightarrow{(\rho_1, \rho_2)} (X_2, Y_2)$$

We can draw in our morphism  $(f, g)$ , and take its composition with  $(\pi_1, \pi_2)$ .

$$\begin{array}{ccc}
 (X_1 \times Y_1, X_1 \times Y_1) & \xrightarrow{(\pi_1, \pi_2)} & (X_1, Y_1) \\
 \searrow (f \circ \pi_1, g \circ \pi_2) & & \downarrow (f, g) \\
 (X_2 \times Y_2, X_2 \times Y_2) & \xrightarrow{(\rho_1, \rho_2)} & (X_2, Y_2)
 \end{array}$$

Now forget about the top right of the diagram. I'll erase it to make this easier.

$$\begin{array}{ccc}
 (X_1 \times Y_1, X_1 \times Y_1) & & \\
 \searrow (f \circ \pi_1, g \circ \pi_2) & & \\
 (X_2 \times Y_2, X_2 \times Y_2) & \xrightarrow{(\rho_1, \rho_2)} & (X_2, Y_2)
 \end{array}$$

The universal property for products says that there exists a unique map  $h: X_1 \times Y_1 \rightarrow X_2 \times Y_2$  such that the diagram below commutes.

$$\begin{array}{ccc}
 (X_1 \times Y_1, X_1 \times Y_1) & & X_1 \times Y_1 \\
 \downarrow (h,h) & \searrow (f \circ \pi_1, g \circ \pi_2) & \downarrow \exists! h \\
 (X_2 \times Y_2, X_2 \times Y_2) & \xrightarrow{(\rho_1, \rho_2)} & (X_1, X_2) \\
 & & \downarrow \\
 & & X_2 \times Y_2
 \end{array}$$

And  $h$  is what we will use for the product  $f \times g$ .

Of course, we must also check that  $h$  behaves appropriately. Draw two copies of the diagram for the terminal object in  $(\Delta \downarrow (X, Y))$  and identity arrows between them.

$$\begin{array}{ccc}
 (X \times Y, X \times Y) & \xrightarrow{(\pi_1, \pi_2)} & (X, Y) \\
 \downarrow (\text{id}_{X \times Y}, \text{id}_{X \times Y}) & & \downarrow (\text{id}_X, \text{id}_Y) \\
 (X \times Y, X \times Y) & \xrightarrow{(\pi_1, \pi_2)} & (X, Y)
 \end{array}$$

Just as before, we compose the morphisms to and from the top right to draw a diagonal arrow, and then erase the top right object and the arrows to and from it.

$$\begin{array}{ccc}
 (X \times Y, X \times Y) & & X \times Y \\
 \downarrow (\text{id}_{X \times Y}, \text{id}_{X \times Y}) = (\text{id}_X \times \text{id}_Y, \text{id}_X \times \text{id}_Y) & \searrow (\text{id}_X \circ \pi_1, \text{id}_Y \circ \pi_2) & \downarrow \text{id}_X \times \text{id}_Y = \text{id}_X \times \text{id}_Y \\
 (X \times Y, X \times Y) & \xrightarrow{(\pi_1, \pi_2)} & (X, Y) \\
 & & \downarrow \\
 & & X \times Y
 \end{array}$$

By definition, the arrow on the right is  $\text{id}_X \times \text{id}_Y$ . It is also  $\text{id}_{X \times Y}$ , and by the universal property it is unique. Therefore  $\text{id}_{X \times Y} = \text{id}_X \times \text{id}_Y$ .

Next, put three of these objects together. The proof of the last part is immediate.

$$\begin{array}{ccc}
 (X_1 \times Y_1, X_1 \times Y_1) & & (X_1, Y_1) \\
 \downarrow (f \times g, f \times g) & & \downarrow (f, g) \\
 (X_2 \times Y_2, X_2 \times Y_2) & & (X_2, Y_2) \\
 \downarrow (f' \times g', f' \times g') & & \downarrow (f', g') \\
 (X_3 \times Y_3, X_3 \times Y_3) & & (X_3, Y_3)
 \end{array}$$

Curved arrows on the left:  $(f' \times g') \circ (f \times g) = (g' \circ g) \times (f' \circ f)$  from top-left to bottom-left;  $(g' \circ g, f' \circ f)$  from top-right to bottom-right.

□

The meaning of this theorem is that in any category where you can take products of the objects, you can also take products of the morphisms.

**Example 72** (diagonal functor). Let  $\mathcal{C}$  be a category,  $\mathcal{C} \times \mathcal{C}$  the product category of  $\mathcal{C}$  with itself. The diagonal functor  $\Delta: \mathcal{C} \rightsquigarrow \mathcal{C} \times \mathcal{C}$  is the functor which sends

- each object  $A \in \text{Obj}(\mathcal{C})$  to the pair  $(A, A) \in \text{Obj}(\mathcal{C} \times \mathcal{C})$ , and
- each morphism  $f: A \rightarrow B$  to the ordered pair

$$(f, f) \in \text{Hom}_{\mathcal{C} \times \mathcal{C}}(A \times B, A \times B).$$

**Example 73.** The category  $\text{Vect}_k$  of vector spaces over a field  $k$  has the direct sum  $\oplus$  as a product.

The product is, in an appropriate way, commutative.

**Lemma 74.** *There is a natural isomorphism between the following functors  $\mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$*

$$\times: (A, B) \rightarrow A \times B \quad \text{and} \quad \tilde{\times}: (A, B) \rightarrow B \times A.$$

*Proof.* We define a natural transformation  $\Phi: \times \Rightarrow \tilde{\times}$  with components

$$\Phi_{A,B}: A \times B \rightarrow B \times A$$

as follows. Denote the canonical projections for the product  $A \times B$  by  $\pi_A$  and  $\pi_B$ . Then  $(\pi_B, \pi_A)$  is a map  $A \times B \rightarrow (B, A)$ , and the universal property for products gives us a map  $A \times B \rightarrow B \times A$ . We can pull the same trick to go from  $B \times A$  to  $A \times B$ , using the pair  $(\pi_A, \pi_B)$  and the universal property. Furthermore, these maps are inverse to each other, so  $\Phi_{A,B}$  is an isomorphism.

We need only check naturality, i.e. that for  $f: A \rightarrow A'$ ,  $g: B \rightarrow B'$ , the following square commutes.

$$\begin{array}{ccc} A \times B & \longrightarrow & A' \times B' \\ \downarrow & & \downarrow \\ B \times A & \longrightarrow & B' \times A' \end{array}$$

□

*Note 75.* It is an important fact that the product is associative. We shall see this in [Theorem 107](#), after we have developed the machinery to do it cleanly.

## 2.3 Coproducts

**Definition 76.** Let  $\mathcal{C}$  be a category,  $X_1$  and  $X_2 \in \text{Obj}(\mathcal{C})$ . The coproduct of  $X_1$  and  $X_2$ , denoted  $X_1 \amalg X_2$ , is the initial object in the category  $((X_1, X_2) \downarrow \Delta)$ . In everyday language, we have the following.

An object  $X_1 \amalg X_2$  is called the coproduct of  $X_1$  and  $X_2$  if

1. there exist morphisms  $i_1: X_1 \rightarrow X_1 \amalg X_2$  and  $i_2: X_2 \rightarrow X_1 \amalg X_2$  called *canonical injections* such that

2. for any object  $Y$  and morphisms  $f_1: X_1 \rightarrow Y$  and  $f_2: X_2 \rightarrow Y$  there exists a unique morphism  $f: X_1 \amalg X_2 \rightarrow Y$  such that  $f_1 = f \circ i_1$  and  $f_2 = f \circ i_2$ , i.e. the following diagram commutes.

$$\begin{array}{ccccc} & & Y & & \\ & \nearrow f_1 & \uparrow f & \nwarrow f_2 & \\ X_1 & \xrightarrow{i_1} & X_1 \amalg X_2 & \xleftarrow{i_2} & X_2 \end{array}$$

**Definition 77** (category with coproducts). We say that a category  $C$  has coproducts if for all  $A, B \in \text{Obj}(C)$ , the coproduct  $A \amalg B$  is in  $\text{Obj}(C)$ .

We have the following analog of [Theorem 71](#).

**Theorem 78.** Let  $C$  be a category with coproducts. Then we have a functor  $\amalg: C \times C \rightsquigarrow C$ .

*Proof.* We verify that  $\amalg$  allows us to define canonically a coproduct of morphisms. Let  $X_1, X_2, Y_1, Y_2 \in \text{Obj}(C)$ , and let  $f: X_1 \rightarrow Y_1$  and  $g: X_2 \rightarrow Y_2$ . We have the following diagram.

$$\begin{array}{ccccc} X_1 & \xrightarrow{i_{1,X}} & X_1 \amalg X_2 & \xleftarrow{i_{2,X}} & X_2 \\ & \searrow i_{1,Y} \circ f & & \swarrow i_{2,Y} \circ g & \\ & & Y_1 \amalg Y_2 & & \\ \downarrow f & & & & \downarrow g \\ Y_1 & \xrightarrow{i_{1,Y}} & Y_1 \amalg Y_2 & \xleftarrow{i_{2,Y}} & Y_2 \end{array}$$

But by the universal property of coproducts, the diagonal morphisms induce a map  $X_1 \amalg X_2 \rightarrow Y_1 \amalg Y_2$ , which we define to be  $f \amalg g$ .

$$\begin{array}{ccccc} X_1 & \xrightarrow{i_{1,X}} & X_1 \amalg X_2 & \xleftarrow{i_{2,X}} & X_2 \\ & \searrow i_{1,Y} \circ f & \downarrow f \amalg g & \swarrow i_{2,Y} \circ g & \\ & & Y_1 \amalg Y_2 & & \end{array}$$

The rest of the verification that  $\amalg$  really is a functor is identical to that in [Theorem 71](#).  $\square$

**Example 79.** In  $\text{Set}$ , the coproduct is the disjoint union.

**Example 80.** In  $\text{Vect}_k$ , the coproduct  $\oplus$  is the direct sum.

**Example 81.** In  $k\text{-Alg}$  the tensor product is the coproduct. To see this, let  $A, B$ , and  $R$  be  $k$ -algebras. The tensor product  $A \otimes_k B$  has canonical injections  $\iota_1: A \rightarrow A \otimes_k B$  and  $\iota_2: B \rightarrow A \otimes_k B$  given by

$$\iota_A: v \mapsto v \otimes \text{id}_B \quad \text{and} \quad \iota_B: v \mapsto \text{id}_A \otimes v.$$

Let  $f_1: A \rightarrow R$  and  $f_2: B \rightarrow R$  be  $k$ -algebra homomorphisms. Then there is a unique homomorphism  $f: A \otimes_k B \rightarrow R$  which makes the following diagram commute.

$$\begin{array}{ccccc} A & \xrightarrow{\iota_A} & A \otimes B & \xleftarrow{\iota_B} & B \\ & \searrow f_1 & \downarrow f & \swarrow f_2 & \\ & & R & & \end{array}$$

## 2.4 Biproducts

A lot of the stuff in this section was adapted and expanded from [33].

One often hears that a biproduct is an object which is both a product and a coproduct, but this is both misleading and unnecessarily vague. Objects satisfying universal properties are only defined up to isomorphism, so it doesn't make much sense to demand that products *coincide* with coproducts. However, demanding only that they be isomorphic (or even naturally isomorphic) is too weak, and does not determine a biproduct uniquely. In this section we will give the correct definition which encapsulates all of the properties of the product and the coproduct we know and love.

In order to talk about biproducts, we need to be aware of the following result, which we will consider in much more detail in [Definition 7.2](#).

**Definition 82** (zero morphism). Let  $\mathcal{C}$  be a category with zero object  $0$ . For any two objects  $A, B \in \text{Obj}(\mathcal{C})$ , the zero morphism  $0_{A,B}$  is the unique morphism  $A \rightarrow B$  which factors through  $0$ .

$$\begin{array}{ccccc} & & 0_{A,B} & & \\ & \searrow & & \swarrow & \\ A & \longrightarrow & 0 & \longrightarrow & B \end{array}$$

*Notation 83.* It will often be clear what the source and destination of the zero morphism are; in this case we will drop the subscripts, writing  $0$  instead of  $0_{AB}$ . With this notation, for all morphisms  $f$  and  $g$  we have  $f \circ 0 = 0$  and  $0 \circ g = 0$ .

**Definition 84** (category with biproducts). Let  $\mathcal{C}$  be a category with zero object  $0$ , products  $\times$  (with canonical projections  $\pi$ ), and coproducts  $\amalg$  (with natural injections  $\iota$ ). We say that  $\mathcal{C}$  has biproducts if for each two objects  $A_1, A_2 \in \text{Obj}(\mathcal{C})$ , there exists an isomorphism

$$\Phi_{A_1, A_2} : A_1 \amalg A_2 \rightarrow A_1 \times A_2$$

such that

$$A_i \xrightarrow{\iota_i} A_1 \amalg A_2 \xrightarrow{\Phi_{A_1, A_2}} A_1 \times A_2 \xrightarrow{\pi_j} A_j = \begin{cases} \text{id}_{A_i}, & i = j \\ 0, & i \neq j. \end{cases}$$

Here is a picture.

$$\begin{array}{ccccc} & & A_1 \amalg A_2 & & \\ & \swarrow \iota_1 & \downarrow \Phi_{A_1, A_2} & \nwarrow \iota_2 & \\ A_1 & & & & A_2 \\ & \nwarrow \pi_1 & & \swarrow \pi_2 & \\ & & A_1 \times A_2 & & \end{array}$$

**Lemma 85.** *The isomorphisms  $\Phi_{A,B}$  are unique if they exist.*

*Proof.* We can compose  $\Phi_{A_1, A_2}$  with  $\pi_1$  and  $\pi_2$  to get maps  $A_1 \amalg A_2 \rightarrow A_1$  and  $A_1 \amalg A_2 \rightarrow A_2$ . The universal property for products tells us that there is a unique map  $\varphi : A_1 \amalg A_2 \rightarrow A_1 \times A_2$  such that  $\pi_1 \circ \varphi = \pi_1 \circ \Phi_{A_1, A_2}$  and  $\pi_2 \circ \varphi = \pi_2 \circ \Phi_{A_1, A_2}$ ; but  $\varphi$  is just  $\Phi_{A_1, A_2}$ . Hence  $\Phi_{A_1, A_2}$  is unique.  $\square$

**Lemma 86.** In any category  $\mathcal{C}$  with biproducts  $\Phi_{A,B}: A \amalg B \rightarrow A \times B$ , any map  $A \amalg B \rightarrow A' \times B'$  is completely determined by its components  $A \rightarrow A'$ ,  $A \rightarrow B'$ ,  $B \rightarrow A'$ , and  $B \rightarrow B'$ . That is, given any map  $f: A \amalg B \rightarrow A' \times B'$ , we can create four maps

$$\pi_{A'} \circ f \circ \iota_A: A \rightarrow A', \quad \pi_{B'} \circ f \circ \iota_A: A \rightarrow B', \quad \text{etc,}$$

and given four maps

$$\psi_{A,A'}: A \rightarrow A'; \quad \psi_{A,B'}: A \rightarrow B'; \quad \psi_{B,A'}: B \rightarrow A', \quad \text{and } \psi_{B,B'}: B \rightarrow B',$$

we can construct a unique map  $\psi: A \amalg B \rightarrow A' \times B'$  such that

$$\psi_{A,A'} = \pi_{A'} \circ \psi \circ \iota_A, \quad \psi_{A,B'} = \pi_{B'} \circ \psi \circ \iota_A, \quad \text{etc.}$$

*Proof.* The universal property for coproducts give allows us to turn the morphisms  $\psi_{A,A'}$  and  $\psi_{A,B'}$  into a map  $\psi_A: A \rightarrow B \times B'$ , the unique map such that

$$\pi_{A'} \circ \psi_A = \psi_{A,A'} \quad \text{and} \quad \pi_{B'} \circ \psi_A = \psi_{A,B'}.$$

The morphisms  $\psi_{B,A'}$  and  $\psi_{B,B'}$  give us a map  $\psi_B$  which is unique in the same way.

Now the universal property for coproducts gives us a map  $\psi: A \amalg B \rightarrow A' \times B'$ , the unique map such that  $\psi \circ \iota_A = \psi_A$  and  $\psi \circ \iota_B = \psi_B$ .  $\square$

**Theorem 87.** The  $\Phi_{A,B}$  defined above form the components of a natural isomorphism.

*Proof.* Let  $A, B, A'$ , and  $B' \in \text{Obj}(\mathcal{C})$ , and let  $f: A \rightarrow A'$  and  $g: B \rightarrow B'$ . To check that  $\Phi_{A,B}$  are the components of a natural isomorphism, we have to check that the following naturality square commutes.

$$\begin{array}{ccc} A \amalg B & \xrightarrow{f \amalg g} & A' \amalg B' \\ \Phi_{A,B} \downarrow & & \downarrow \Phi_{A',B'} \\ A \times B & \xrightarrow{f \times g} & A' \times B' \end{array}$$

That is, we need to check that  $(f \times g) \circ \Phi_{A,B} = \Phi_{A',B'} \circ (f \amalg g)$ .

Both of these are morphisms  $A \amalg B \rightarrow A' \times B'$ , and by [Lemma 86](#), it suffices to check that their components agree, i.e. that  $\square$

**Example 88.** In the category  $\text{Vect}_k$  of vector spaces over a field  $k$ , the direct sum  $\oplus$  is a biproduct.

**Example 89.** In the category  $\text{Ab}$  of abelian groups, the direct sum  $\oplus$  is both a product and a coproduct. Hence  $\text{Ab}$  has biproducts.

## 2.5 Exponentials

Astonishingly, we can talk about functional evaluation purely in terms of products and universal properties.



**Definition 90** (exponential). Let  $\mathcal{C}$  be a category with products,  $A, B \in \text{Obj}(\mathcal{C})$ . The exponential of  $A$  and  $B$  is an object  $B^A \in \text{Obj}(\mathcal{C})$  together with a morphism  $\varepsilon: B^A \times A \rightarrow B$ , called the *evaluation morphism*, which satisfies the following universal property.

For any object  $X \in \text{Obj}(\mathcal{C})$  and morphism  $f: X \times A \rightarrow B$ , there exists a unique morphism  $\bar{f}: X \rightarrow B^A$  which makes the following diagram commute.

$$\begin{array}{ccc} B^A & & B^A \times A \xrightarrow{\varepsilon} B \\ \exists! \bar{f} \uparrow & & \bar{f} \times \text{id}_A \uparrow \quad \nearrow f \\ X & & X \times A \end{array}$$

**Example 91.** In  $\text{Set}$ , the exponential object  $B^A$  is the set of functions  $A \rightarrow B$ , and the evaluation morphism  $\varepsilon$  is the map which assigns  $(f, a) \mapsto f(a)$ . Let us check that these objects indeed satisfy the universal property given.

Suppose we are given a function  $f: X \times A \rightarrow B$ . We want to construct from this a function  $\bar{f}: X \rightarrow B^A$ , i.e. a function which takes an element  $x \in X$  and returns a function  $\bar{f}(x): A \rightarrow B$ . There is a natural way to do this: fill the first slot of  $f$  with  $x$ ! That is to say, define  $\bar{f}(x) = f(x, -)$ . It is easy to see that this makes the diagram commute:

$$\begin{array}{ccc} (f(x, -), a) & \xrightarrow{\varepsilon} & f(x, a) \\ \bar{f} \times \text{id}_A \uparrow & & \nearrow f \\ (x, a) & & \end{array}$$

Furthermore,  $\bar{f}$  is unique since if it sent  $x$  to any function other than  $f$  the diagram would not commute.

**Example 92.** One might suspect that the above generalizes to all sorts of categories. For example, one might hope that in  $\text{Grp}$ , the exponential  $H^G$  of two groups  $G$  and  $H$  would somehow capture all homomorphisms  $G \rightarrow H$ . This turns out to be impossible; we will see why in REF.

## 2.6 Cartesian closed categories

**Definition 93** (cartesian closed category). A category  $\mathcal{C}$  is cartesian closed if it has

1. products: for all  $A, B \in \text{Obj}(\mathcal{C})$ ,  $A \times B \in \text{Obj}(\mathcal{C})$ ;
2. exponentials: for all  $A, B \in \text{Obj}(\mathcal{C})$ ,  $B^A \in \text{Obj}(\mathcal{C})$ ;
3. a terminal element ([Definition 56](#))  $1 \in \mathcal{C}$ .

Cartesian closed categories have many interesting properties. For example, they replicate many properties of the integers: we have the following familiar formulae for any objects  $A, B$ , and  $C$  in a Cartesian closed category with coproducts  $+$ .

1.  $A \times (B + C) \simeq (A \times B) + (A \times C)$
2.  $C^{A+B} \simeq C^A \times C^B$ .
3.  $(C^A)^B \simeq C^{A \times B}$

4.  $(A \times B)^C \simeq A^C \times B^C$

5.  $C^1 \simeq C$

We could prove these immediately, by writing down diagrams and appealing to the universal properties. However, we will soon have a powerful tool, the Yoneda lemma, that makes their proof completely routine.

# 3 Hom functors and the Yoneda lemma

## 3.1 The Hom functor

Given any locally small category (Definition 23)  $\mathcal{C}$  and two objects  $A, B \in \text{Obj}(\mathcal{C})$ , we have thus far notated the set of all morphisms  $A \rightarrow B$  by  $\text{Hom}_{\mathcal{C}}(A, B)$ . This may have seemed a slightly odd notation, but there was a good reason for it:  $\text{Hom}_{\mathcal{C}}$  is really a functor.

To be more explicit, we can view  $\text{Hom}_{\mathcal{C}}$  in the following way: it takes two objects, say  $A$  and  $B$ , and returns the set of morphisms  $A \rightarrow B$ . It's a functor  $\mathcal{C} \times \mathcal{C}$  to  $\text{Set}$ !

(Actually, as we'll see, this isn't quite right: it is actually a functor  $\mathcal{C}^{\text{op}} \times \mathcal{C} \rightarrow \text{Set}$ . But this is easier to understand if it comes about in a natural way, so we'll keep writing  $\mathcal{C} \times \mathcal{C}$  for the time being.)

Okay, so it takes a pair of objects and returns the set of morphisms between them, but any functor has to send morphisms to morphisms. How does it do that?

A morphism in  $\mathcal{C} \times \mathcal{C}$  between two objects  $(A', A)$  and  $(B', B)$  is an ordered pair  $(f', f)$  of two morphisms:

$$f: A \rightarrow B \quad \text{and} \quad f': A' \rightarrow B'.$$

We can draw this as follows.

$$\begin{array}{ccc} A' & \xrightarrow{f'} & B' \\ A & \xrightarrow{f} & B \end{array}$$

We have to send this to a set-function  $\text{Hom}_{\mathcal{C}}(A', A) \rightarrow \text{Hom}_{\mathcal{C}}(B', B)$ . So let  $m$  be a morphism in  $\text{Hom}_{\mathcal{C}}(A, A')$ . We can draw this into our little diagram above like so.

$$\begin{array}{ccc} A' & \xrightarrow{f'} & B' \\ m \downarrow & & \\ A & \xrightarrow{f} & B \end{array}$$

Notice: we want to build from  $m$ ,  $f$ , and  $f'$  a morphism  $B' \rightarrow B$ . Suppose  $f'$  were going the other way.

$$\begin{array}{ccc} A' & \xleftarrow{f'} & B' \\ m \downarrow & & \\ A & \xrightarrow{f} & B \end{array}$$

Then we could get what we want simply by taking the composition  $f \circ m \circ f'$ .

$$\begin{array}{ccc} A' & \xleftarrow{f'} & B' \\ m \downarrow & & \downarrow f \circ m \circ f' \\ A & \xrightarrow{f} & B \end{array}$$

But we can make  $f'$  go the other way simply by making the first argument of  $\text{Hom}_C$  come from the opposite category: that is, we want  $\text{Hom}_C$  to be a functor  $C^{\text{op}} \times C \rightarrow \text{Set}$ .

As the function  $m \mapsto f \circ m \circ f'$  is the action of the functor  $\text{Hom}_C$  on the morphism  $(f', f)$ , it is natural to call it  $\text{Hom}_C(f', f)$ .

Of course, we should check that this *really* is a functor, i.e. that it treats identities and compositions correctly. This is completely routine, and you should skip down to [Definition 94](#) if you read the last sentence with annoyance.

First, we need to show that  $\text{Hom}_C(\text{id}_{A'}, \text{id}_A)$  is the identity function  $\text{id}_{\text{Hom}_C(A', A)}$ . It is, since if  $m \in \text{Hom}_C(A', A)$ ,

$$\text{Hom}_C(\text{id}_{A'}, \text{id}_A): m \mapsto \text{id}_A \circ m \circ \text{id}_{A'} = m.$$

Next, we have to check that compositions work the way they're supposed to. Suppose we have objects and morphisms like this:

$$\begin{array}{ccccc} A' & \xleftarrow{f'} & B' & \xleftarrow{g'} & C' \\ A & \xrightarrow{f} & B & \xrightarrow{g} & C \end{array}$$

where the primed stuff is in  $C^{\text{op}}$  and the unprimed stuff is in  $C$ . This can be viewed as three objects  $(A', A)$ , etc. in  $C^{\text{op}} \times C$  and two morphisms  $(f', f)$  and  $(g', g)$  between them.

Okay, so we can compose  $(f', f)$  and  $(g', g)$  to get a morphism

$$(g', g) \circ (f', f) = (f' \circ g', g \circ f): (A', A) \rightarrow (C', C).$$

Note that the order of the composition in the first argument has been turned around: this is expected since the first argument lives in  $C^{\text{op}}$ . To check that  $\text{Hom}_C$  handles compositions correctly, we need to verify that

$$\text{Hom}_C(g, g') \circ \text{Hom}_C(f, f') = \text{Hom}_C(f' \circ g', g \circ f).$$

Let  $m \in \text{Hom}_C(A', A)$ . We victoriously compute

$$\begin{aligned} [\text{Hom}_C(g, g') \circ \text{Hom}_C(f, f')](m) &= \text{Hom}_C(g, g')(f \circ m \circ f') \\ &= g \circ f \circ m \circ f' \circ g' \\ &= \text{Hom}_C(f' \circ g', g \circ f)(m). \end{aligned}$$

Let's formalize this in a definition.

**Definition 94** (hom functor). Let  $C$  be a locally small category. The hom functor  $\text{Hom}_C$  is the functor

$$C^{\text{op}} \times C \rightsquigarrow \text{Set}$$

which sends the object  $(A', A)$  to the set  $\text{Hom}_C(A', A)$  of morphisms  $A' \rightarrow A$ , and the morphism  $(f', f): (A', A) \rightarrow (B', B)$  to the function

$$\text{Hom}_C(f', f): \text{Hom}_C(A', A) \rightarrow \text{Hom}_C(B', B); \quad m \mapsto f \circ m \circ f'.$$

**Example 95.** Hom functors give us a new way of looking at the universal property for products, coproducts, and exponentials.

Let  $\mathcal{C}$  be a locally small category with products, and let  $X, A, B \in \text{Obj}(\mathcal{C})$ . Recall that the universal property for the product  $A \times B$  allows us to exchange two morphisms

$$f_1: X \rightarrow A \quad \text{and} \quad f_2: X \rightarrow B$$

for a morphism

$$f: X \rightarrow A \times B.$$

We can also compose a morphism  $g: X \rightarrow A \times B$  with the canonical projections

$$\pi_A: A \times B \rightarrow A \quad \text{and} \quad \pi_B: A \times B \rightarrow B$$

to get two morphisms

$$\pi_A \circ f: X \rightarrow A \quad \text{and} \quad \pi_B \circ f: X \rightarrow B.$$

This means that there is a bijection

$$\text{Hom}_{\mathcal{C}}(X, A \times B) \simeq \text{Hom}_{\mathcal{C}}(X, A) \times \text{Hom}_{\mathcal{C}}(X, B).$$

In fact this bijection is natural in  $X$ . That is to say, there is a natural bijection between the following functors  $\mathcal{C}^{\text{op}} \rightarrow \text{Set}$ :

$$h_{A \times B}: X \rightarrow \text{Hom}_{\mathcal{C}}(X, A \times B) \quad \text{and} \quad h_A \times h_B: X \rightarrow \text{Hom}_{\mathcal{C}}(X, A) \times \text{Hom}_{\mathcal{C}}(X, B).$$

Let's prove naturality. Let

$$\Phi_X: \text{Hom}(X, A \times B) \rightarrow \text{Hom}(X, A) \times \text{Hom}(X, B); \quad f \mapsto (\pi_A \circ f, \pi_B \circ f)$$

be the components of the above transformation, and let  $g: X' \rightarrow X$ . Naturality follows from the fact that the diagram below commutes.

$$\begin{array}{ccc} \text{Hom}(X, A \times B) & \xrightarrow{\text{Hom}(g, \text{id}_{A \times B})} & \text{Hom}(X', A \times B) \\ \Phi_X \downarrow & & \downarrow \Phi_{X'} \\ \text{Hom}(X, A) \times \text{Hom}(X, B) & \xrightarrow{\text{Hom}(g, \text{id}_A) \times \text{Hom}(g, \text{id}_B)} & \text{Hom}(X', A) \times \text{Hom}(X', B) \\ & & \\ f \mapsto & \xrightarrow{\quad} & f \circ g \\ \downarrow & & \downarrow \\ (\pi_A \circ f, \pi_B \circ f) & \mapsto & (\pi_A \circ f \circ g, \pi_B \circ f \circ g) \end{array}$$

The coproduct does a similar thing: it allows us to trade two morphisms

$$A \rightarrow X \quad \text{and} \quad B \rightarrow X$$

for a morphism

$$A \amalg B \rightarrow X,$$

and vice versa. Similar reasoning yields a natural bijection between the following functors  $C \rightsquigarrow \text{Set}$ :

$$h^{A \amalg B} \Rightarrow h^A \times h^B.$$

The exponential is a little bit more complicated: it allows us to trade a morphism

$$X \times A \rightarrow B$$

for a morphism

$$X \rightarrow B^A,$$

and vice versa. That is to say, we have a bijection between two functors  $C^{\text{op}} \rightsquigarrow \text{Set}$

$$X \mapsto \text{Hom}_C(X \times A, B) \quad \text{and} \quad X \mapsto \text{Hom}_C(X, B^A).$$

The fact that the functors are more complicated does not hurt us: the above bijection is still natural.

The hom functor as defined above is cute, but not a whole lot else. Things get interesting when we curry it.

Recall from computer science the concept of currying. Suppose we are given a function of two arguments, say  $f(x, y)$ . The idea of currying is this: if we like, we can view  $f$  as a family of functions of only one variable  $y$ , indexed by  $x$ :

$$h_x(y) = f(x, y).$$

We can even view  $h$  as a function which takes one argument  $x$ , and which returns a *function*  $h_x$  of one variable  $y$ .

This sets up a correspondence between functions  $f: A \times B \rightarrow C$  and functions  $h: A \rightarrow C^B$ , where  $C^B$  is the set of functions  $B \rightarrow C$ . The map which replaces  $f$  by  $h$  is called *currying*. We can also go the other way (i.e.  $h \mapsto f$ ), which is called *uncurrying*.

We have been intentionally vague about the nature of our function  $f$ , and what sort of arguments it might take; everything we have said also holds for, say, bifunctors.

In particular, it gives us two more ways to view our bifunctor  $\text{Hom}_C$ . We can fix any  $A \in \text{Obj}(C)$  and curry either argument. This gives us the following.

**Definition 96** (curried hom functor). Let  $C$  be a locally small category,  $A \in \text{Obj}(C)$ . We can construct from the hom functor  $\text{Hom}_C$

- a functor  $h^A: C \rightsquigarrow \text{Set}$  which maps
  - an object  $B \in \text{Obj}(C)$  to the set  $\text{Hom}_C(A, B)$ , and
  - a morphism  $f: B \rightarrow B'$  to a Set-function

$$h^A(f): \text{Hom}_C(A, B) \rightarrow \text{Hom}_C(A, B'); \quad m \mapsto f \circ m.$$

- a functor  $h_A: C^{\text{op}} \rightsquigarrow \text{Set}$  which maps
  - an object  $B \in \text{Obj}(C)$  to the set  $\text{Hom}_C(B, A)$ , and
  - a morphism  $f: B \rightarrow B'$  to a Set-function

$$h_A(f): \text{Hom}_C(B', A) \rightarrow \text{Hom}_C(B, A); \quad m \mapsto m \circ f.$$

## 3.2 Representable functors

Roughly speaking, a functor  $C \rightsquigarrow \text{Set}$  is representable if it is

**Definition 97** (representable functor). Let  $C$  be a category. A functor  $\mathcal{F}: C \rightsquigarrow \text{Set}$  is representable if there is an object  $A \in \text{Obj}(C)$  and a natural isomorphism (Definition 38)

$$\eta: \mathcal{F} \Rightarrow \begin{cases} h^A, & \text{if } \mathcal{F} \text{ is covariant} \\ h_A, & \text{if } \mathcal{F} \text{ is contravariant.} \end{cases}$$

*Note 98.* Since natural isomorphisms are invertible, we could equivalently define a representable functor with the natural isomorphism going the other way.

**Example 99.** Consider the forgetful functor  $\mathcal{U}: \text{Grp} \rightsquigarrow \text{Set}$  which sends a group to its underlying set, and a group homomorphism to its underlying function. This functor is represented by the group  $(\mathbb{Z}, +)$ .

To see this, we have to check that there is a natural isomorphism  $\eta$  between  $\mathcal{U}$  and  $h^{\mathbb{Z}} = \text{Hom}_{\text{Grp}}(\mathbb{Z}, -)$ . That is to say, for each group  $G$ , there a Set-isomorphism (i.e. a bijection)

$$\eta_G: \mathcal{U}(G) \rightarrow \text{Hom}_{\text{Grp}}(\mathbb{Z}, G)$$

satisfying the naturality conditions in Definition 37.

First, let's show that there's a bijection by providing an injection in both directions. Pick some  $g \in G$ . Then there is a unique group homomorphism which sends  $1 \mapsto g$ , so we have an injection  $\mathcal{U}(G) \hookrightarrow \text{Hom}_{\text{Grp}}(\mathbb{Z}, G)$ .

Now suppose we are given a group homomorphism  $\mathbb{Z} \rightarrow G$ . This sends 1 to some element  $g \in G$ , and this completely determines the rest of the homomorphism. Thus, we have an injection  $\text{Hom}_{\text{Grp}}(\mathbb{Z}, G) \hookrightarrow \mathcal{U}(G)$ .

All that is left is to show that  $\eta$  satisfies the naturality condition. Let  $F$  and  $H$  be groups, and  $f: G \rightarrow H$  a homomorphism. We need to show that the following diagram commutes.

$$\begin{array}{ccc} \mathcal{U}(G) & \xrightarrow{\mathcal{U}(f)} & \mathcal{U}(H) \\ \eta_G \downarrow & & \downarrow \eta_H \\ \text{Hom}_{\text{Grp}}(\mathbb{Z}, G) & \xrightarrow{h^{\mathbb{Z}}(f)} & \text{Hom}_{\text{Grp}}(\mathbb{Z}, H) \end{array}$$

The upper path from top left to bottom right assigns to each  $g \in G$  the function  $\mathbb{Z} \rightarrow G$  which maps  $1 \mapsto f(g)$ . Walking down  $\eta_G$  from  $\mathcal{U}(G)$  to  $\text{Hom}_{\text{Grp}}(\mathbb{Z}, G)$ ,  $g$  is mapped to the function  $\mathbb{Z} \rightarrow G$  which maps  $1 \mapsto g$ . Walking right, we compose this function with  $f$  to get a new function  $\mathbb{Z} \rightarrow H$  which sends  $1 \mapsto f(g)$ . This function is really the image of a homomorphism and is therefore unique, so the diagram commutes.

## 3.3 The Yoneda embedding

The Yoneda embedding is a very powerful tool which allows us to prove things about any locally small category by embedding that category into  $\text{Set}$ , and using the enormous amount of structure that  $\text{Set}$  has.

**Definition 100** (Yoneda embedding). Let  $\mathcal{C}$  be a locally small category. The Yoneda embedding is the functor

$$\mathcal{Y}: \mathcal{C} \rightsquigarrow [\mathcal{C}^{\text{op}}, \text{Set}], \quad A \mapsto h_A = \text{Hom}_{\mathcal{C}}(-, A).$$

where  $[\mathcal{C}^{\text{op}}, \text{Set}]$  is the category of functors  $\mathcal{C}^{\text{op}} \rightsquigarrow \text{Set}$ , defined in [Definition 45](#).

Of course, we also need to say how  $\mathcal{Y}$  behaves on morphisms. Let  $f: A \rightarrow A'$ . Then  $\mathcal{Y}(f)$  will be a morphism from  $h_A$  to  $h_{A'}$ , i.e. a natural transformation  $h_A \Rightarrow h_{A'}$ . We can specify how it behaves by specifying its components  $(\mathcal{Y}(f))_B$ .

Plugging in definitions, we find that  $(\mathcal{Y}(f))_B$  is a map  $\text{Hom}_{\mathcal{C}}(B, A) \rightarrow \text{Hom}_{\mathcal{C}}(B, A')$ . But we know how to get such a map—we can compose all of the maps  $B \rightarrow A$  with  $f$  to get maps  $B \rightarrow A'$ . So  $\mathcal{Y}(f)$ , as a natural transformation  $\text{Hom}_{\mathcal{C}}(-, A) \rightarrow \text{Hom}_{\mathcal{C}}(-, A')$ , simply composes everything in sight with  $f$ .

**Theorem 101** (Yoneda lemma). Let  $\mathcal{F}$  be a functor from  $\mathcal{C}^{\text{op}}$  to  $\text{Set}$ . Let  $A \in \text{Obj}(\mathcal{C})$ . Then there is a set-isomorphism (i.e. a bijection)  $\eta$  between the set  $\text{Hom}_{[\mathcal{C}^{\text{op}}, \text{Set}]}(h_A, \mathcal{F})$  of natural transformations  $h_A \Rightarrow \mathcal{F}$  and the set  $\mathcal{F}(A)$ . Furthermore, this isomorphism is natural in  $A$ .

*Note 102.* A quick admission before we begin: we will be sweeping issues with size under the rug in what follows by tacitly assuming that  $\text{Hom}_{[\mathcal{C}^{\text{op}}, \text{Set}]}(h_A, \mathcal{F})$  is a set. The reader will have to trust that everything works out in the end.

*Proof.* A natural transformation  $\Phi: h_A \Rightarrow \mathcal{F}$  consists of a collection of  $\text{Set}$ -morphisms (that is to say, functions)  $\Phi_B: \text{Hom}_{\mathcal{C}}(B, A) \rightarrow \mathcal{F}(A)$ , one for each  $B \in \text{Obj}(\mathcal{C})$ . We need to show that to each element of  $\mathcal{F}(A)$  there corresponds exactly one  $\Phi$ . We will do this by showing that any  $\Phi$  is completely determined by where  $\Phi_A$  sends the identity morphism  $\text{id}_A \in \text{Hom}_{\mathcal{C}}(A, A)$ , so there is exactly one natural transformation for each place  $\Phi$  can send  $\text{id}_A$ .

The proof that this is the case can be illustrated by the following commutative diagram.

$$\begin{array}{ccc}
 \text{Hom}(A, A) & \xrightarrow{h_A(f)} & \text{Hom}(B, A) \\
 \downarrow \Phi_A & & \downarrow \Phi_B \\
 & \begin{array}{ccc} \text{id}_A & \xrightarrow{\quad} & f \\ \downarrow & & \downarrow \\ a & \xrightarrow{\quad} & (\mathcal{F}f)(a) \stackrel{!}{=} \Phi_B(f) \end{array} & \\
 \mathcal{F}(A) & \xrightarrow{\mathcal{F}(f)} & \mathcal{F}(B)
 \end{array}$$

Here's what the above diagram means. The natural transformation  $\Phi: h_A \Rightarrow \mathcal{F}$  has a component  $\Phi_A: \text{Hom}_{\mathcal{C}}(A, A) \rightarrow \mathcal{F}(A)$ , and  $\Phi_A$  has to send the identity transformation  $\text{id}_A$  *somewhere*. It can send it to any element of  $\mathcal{F}(A)$ ; let's call  $\Phi_A(\text{id}_A) = a$ .

Now the naturality conditions force our hand. For any  $B \in \text{Obj}(\mathcal{C})$  and any  $f: B \rightarrow A$ , the naturality square above means that  $\Phi_B(f)$  *has to be* equal to  $(\mathcal{F}f)(a)$ . We get no choice in the matter.

But this completely determines  $\Phi$ ! So we have shown that there is exactly one natural transformation for every element of  $\mathcal{F}(A)$ . We are done!



Well, almost. We still have to show that the bijection we constructed above is natural. To that end, let  $f: B \rightarrow A$ . We need to show that the following square commutes.

$$\begin{array}{ccc} \text{Hom}_{[\mathbf{C}^{\text{op}}, \mathbf{Set}]}(h_A, \mathcal{F}) & \xrightarrow{\eta_A} & \mathcal{F}(A) \\ \text{Hom}_{[\mathbf{C}^{\text{op}}, \mathbf{Set}]}(\mathcal{Y}(f), \mathcal{F}) \downarrow & & \downarrow \mathcal{F}(f) \\ \text{Hom}_{[\mathbf{C}^{\text{op}}, \mathbf{Set}]}(h_B, \mathcal{F}) & \xrightarrow{\eta_B} & \mathcal{F}(B) \end{array}$$

This is notationally dense, and deserves a lot of explanation. The natural transformation  $\text{Hom}_{[\mathbf{C}^{\text{op}}, \mathbf{Set}]}(\mathcal{Y}(f), \mathcal{F})$  looks complicated, but it's really not since we know what the hom functor does: it takes every natural transformation  $h_A \Rightarrow \mathcal{F}$  and pre-composes it with  $\mathcal{Y}(f)$ . The natural transformation  $\eta_A$  takes a natural transformation  $\Phi: h_A \Rightarrow \mathcal{F}$  and sends it to the element  $\Phi_A(\text{id}_A) \in \mathcal{F}(A)$ .

So, starting at the top left with a natural transformation  $\Phi: h_A \Rightarrow \mathcal{F}$ , we can go to the bottom right in two ways.

1. We can head down to  $\text{Hom}_{[\mathbf{C}^{\text{op}}, \mathbf{Set}]}(h_B, \mathcal{F})$ , mapping

$$\Phi \mapsto \Phi \circ \mathcal{Y}(f),$$

then use  $\eta_B$  to map this to  $\mathcal{F}(B)$ :

$$\Phi \circ \mathcal{Y}(f) \mapsto (\Phi \circ \mathcal{Y}(f))_B(\text{id}_B).$$

We can simplify this right away. The component of the composition of natural transformations is the composition of the components, i.e.

$$(\Phi \circ \mathcal{Y}(f))_B(\text{id}_B) = (\Phi_B \circ \mathcal{Y}(f)_B)(\text{id}_B).$$

We also know how  $\mathcal{Y}(f)$  behaves: it composes everything in sight with  $f$ .

$$\mathcal{Y}(f)(\text{id}_B) = f.$$

Thus, we have

$$(\Phi \circ \mathcal{Y}(f))(\text{id}_B) = \Phi_B(f).$$

2. We can first head to the right using  $\eta_A$ . This sends  $\Phi$  to

$$\Phi_A(\text{id}_A) \in \mathcal{F}(A).$$

We can then map this to  $\mathcal{F}(B)$  with  $f$ , getting

$$\mathcal{F}(f)(\Phi_A(\text{id}_A)).$$

The naturality condition is thus

$$(\mathcal{F}(f))(\Phi_A(\text{id}_A)) = \Phi_B(f),$$

which we saw above was true for any natural transformation  $\Phi$ . □

**Lemma 103.** *The Yoneda embedding is fully faithful (Definition 32).*

*Proof.* We have to show that for all  $A, B \in \text{Obj}(\mathcal{C})$ , the map

$$\mathcal{Y}_{A,B}: \text{Hom}_{\mathcal{C}}(A, B) \rightarrow \text{Hom}_{[\mathcal{C}^{\text{op}}, \text{Set}]}(h_A, h_B)$$

is a bijection.

Fix  $B \in \text{Obj}(\mathcal{C})$ , and consider the functor  $h_B$ . By the Yoneda lemma, there is a bijection between  $\text{Hom}_{[\mathcal{C}^{\text{op}}, \text{Set}]}(h_A, h_B)$  and  $h_B(A)$ . By definition,

$$h_B(A) = \text{Hom}_{\mathcal{C}}(A, B).$$

But  $\text{Hom}_{[\mathcal{C}^{\text{op}}, \text{Set}]}(h_A, h_B)$  is nothing else but  $\text{Hom}_{[\mathcal{C}^{\text{op}}, \text{Set}]}(h_A, h_B)$ , so we are done.  $\square$

*Note 104.* We defined the Yoneda embedding to be the functor  $A \mapsto h_A$ ; this is sometimes called the *contravariant Yoneda embedding*. We could also have studied to map  $A$  to  $h^A$ , called the *covariant Yoneda embedding*, in which case a slight modification of the proof of the Yoneda lemma would have told us that the map

$$\text{Hom}_{\mathcal{C}^{\text{op}}}(B, A) \rightarrow \text{Hom}_{[\mathcal{C}, \text{Set}]}(h^A, h^B)$$

is a natural bijection. This is often called the *covariant Yoneda lemma*.

Here is a situation in which the Yoneda lemma is commonly used.

**Corollary 105.** *Let  $\mathcal{C}$  be a locally small category. Suppose for all  $A \in \text{Obj}(\mathcal{C})$  there is a bijection*

$$\text{Hom}_{\mathcal{C}}(A, B) \xrightarrow{\sim} \text{Hom}_{\mathcal{C}}(A, B')$$

*which is natural in  $A$ . Then  $B \simeq B'$*

*Proof.* We have a natural isomorphism  $h_B \Rightarrow h_{B'}$ . Since the Yoneda embedding is fully faithful, it is injective on objects up to isomorphism (Lemma 34). Thus, since  $h_B$  and  $h_{B'}$  are isomorphic, so must be  $B \simeq B'$ .  $\square$

## 3.4 Applications

We have now built up enough machinery to make the proofs of a great variety of things trivial, as long as we accept a few assertions.

It is possible, for example, to prove that the product is associative in *any* locally small category, just from the fact that it is associative in **Set**.

**Lemma 106.** *The Cartesian product is associative in **Set**. That is, there is a natural isomorphism  $\alpha$  between  $(A \times B) \times C$  and  $A \times (B \times C)$  for any sets  $A, B$ , and  $C$ .*

*Proof.* The isomorphism is given by  $\alpha_{A,B,C}: ((a, b), c) \mapsto (a, (b, c))$ . This is natural because for functions like this,

$$\begin{array}{ccc} A & \xrightarrow{f} & A' \\ B & \xrightarrow{g} & B' \\ C & \xrightarrow{h} & C' \end{array}$$

the following diagram commutes.

$$\begin{array}{ccc}
((a, b), c) & \xrightarrow{((f, g), h)} & ((f(a), g(b)), h(c)) \\
\alpha_{A, B, C} \downarrow & & \downarrow \alpha_{A', B', C'} \\
(a, (b, c)) & \xrightarrow{(f, (g, h))} & (f(a), (g(b), h(c)))
\end{array}$$

□

**Theorem 107.** *In any locally small category  $C$  with products, there is a natural isomorphism  $(A \times B) \times C \simeq A \times (B \times C)$ .*

*Proof.* We have the following string of natural isomorphisms for any  $X, A, B, C \in \text{Obj}(C)$ .

$$\begin{aligned}
\text{Hom}_C(X, (A \times B) \times C) &\simeq \text{Hom}_C(X, A \times B) \times \text{Hom}_C(X, C) \\
&\simeq (\text{Hom}_C(X, A) \times \text{Hom}_C(X, B)) \times \text{Hom}_C(X, C) \\
&\simeq \text{Hom}_C(X, A) \times (\text{Hom}_C(X, B) \times \text{Hom}_C(X, C)) \\
&\simeq \text{Hom}_C(X, A) \times \text{Hom}_C(X, B \times C) \\
&\simeq \text{Hom}_C(X, A \times (B \times C)).
\end{aligned}$$

Thus, by [Corollary 105](#),  $(A \times B) \times C \simeq A \times (B \times C)$ .

□

*Note 108.* By induction, all finite products are associative.

**Theorem 109.** *In any category with products  $\times$ , coproducts  $+$ , initial object  $0$ , final object  $1$ , and exponentials, we have the following natural isomorphisms.*

1.  $A \times (B + C) \simeq (A \times B) + (A \times C)$
2.  $C^{A+B} \simeq C^A \times C^B$ .
3.  $(C^A)^B \simeq C^{A \times B}$
4.  $(A \times B)^C \simeq A^C \times B^C$
5.  $C^0 \simeq 1$
6.  $C^1 \simeq C$

*Proof.*

1. We have the following list of natural isomorphisms.

$$\begin{aligned}
\text{Hom}_C(A \times (B + C), X) &\simeq \text{Hom}_C(B + C, X^A) \\
&\simeq \text{Hom}_C(B, X^A) \times \text{Hom}_C(C, X^A) \\
&\simeq \text{Hom}_C(B \times A, X) \times \text{Hom}_C(C \times A, X) \\
&\simeq \text{Hom}_C((B \times A) + (C \times A), X).
\end{aligned}$$

2. We have the following list of natural isomorphisms.

$$\begin{aligned}
\text{Hom}(X, C^{A+B}) &\simeq \text{Hom}(X \times (A + B), C) \\
&\simeq \text{Hom}_C((X \times A) + (X \times B), C) \\
&\simeq \text{Hom}_C(X \times A, C) \times \text{Hom}_C(X \times B, C) \\
&\simeq \text{Hom}_C(X, C^A) \times \text{Hom}_C(X, C^B) \\
&\simeq \text{Hom}_C(X, C^A \times C^B).
\end{aligned}$$

Etc.

□

# 4 Limits

## 4.1 Limits and colimits

The reader may have noticed that there is a lot of difference between

**Definition 110** (diagram). Let  $J$  and  $C$  be categories. A diagram of type  $J$  in  $C$  is a (covariant) functor

$$\mathcal{D}: J \rightsquigarrow C.$$

One thinks of the functor  $\mathcal{D}$  embedding the index category  $J$  into  $C$ .

**Definition 111** (cone). Let  $C$  be a category,  $J$  an index category, and  $\mathcal{D}: J \rightsquigarrow C$  be a diagram. Let  $1$  be the category with one object and one morphism ([Example 4](#)) and  $\mathcal{F}_X$  the functor  $1 \rightsquigarrow C$  which picks out  $X \in \text{Obj}(C)$  (see [Example 27](#)). Let  $\mathcal{K}$  be the unique functor  $J \rightsquigarrow 1$ .

$$\begin{array}{ccc} & 1 & \\ \mathcal{K} \nearrow & & \searrow \mathcal{F}_X \\ J & \xrightarrow{\mathcal{D}} & C \end{array}$$

A cone of shape  $J$  from  $X$  is an object  $X \in \text{Obj}(C)$  together with a natural transformation

$$\varepsilon: \mathcal{F}_X \circ \mathcal{K} \Rightarrow \mathcal{D}.$$

That is to say, a cone to  $J$  is an object  $X \in \text{Obj}(C)$  together with a family of morphisms  $\Phi_A: X \rightarrow \mathcal{D}(A)$  (one for each  $A \in \text{Obj}(J)$ ) such that for all  $A, B \in \text{Obj}(J)$  and all  $f: A \rightarrow B$  the following diagram commutes.

$$\begin{array}{ccc} & X & \\ \Phi_A \swarrow & & \searrow \Phi_B \\ \mathcal{D}(A) & \xrightarrow{\mathcal{D}(f)} & \mathcal{D}(B) \end{array}$$

*Note 112.* Here is an alternate definition. Let  $\Delta$  be the functor  $C \rightsquigarrow [J, C]$  (the category of functors  $J \rightsquigarrow C$ , see [TODO](#)) which assigns to each object  $X \in \text{Obj}(C)$  the constant functor  $\Delta_X: J \rightsquigarrow C$ , i.e. the functor which maps every object of  $J$  to  $X$  and every morphism to  $\text{id}_X$ . A cone over  $\mathcal{D}$  is then an object in the comma category ([Definition 52](#)) ( $\Delta \downarrow \mathcal{D}$ ) given by the diagram

$$C \rightsquigarrow^{\Delta} [J, C] \xleftarrow{\mathcal{D}} 1.$$

The objects of this category are pairs  $(X, f)$ , where  $X \in \text{Obj}(C)$  and  $f: \Delta(X) \rightarrow \mathcal{D}$ ; that is to say,  $f$  is a natural transformation  $\Delta_X \Rightarrow \mathcal{D}$ .

This allows us to make the following definition.

**Definition 113** (category of cones over a diagram). Let  $\mathcal{C}$  be a category,  $\mathcal{J}$  an index category, and  $\mathcal{D}: \mathcal{J} \rightarrow \mathcal{C}$  a diagram. The category of cones over  $\mathcal{D}$  is the category  $(\Delta \downarrow \mathcal{D})$ .

*Note 114.* The alternate definition given in [Note 112](#) not only reiterates what cones look like, but even prescribes what morphisms between cones look like. Let  $(X, \Phi)$  be a cone over a diagram  $\mathcal{D}: \mathcal{J} \rightsquigarrow \mathcal{C}$ , i.e.

- an object in the category  $(\Delta \downarrow \mathcal{D})$ , i.e.
- a pair  $(X, \Phi)$ , where  $X \in \text{Obj}(\mathcal{C})$  and  $\Phi: \Delta_X \Rightarrow \mathcal{D}$  is a natural transformation, i.e.
- for each  $J \in \text{Obj}(\mathcal{J})$  a morphism  $\Phi_J: X \rightarrow \mathcal{D}(J)$  such that for any other object  $J' \in \text{Obj}(\mathcal{J})$  and any morphism  $f: J \rightarrow J'$  the following diagram commutes.

$$\begin{array}{ccc} & X & \\ \Phi_J \swarrow & & \searrow \Phi_{J'} \\ \mathcal{D}(J) & \xrightarrow{\mathcal{D}(f)} & \mathcal{D}(J') \end{array}$$

This agrees with our previous definition of a cone.

Let  $(Y, \Gamma)$  be another cone over  $\mathcal{D}$ . Then a morphism  $\Xi: (X, \Phi) \rightarrow (Y, \Gamma)$  is

- a morphism  $\Xi \in \text{Hom}_{(\Delta \downarrow \mathcal{D})}((X, \Phi), (Y, \Gamma))$ , i.e.
- a natural transformation  $\Xi: \Delta_X \Rightarrow \Delta_Y$  (i.e. a morphism  $\Delta_X \rightarrow \Delta_Y$  in the category  $[\mathcal{J}, \mathcal{C}]$ ) such that the diagram

$$\begin{array}{ccc} \Delta_X & \xRightarrow{\Xi} & \Delta_Y \\ \Phi \searrow & & \swarrow \Gamma \\ & \mathcal{D} & \end{array}$$

commutes, i.e.

- a morphism  $\xi: X \rightarrow Y$  such that for each  $J \in \text{Obj}(\mathcal{J})$ , the diagram

$$\begin{array}{ccc} X & \xrightarrow{\xi} & Y \\ \Phi_J \searrow & & \swarrow \Gamma_J \\ & \mathcal{D}(J) & \end{array}$$

commutes.

Cocones are the dual notion to cones. We make the following definition.

**Definition 115** (cocone). A cocone over a diagram  $\mathcal{D}$  is an object in the comma category  $(\mathcal{D} \downarrow \Delta)$ .

**Definition 116** (category of cocones). The category of cocones over a diagram  $\mathcal{D}$  is the category  $(\mathcal{D} \downarrow \Delta)$ .

The categorical definitions of cones and cocones allow us to define limits and colimits succinctly.

**Definition 117** (limits, colimits). A limit of a diagram  $\mathcal{D}: \mathcal{J} \rightsquigarrow \mathcal{C}$  is a final object in the category  $(\Delta \downarrow \mathcal{D})$ . A colimit is an initial object in the category  $(\mathcal{D} \downarrow \Delta)$ .

*Note 118.* The above definition of a limit unwraps as follows. The limit of a diagram  $\mathcal{D}: J \rightsquigarrow \mathcal{C}$  is a cone  $(X, \Phi)$  over  $\mathcal{D}$  such that for any other cone  $(Y, \Gamma)$  over  $\mathcal{D}$ , there is a unique map  $\xi: Y \rightarrow X$  such that for each  $J \in \text{Obj}(J)$ , the following diagram commutes.

$$\begin{array}{ccc} Y & \xrightarrow{\xi} & X \\ \Gamma_J \searrow & & \swarrow \Phi_J \\ & \mathcal{D}(J) & \end{array}$$

*Notation 119.* We often denote the limit over the diagram  $\mathcal{D}: J \rightsquigarrow \mathcal{C}$  by

$$\lim_{\leftarrow} \mathcal{D}.$$

Similarly, we will denote the colimit over  $\mathcal{D}$  by

$$\lim_{\rightarrow} \mathcal{D}.$$

If there is notational confusion over which functor we are taking a (co)limit, we will add a dummy index:

$$\lim_{\leftarrow i} \mathcal{D}_i \quad \text{or} \quad \lim_{\rightarrow i} \mathcal{D}_i.$$

**Example 120.** Here is a definition of the product  $A \times B$  equivalent to that given in [Example 68](#): it is the limit of the following somewhat trivial diagram.

$$\text{id}_A \hookrightarrow A \quad B \rightrightarrows \text{id}_B$$

Let us unwrap this definition. We are saying that the product  $A \times B$  is a cone over  $A$  and  $B$ .

$$\begin{array}{ccc} & A \times B & \\ \pi_A \swarrow & & \searrow \pi_B \\ A & & B \end{array}$$

But not just any cone: a cone which is universal in the sense that any *other* cone factors through it uniquely.

$$\begin{array}{ccccc} & & X & & \\ & f_1 \swarrow & \downarrow \exists! f & \searrow f_2 & \\ A & \xleftarrow{\pi_A} & A \times B & \xrightarrow{\pi_B} & B \end{array}$$

You will recognize this as precisely the diagram defining the product.

In fact, this allows us to generalize the product: the product of  $n$  objects  $\prod_{i=1}^n A_i$  is the limit over diagram consisting of all the  $A_i$  with no morphisms between them.

**Definition 121** (equalizer). Let  $J$  be the category with objects and morphisms as follows. (The necessary identity arrows are omitted.)

$$J \rightrightarrows J'$$

A diagram  $\mathcal{D}$  of shape  $J$  in some category  $C$  looks like the following.

$$A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B$$

The equalizer of  $f$  and  $g$  is the limit of the diagram  $\mathcal{D}$ ; that is to say, it is an object  $\text{eq} \in \text{Obj}(C)$  and a morphism  $e: \text{eq} \rightarrow A$

$$\text{eq} \xrightarrow{e} A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B$$

such that for any *other* object  $Z$  and morphism  $i: Z \rightarrow A$  such that  $f \circ i = g \circ i$ , there is a unique morphism  $e: Z \rightarrow \text{eq}$  making the following diagram commute.

$$\begin{array}{ccc} Z & & \\ \downarrow \exists! e & \searrow i & \\ \text{eq} & \xrightarrow{e} & A \begin{array}{c} \xrightarrow{f} \\ \xrightarrow{g} \end{array} B \end{array}$$

## 4.2 Pullbacks and kernels

In what follows,  $C$  will be a category and  $A, B$ , etc. objects in  $\text{Obj}(C)$ .

**Definition 122** (pullback). Let  $f, g$  be morphisms as follows.

$$\begin{array}{ccc} & B & \\ & \downarrow g & \\ A & \xrightarrow{f} & C \end{array}$$

A pullback of  $f$  along  $g$  (also called a pullback of  $g$  over  $f$ , sometimes notated  $A \times_C B$ ) is a commuting square

$$\begin{array}{ccc} U & \xrightarrow{q} & B \\ p \downarrow & & \downarrow g \\ A & \xrightarrow{f} & C \end{array}$$

such that for any other commuting square

$$\begin{array}{ccc} V & \xrightarrow{t} & B \\ s \downarrow & & \downarrow g \\ A & \xrightarrow{f} & C \end{array}$$

there is a unique morphism  $h: V \rightarrow U$  such that the diagram

$$\begin{array}{ccccc} V & & \xrightarrow{t} & & B \\ & \searrow \exists! h & & \searrow q & \\ & & U & \xrightarrow{q} & B \\ & & p \downarrow & & \downarrow g \\ & & A & \xrightarrow{f} & C \\ & \swarrow s & & & \end{array}$$

commutes.



*Note 123.* Here is another definition: the pullback  $A \times_C B$  is the limit of the diagram

$$\begin{array}{ccc} & B & \\ & \downarrow g & \\ A & \xrightarrow{f} & C \end{array}$$

This might at first seem odd; after all, don't we also need an arrow  $A \times_C B \rightarrow C$ ? But this arrow is completely determined by the commutativity conditions, so it is superfluous.

**Example 124.** In  $\mathbf{Set}$ ,  $U$  is given (up to unique isomorphism) by

$$U = \{(a, b) \in A \times B \mid f(a) = g(b)\}.$$

The morphisms  $p$  and  $q$  are given by the projections  $p(a, b) = a$ ,  $q(a, b) = b$ .

To see that this really does satisfy the universal property, consider any other set  $V$  and functions  $s: V \rightarrow A$  and  $t: V \rightarrow B$  making the above diagram commute. Then for all  $v \in V$ ,  $f(s(v)) = t(g(v))$ .

Now consider the map  $V \rightarrow U$  sending  $v$  to  $(s(v), t(v))$ . This certainly makes the above diagram commute; furthermore, any other map from  $V$  to  $U$  would not make the diagram commute. Thus  $U$  and  $h$  together satisfy the universal property.

**Lemma 125.** Let  $f: X \rightarrow Y$  be a monomorphism. Then any pullback of  $f$  is a monomorphism.

*Proof.* Suppose we have the following pullback square.

$$\begin{array}{ccc} X' & \xrightarrow{p_1} & X \\ p_2 \downarrow & & \downarrow f \\ Y' & \xrightarrow{g} & Y \end{array}$$

Our aim is to show that  $p_2$  is a monomorphism.

Suppose we are given an object  $Z$  and two morphisms  $\alpha, \beta: Z \rightarrow X'$ .

$$\begin{array}{ccccc} & Z & & & \\ & \searrow \alpha & & & \\ & \searrow \beta & & & \\ & X' & \xrightarrow{p_1} & X & \\ p_2 \downarrow & & & \downarrow f & \\ & Y' & \xrightarrow{g} & Y & \end{array}$$

We can compose  $\alpha$  and  $\beta$  with  $p_2$ . Suppose that these agree, i.e.

$$p_2 \circ \alpha = p_2 \circ \beta.$$

We will be done if we can show that this implies that  $p_1 \circ \alpha = p_1 \circ \beta$ .

We can compose with  $g$  to find that

$$g \circ p_2 \circ \alpha = g \circ p_2 \circ \beta.$$

but since the pullback square commutes, we can replace  $g \circ p_2$  by  $f \circ p_1$ .

$$f \circ p_1 \circ \alpha = f \circ p_1 \circ \beta.$$

since  $f$  is a monomorphism, this implies that

$$p_1 \circ \alpha = p_1 \circ \beta.$$

Now forget  $\alpha$  and  $\beta$  for a minute. We have constructed a commuting square as follows.

$$\begin{array}{ccc} Z & \xrightarrow{p_1 \circ \alpha = p_1 \circ \beta} & X \\ \downarrow p_2 \circ \alpha = p_2 \circ \beta & & \downarrow f \\ X' & \xrightarrow{p_1} & X \\ \downarrow p_2 & & \downarrow g \\ Y' & \xrightarrow{g} & Y \end{array}$$

the universal property for pullbacks tells us that there is a unique morphism  $Z \rightarrow X'$  making the diagram commute. But either  $\alpha$  or  $\beta$  will do! So  $\alpha = \beta$ .  $\square$

**Definition 126** (kernel of a morphism). Let  $C$  be a category with an initial object (Definition 56)  $\emptyset$  and pullbacks. The kernel  $\ker(f)$  of a morphism  $f: A \rightarrow B$  is the pullback along  $f$  of the unique morphism  $\emptyset \rightarrow B$ .

$$\begin{array}{ccc} \ker(f) & \longrightarrow & \emptyset \\ \downarrow \iota & & \downarrow \\ A & \xrightarrow{f} & B \end{array}$$

That is to say, the kernel of  $f$  is a pair  $(\ker(f), \iota)$ , where  $\ker(f) \in \text{Obj}(C)$  and  $\iota: \ker(f) \rightarrow A$  which satisfies the above universal property.

*Note 127.* Although the kernel of a morphism  $f$  is a pair  $(\ker(f), \iota)$  as described above, we will sometimes sloppily say that the object  $\ker(f)$  is the kernel of  $f$ , especially when the the morphism  $\iota$  is obvious or understood. Such abuses of terminology are common; one occasionally even sees the morphism  $\iota$  being called the kernel of  $f$ .

**Example 128.** In  $\text{Vect}_k$ , the initial object is the zero vector space  $\{0\}$ . For any vector spaces  $V$  and  $W$  and any linear map  $f: V \rightarrow W$ , the kernel of  $f$  is the pair  $(\ker(f), \iota)$  where  $\ker(f)$  is the vector space

$$\ker(f) = \{v \in V \mid f(v) = 0\}$$

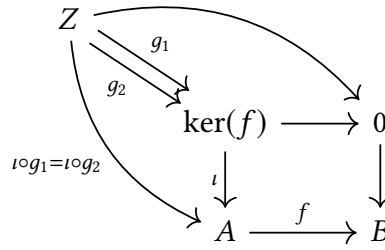
and  $\iota$  is the obvious injection  $\ker(f) \rightarrow V$ .

**Lemma 129.** Let  $f: A \rightarrow B$ , and let  $(\iota, \ker(f))$  be the kernel of  $f$ . Then  $\iota$  is a monomorphism (Definition 14).

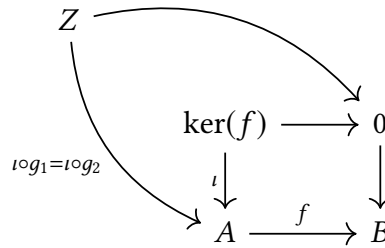
*Proof.* Suppose we have an object  $Z \in \text{Obj}(C)$  and two morphisms  $g_1, g_2: Z \rightarrow \ker(f)$ . We have the following diagram.

$$\begin{array}{ccc} Z & \xrightarrow{g_1} & \ker(f) \\ & \searrow g_2 & \downarrow \iota \\ \ker(f) & \longrightarrow & 0 \\ \downarrow \iota & & \downarrow \\ A & \xrightarrow{f} & B \end{array}$$

Further suppose that  $\iota \circ g_1 = \iota \circ g_2$ .



Now pretend that we don't know about  $g_1$  and  $g_2$ .



The universal property for kernels tells us that there is a unique map  $Z \rightarrow \text{ker}(f)$  making the above diagram commute. But since  $g_1$  and  $g_2$  both make the diagram commute,  $g_1$  and  $g_2$  must be the same map, i.e.  $g_1 = g_2$ .  $\square$

## 4.3 Pushouts and cokernels

Pushouts are the dual notion to pullbacks.

**Definition 130** (pushouts). Let  $f, g$  be morphisms as follows.

$$\begin{array}{ccc}
 C & \xrightarrow{g} & B \\
 f \downarrow & & \\
 A & & 
 \end{array}$$

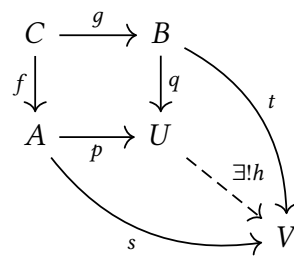
The pushout of  $f$  along  $g$  (or  $g$  along  $f$ ) is a commuting square

$$\begin{array}{ccc}
 C & \xrightarrow{g} & B \\
 f \downarrow & & \downarrow q \\
 A & \xrightarrow{p} & U
 \end{array}$$

such that for any other commuting square

$$\begin{array}{ccc}
 C & \xrightarrow{g} & B \\
 f \downarrow & & \downarrow t \\
 A & \xrightarrow{s} & V
 \end{array}$$

there exists a unique morphism  $h: U \rightarrow V$  such that the diagram

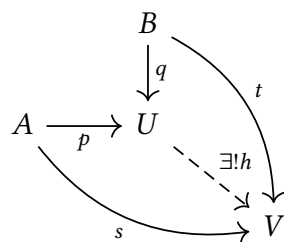


commutes.

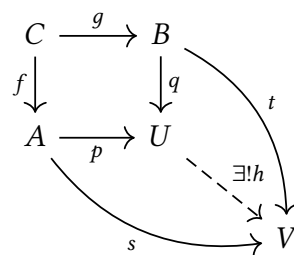
*Note 131.* As with pullbacks, we can also define a pushout as the colimit of the following diagram.

$$\begin{array}{ccc}
 C & \xrightarrow{g} & B \\
 f \downarrow & & \\
 A & & 
 \end{array}$$

**Example 132.** Let us construct the pushout in  $\mathbf{Set}$ . If we ignore the object  $C$  and the morphisms  $f$  and  $g$ , we discover that  $U$  must satisfy the universal property of the coproduct of  $A$  and  $B$ .



Let us therefore make the ansatz that  $U = A \amalg B = A \sqcup B$  and see what happens when we add  $C$ ,  $f$ , and  $g$  back in.



In doing so, we find that the square  $A$ - $C$ - $B$ - $U$  must also commute, i.e. we must have that  $(q \circ g)(c) = (p \circ f)(c)$  for all  $c \in C$ . Since  $p$  and  $q$  are just inclusions, we see that

$$U = A \amalg B / \sim,$$

where  $\sim$  is the equivalence relation generated by the relations  $f(c) \sim g(c)$  for all  $c \in C$ .

**Definition 133** (cokernel of a morphism). Let  $\mathbf{C}$  be a category with terminal object  $1$ . The cokernel of a morphism  $f: A \rightarrow B$  is the pushout of  $f$  along the unique morphism  $A \rightarrow 1$ .

$$\begin{array}{ccc}
 A & \xrightarrow{f} & B \\
 \downarrow & & \downarrow \pi \\
 1 & \longrightarrow & \text{coker}(f)
 \end{array}$$

**Example 134.** In  $\text{Vect}_k$ , the terminal object is the vector space  $\{0\}$ . If  $V$  and  $W$  are  $k$ -vector spaces and  $f$  is a linear map  $V \rightarrow W$ , then  $\text{coker}(f)$  is

$$W/\sim,$$

where  $\sim$  is the relation generated by  $f(v) \sim 0$  for all  $v \in V$ . But this relation is exactly the one which mods out by  $\text{im}(f)$ , so  $\text{coker}(f) = W/\text{im}(f)$ .

**Lemma 135.** For any morphism  $f: A \rightarrow B$ , the canonical projection  $\pi: B \rightarrow \text{coker}(f)$  is an epimorphism.

*Proof.* The proof is dual to the proof that the canonical injection  $\iota$  is mono (Lemma 129).  $\square$

**Definition 136** (normal monomorphism). A monomorphism (Definition 14)  $f: A \rightarrow B$  is normal if it is the kernel of some morphism. To put it more plainly,  $f$  is normal if there exists an object  $C$  and a morphism  $g: B \rightarrow C$  such that  $(A, f)$  is the kernel of  $g$ .

$$A \xrightarrow{f} B \xrightarrow{g} C$$

**Example 137.** In  $\text{Vect}_k$ , monomorphisms are injective linear maps (Example 17). If  $f$  is injective then sequence

$$\{0\} \longrightarrow V \xrightarrow{f} W \xrightarrow{\pi} W/\text{im}(f), \longrightarrow \{0\}$$

is exact, and we always have that  $\text{im}(f) = \ker(\pi)$ . Thus in  $\text{Vect}_k$ , every monomorphism is normal.

**Definition 138** (conormal epimorphism). An epimorphism  $f: A \rightarrow B$  is conormal if it is the cokernel of some morphism. That is to say, if there exists an object  $C$  and a morphism  $g: C \rightarrow A$  such that  $(B, f)$  is the cokernel of  $g$ .

**Example 139.** In  $\text{Vect}_k$ , epimorphisms are surjective linear maps. If  $f: V \rightarrow W$  is a surjective linear map, then the sequence

$$\{0\} \longrightarrow \ker(f) \xrightarrow{\iota} V \xrightarrow{f} W \longrightarrow \{0\}$$

is exact. But then  $\text{im}(\iota) = \ker(f)$ , so  $f$  is conormal. Thus in  $\text{Vect}_k$ , every epimorphism is conormal.

*Note 140.* To show that in our proofs that in  $\text{Vect}_k$  monomorphisms were normal and epimorphisms were conormal, we showed that monomorphisms were the kernels of their cokernels, and epimorphisms were the cokernels of their kernels. This will be a general feature of Abelian categories.

**Definition 141** (binormal category). A category is binormal if all monomorphisms are normal and all epimorphisms are conormal.

**Example 142.** As we have seen,  $\text{Vect}_k$  is binormal.

## 4.4 A necessary and sufficient condition for the existence of finite limits

In this section we prove a simple criterion to check that a category has all finite limits (i.e. limits over diagrams with a finite number of objects and a finite number of morphisms). The idea is as follows.

In general, adding more objects to a diagram makes the limit over it larger, and adding more morphisms makes the limit smaller. In the extreme case in which there are no morphisms (apart from the identity morphisms), the limit is simply the categorical product. As we add morphisms, roughly speaking, we have to get rid of the parts of the product which prevent the triangles they form from commuting. Thus, to make the universal cone over a diagram, we can start with the product, and cut out the bare minimum we need to make everything commute: the way to do that is with an equalizer.

The following proof was adapted from [25].

**Theorem 143.** *Let  $C$  be a category. Then if  $C$  has all finite products and equalizers,  $C$  has all finite limits.*

*Proof.* Let  $\mathcal{D}: J \rightsquigarrow C$  be a finite diagram. We want to prove that  $\mathcal{D}$  has a limit; we will do this by constructing a universal cone over it, i.e.

- an object  $L \in \text{Obj}(C)$ , and
- for each  $j \in \text{Obj}(J)$ , a morphism  $P_j: L \rightarrow \mathcal{D}(j)$

such that

1. for any  $i, j \in \text{Obj}(J)$  and any  $\alpha: i \rightarrow j$  the following diagram commutes,

$$\begin{array}{ccc} & L & \\ P_i \swarrow & & \searrow P_j \\ \mathcal{D}(i) & \xrightarrow{\mathcal{D}(\alpha)} & \mathcal{D}(j) \end{array}$$

and

2. for any other object  $L' \in \text{Obj}(C)$  and family of morphisms  $Q_j: L' \rightarrow \mathcal{D}(j)$  which make the diagrams

$$\begin{array}{ccc} & L' & \\ Q_i \swarrow & & \searrow Q_j \\ \mathcal{D}(i) & \xrightarrow{\mathcal{D}(\alpha)} & \mathcal{D}(j) \end{array}$$

commute for all  $i, j$ , and  $\alpha$ , there is a unique morphism  $f: L' \rightarrow L$  such that  $Q_j = P_j \circ f$  for all  $j \in \text{Obj}(J)$ .

Denote by  $\text{Mor}(J)$  the set of all morphisms in  $J$ . For any  $\alpha \in \text{Mor}(J)$ , denote by  $\text{dom}(\alpha)$  the domain of  $\alpha$ , and by  $\text{cod}(\alpha)$  the codomain.

Consider the following finite products:

$$A = \prod_{j \in \text{Obj}(J)} \mathcal{D}(j) \quad \text{and} \quad B = \prod_{\alpha \in \text{Mor}(J)} \mathcal{D}(\text{cod}(\alpha)).$$

From the universal property for products, we know that we can construct a morphism  $f: A \rightarrow B$  by specifying a family of morphisms  $f_\alpha: A \rightarrow \mathcal{D}(\text{cod}(\alpha))$ , one for each  $\alpha \in \text{Mor}(\mathcal{J})$ . We will define two morphisms  $R, S: A \rightarrow B$  in this way:

$$R_\alpha = \pi_{\mathcal{D}(\text{cod}(\alpha))}; \quad S_\alpha = \mathcal{D}(\alpha) \circ \pi_{\mathcal{D}(\text{dom}(\alpha))}.$$

Now let  $e: L \rightarrow A$  be the equalizer of  $R$  and  $S$  (we are guaranteed the existence of this equalizer by assumption). Further, define  $P_j: L \rightarrow \mathcal{D}(j)$  by

$$P_j = \pi_{\mathcal{D}(j)} \circ e$$

for all  $j \in \text{Obj}(\mathcal{J})$ .

The claim is that  $L$  together with the  $P_j$  is the limit of  $\mathcal{D}$ . We need to verify conditions 1 and 2 on  $L$  and  $P_j$  listed above.

1. We need to show that for all  $i, j \in \text{Obj}(\mathcal{J})$  and all  $\alpha: i \rightarrow j$ , we have the equality  $\mathcal{D}(\alpha) \circ P_i = P_j$ . Now, for every  $\alpha: i \rightarrow j$  we have

$$\begin{aligned} \mathcal{D}(\alpha) \circ P_i &= \mathcal{D}(\alpha) \circ \pi_{\mathcal{D}(i)} \circ e \\ &= S_\alpha \circ e \\ &= R_\alpha \circ e \\ &= \pi_{\mathcal{D}(j)} \circ e \\ &= P_j. \end{aligned}$$

2. We need to show that for any other  $L' \in \text{Obj}(\mathcal{C})$  and any other family of morphisms  $Q_j: L' \rightarrow \mathcal{D}(j)$  such that for all  $\alpha: i \rightarrow j$ ,  $Q_j = \mathcal{D}(\alpha) \circ Q_i$ , there is a unique morphism  $h: L' \rightarrow L$  such that  $Q_j = P_j \circ h$  for all  $j \in \text{Obj}(\mathcal{J})$ . Suppose we are given such an  $L'$  and  $Q_j$ .

The universal property for products allows us to construct from the family of morphisms  $Q_j$  a morphism  $Q: L' \rightarrow A$  such that  $Q_j = \pi_{\mathcal{D}(j)} \circ Q$ . Now, for any  $\alpha: i \rightarrow j$ ,

$$\begin{aligned} R_\alpha \circ Q &= \pi_{\mathcal{D}(j)} \circ Q \\ &= Q_j \\ &= \mathcal{D}(\alpha) \circ Q_i \\ &= \mathcal{D}(\alpha) \circ \pi_i \circ Q \\ &= S_\alpha \circ Q. \end{aligned}$$

Thus,  $Q: L' \rightarrow A$  equalizes  $R$  and  $S$ . But the universal property for equalizers guarantees us a unique morphism  $h: L' \rightarrow L$  such that  $Q = P \circ h$ . We can compose both sides of this equation on the left with  $\pi_{\mathcal{D}(j)}$  to find

$$\pi_{\mathcal{D}(j)} \circ Q = \pi_{\mathcal{D}(j)} \circ P \circ h,$$

i.e.

$$Q_j = P_j \circ h$$

as required. □

## 4.5 The hom functor preserves limits

**Theorem 144.** *Let  $\mathcal{C}$  be a locally small category. The hom functor  $\text{Hom}_{\mathcal{C}}: \mathcal{C}^{\text{op}} \times \mathcal{C} \rightsquigarrow \text{Set}$  preserves limits in the second argument, i.e. for  $\mathcal{D}: \mathcal{J} \rightsquigarrow \mathcal{C}$  a diagram in  $\mathcal{C}$  we have a natural isomorphism*

$$\text{Hom}_{\mathcal{C}}(Y, \lim_{\leftarrow} \mathcal{D}) \simeq \lim_{\leftarrow} \text{Hom}_{\mathcal{C}}(Y, \mathcal{D}),$$

where the limit on the RHS is over the hom-set diagram

$$\text{Hom}_{\mathcal{C}}(Y, -) \circ \mathcal{D}: \mathcal{J} \rightsquigarrow \text{Set}.$$

*Proof.* Let  $L$  be the limit over the diagram  $\mathcal{D}$ . Then for any map  $f: Y \rightarrow L$ , there is a cone from  $Y$  to  $\mathcal{D}$  by composition, and for any cone with tip  $Y$  over  $\mathcal{D}$  we get a map  $f: Y \rightarrow L$  from the universal property of limits. Thus, there is a bijection

$$\text{Hom}_{\mathcal{C}}(Y, \lim_{\leftarrow} \mathcal{D}) \simeq \text{Cones}(Y, \mathcal{D}),$$

which is natural in  $Y$  since the diagram

$$\begin{array}{ccc} \text{Hom}_{\mathcal{C}}(Y, \lim_{\leftarrow} \mathcal{D}) & \xrightarrow{(-) \circ f} & \text{Hom}_{\mathcal{C}}(Z, \lim_{\leftarrow} \mathcal{D}) \\ \downarrow & & \downarrow \\ \text{Cones}(Y, \mathcal{D}) & \xrightarrow{(-) \circ f} & \text{Cones}(Z, \mathcal{D}) \end{array}$$

trivially commutes. We will be done if we can show that there is also a natural isomorphism

$$\text{Cones}(Y, \mathcal{D}) \simeq \lim_{\leftarrow} \text{Hom}_{\mathcal{C}}(Y, \mathcal{D}).$$

Let us understand the elements of the set  $\lim_{\leftarrow} \text{Hom}_{\mathcal{C}}(Y, \mathcal{D})$ . The diagram

$$\text{Hom}_{\mathcal{C}}(Y, -) \circ \mathcal{D}: \mathcal{J} \rightsquigarrow \text{Set}$$

maps  $J \in \text{Obj}(\mathcal{J})$  to  $\text{Hom}_{\mathcal{C}}(Y, \mathcal{D}(J)) \in \text{Obj}(\text{Set})$ . A universal cone over this diagram is a set  $S$  together with, for each  $J_i \in \text{Obj}(\mathcal{J})$ , a function

$$f_i: S \rightarrow \text{Hom}_{\mathcal{C}}(Y, \mathcal{D}(J_i))$$

such that for each  $\alpha \in \text{Hom}_{\mathcal{J}}(J_i, J_j)$ , the diagram

$$\begin{array}{ccc} & S & \\ f_i \swarrow & & \searrow f_j \\ \text{Hom}_{\mathcal{C}}(Y, \mathcal{D}(J_i)) & \xrightarrow{\mathcal{D}(\alpha) \circ (-)} & \text{Hom}_{\mathcal{C}}(Y, \mathcal{D}(J_j)) \end{array}$$

commutes.

Now pick any element  $s \in S$ . Each  $f_i$  maps this to a function  $Y \rightarrow \mathcal{D}(J_i)$  which makes the diagram

$$\begin{array}{ccc} & Y & \\ f_i(s) \swarrow & & \searrow f_j(s) \\ \mathcal{D}(J_i) & \xrightarrow{\mathcal{D}(\alpha)} & \mathcal{D}(J_j) \end{array}$$



commute. But this is exactly an element of  $\text{Cones}(Y, \mathcal{D})$ . Conversely, every element of  $\text{Cones}(Y, \mathcal{D})$  gives us an element of  $S$ , so we have a bijection

$$\text{Cones}(Y, \mathcal{D}) \simeq \lim_{\leftarrow} \text{Hom}_C(Y, \mathcal{D}),$$

which is natural as required.  $\square$

**Corollary 145.** *The first slot of the hom functor turns colimits into limits. That is,*

$$\text{Hom}_C(\lim_{\rightarrow} \mathcal{D}, Y) \simeq \lim_{\leftarrow} \text{Hom}_C(\mathcal{D}, Y).$$

*Proof.* Dual to that of [Theorem 144](#).  $\square$

## 4.6 Filtered colimits and ind-objects

**Definition 146** (preorder). Let  $S$  be a set. A preorder on  $S$  is a binary relation  $\leq$  which is

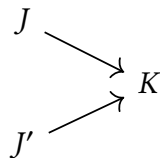
1. reflexive ( $a \leq a$ )
2. transitive (if  $a \leq b$  and  $b \leq c$ , then  $a \leq c$ )

A preorder is said to be directed if for any two objects  $a$  and  $b$ , there exists an ‘upper bound,’ i.e. an object  $r$  such that  $a \leq r$  and  $b \leq r$ .

Filtered categories are a generalization of filtered preorders.

**Definition 147** (filtered category). A category  $J$  is filtered if

- for each pair of objects  $J, J' \in \text{Obj}(J)$ , there exists an object  $K$  and morphisms  $J \rightarrow K$  and  $J' \rightarrow K$ .



That is, every diagram with two objects and no morphisms is the base of a cocone.

- For every pair of morphisms  $i, j: J \rightarrow J'$ , there exists an object  $K$  and a morphism  $f: J' \rightarrow K$  such that  $f \circ i = f \circ j$ , i.e. the following diagram commutes.

$$J \begin{array}{c} \xrightarrow{i} \\ \xrightarrow{j} \end{array} J' \xrightarrow{f} K$$

That is, every diagram of the form  $\bullet \rightrightarrows \bullet$  is the base of a cocone.

**Definition 148** (filtered colimit). A filtered colimit is a colimit over a diagram  $\mathcal{D}: J \rightarrow C$ , where  $J$  is a filtered category.

We now define the so-called *category of inductive objects* (or simply *ind-objects*).

**Definition 149** (category of ind-objects). Let  $C$  be a category. We define the category of ind-objects of  $C$ , denote  $\text{Ind}(C)$  as follows.

- The objects  $F \in \text{Obj}(\text{Ind}(\mathcal{C}))$  are defined to be filtered colimits of objects of diagrams  $\mathcal{F}: \mathcal{D} \rightsquigarrow \mathcal{C}$ .
- For two objects  $F = \lim_{\rightarrow d} \mathcal{F}_d$  and  $G = \lim_{\rightarrow e} \mathcal{G}_e$ , the morphisms  $\text{Hom}_{\text{Ind}(\mathcal{C})}(F, G)$  are defined to be the set

$$\text{Hom}_{\text{Ind}(\mathcal{C})}(F, G) = \lim_{\leftarrow d} \lim_{\rightarrow e} \text{Hom}_{\mathcal{C}}(\mathcal{F}_d, \mathcal{G}_e).$$

*Note 150.* There is a fully faithful embedding  $\mathcal{C} \hookrightarrow \text{Ind}(\mathcal{C})$  which exhibits any object  $A$  as the colimit over the trivial diagram  $\bullet \rightrightarrows \bullet$ .

The importance of the category of ind-objects can be seen in the following example.

**Example 151.** Let  $V$  be an infinite-dimensional vector space over some field  $k$ . Then  $V$  can be realized as an object in the category  $\text{Ind}(\text{FinVect})$ .

In fact, there is an equivalence of categories  $\text{Vect}_k \simeq \text{Ind}(\text{FinVect}_k)$ . Similarly, there is an equivalence of categories  $\text{SVect}_k \simeq \text{Ind}(\text{FinSVect}_k)$ .

*Note 152.* This is stated without proof as Example 3.39 of [11]. I haven't been able to find a real source for it.

# 5 Adjunctions

Consider the following functors:

- $\mathcal{U}: \mathbf{Grp} \rightsquigarrow \mathbf{Set}$ , which sends a group to its underlying set, and
- $\mathcal{F}: \mathbf{Set} \rightsquigarrow \mathbf{Grp}$ , which sends a set to the free group on it.

The functors  $\mathcal{U}$  and  $\mathcal{F}$  are dual in the following sense:  $\mathcal{U}$  is the most efficient way of moving from  $\mathbf{Grp}$  to  $\mathbf{Set}$  since all groups are in particular sets;  $\mathcal{F}$  might be thought of as providing the most efficient way of moving from  $\mathbf{Set}$  to  $\mathbf{Grp}$ . But how would one go about formalizing this?

Well, these functors have the following property. Let  $S$  be a set,  $G$  be a group, and let  $f: S \rightarrow \mathcal{U}(G)$ ,  $s \mapsto f(s)$  be a set-function. Then there is an associated group homomorphism  $\tilde{f}: \mathcal{F}(S) \rightarrow G$ , which sends  $s_1 s_2 \dots s_n \mapsto f(s_1 s_2 \dots s_n) = f(s_1) \cdots f(s_n)$ . In fact,  $\tilde{f}$  is the unique homomorphism  $\mathcal{F}(S) \rightarrow G$  such that  $f(s) = \tilde{f}(s)$  for all  $s \in S$ .

Similarly, for every group homomorphism  $g: \mathcal{F}(S) \rightarrow G$ , there is an associated function  $S \rightarrow \mathcal{U}(G)$  given by restricting  $g$  to  $S$ . In fact, this is the unique function  $\mathcal{F}(S) \rightarrow G$  such that  $f(s) = \tilde{f}(s)$  for all  $s \in S$ .

Thus for each  $f \in \text{Hom}_{\mathbf{Grp}}(S, \mathcal{U}(G))$  we can construct an  $\tilde{f} \in \text{Hom}_{\mathbf{Set}}(\mathcal{F}(S), G)$ , and vice versa.

Let us add some mathematical scaffolding to the ideas explored above. We build two functors  $\mathbf{Set}^{\text{op}} \times \mathbf{Grp} \rightsquigarrow \mathbf{Set}$  as follows.

1. Our first functor maps the object  $(S, G) \in \text{Obj}(\mathbf{Set}^{\text{op}} \times \mathbf{Grp})$  to the hom-set  $\text{Hom}_{\mathbf{Grp}}(\mathcal{F}(S), G)$ , and a morphism  $(\alpha, \beta): (S, G) \rightarrow (S', G')$  to a function

$$\text{Hom}_{\mathbf{Grp}}(\mathcal{F}(S), G) \rightarrow \text{Hom}_{\mathbf{Grp}}(\mathcal{F}(S'), G'); \quad m \mapsto \mathcal{F}(\alpha) \circ m \circ \beta$$

2. Our second functor maps  $(S, G)$  to  $\text{Hom}_{\mathbf{Set}}(S, \mathcal{U}(G))$ , and  $(\alpha, \beta)$  to

$$m \mapsto \alpha \circ m \circ \mathcal{U}(\beta).$$

We can define a natural isomorphism  $\Phi$  between these functors with components

$$\Phi_{S,G}: \text{Hom}_{\mathbf{Grp}}(\mathcal{F}(S), G) \rightarrow \text{Hom}_{\mathbf{Set}}(S, \mathcal{U}(G)); \quad f \rightarrow \tilde{f}.$$

This mathematical structure turns out to be a recurring theme in the study of categories, called an *adjunction*. We have encountered it before: we saw in [Example 95](#) that there was a natural bijection between

$$\text{Hom}_{\mathbf{C}}(X \times (-), B) \quad \text{and} \quad \text{Hom}_{\mathbf{C}}(X, B^{(-)}).$$

**Definition 153** (hom-set adjunction). Let  $\mathbf{C}, \mathbf{D}$  be categories and  $\mathcal{F}, \mathcal{G}$  functors as follows.

$$\begin{array}{ccc} \mathbf{C} & \begin{array}{c} \xrightarrow{\mathcal{F}} \\ \xleftarrow{\mathcal{G}} \end{array} & \mathbf{D} \end{array}$$

We say that  $\mathcal{F}$  is left-adjoint to  $\mathcal{G}$  (or equivalently  $\mathcal{G}$  is right-adjoint to  $\mathcal{F}$ ) and write  $\mathcal{F} \dashv \mathcal{G}$  if there is a natural isomorphism

$$\Phi: \text{Hom}_D(\mathcal{F}(-), -) \Rightarrow \text{Hom}_C(-, \mathcal{G}(-)),$$

which fits between  $\mathcal{F}$  and  $\mathcal{G}$  like this.

$$\begin{array}{ccc} & \text{Hom}_D(\mathcal{F}(-), -) & \\ & \Downarrow \Phi & \\ C^{\text{op}} \times D & & \text{Set} \\ & \text{Hom}_D(-, \mathcal{G}(-)) & \end{array}$$

The natural isomorphism amounts to a family of bijections

$$\Phi_{A,B}: \text{Hom}_D(\mathcal{F}(A), B) \rightarrow \text{Hom}_C(A, \mathcal{G}(B))$$

which satisfies the coherence conditions for a natural transformation.

Here are two equivalent definitions which are often used.

**Definition 154** (unit-counit adjunction). We say that two functors  $\mathcal{F}: C \rightsquigarrow D$  and  $\mathcal{G}: D \rightsquigarrow C$  form a unit-counit adjunction if there are two natural transformations

$$\eta: \text{id}_C \Rightarrow \mathcal{G} \circ \mathcal{F}, \quad \text{and} \quad \varepsilon: \mathcal{F} \circ \mathcal{G} \Rightarrow \text{id}_D,$$

called the *unit* and *counit* respectively, which make the following so-called *triangle diagrams*

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\mathcal{F}\eta} & \mathcal{F}\mathcal{G}\mathcal{F} \\ & \searrow \text{id}_{\mathcal{F}} & \downarrow \varepsilon_{\mathcal{F}} \\ & & \mathcal{F} \end{array} \quad , \quad \begin{array}{ccc} \mathcal{G} & \xrightarrow{\eta\mathcal{G}} & \mathcal{G}\mathcal{F}\mathcal{G} \\ & \searrow \text{id}_{\mathcal{G}} & \downarrow \mathcal{G}\varepsilon \\ & & \mathcal{G} \end{array}$$

commute.

The triangle diagrams take quite some explanation. The unit  $\eta$  is a natural transformation  $\text{id}_C \Rightarrow \mathcal{G} \circ \mathcal{F}$ . We can draw it like this.

$$\begin{array}{ccc} & \text{id}_C & \\ & \Downarrow \eta & \\ C & & C \\ & \text{G} \circ \text{F} & \end{array}$$

Analogously, we can draw  $\varepsilon$  like this.

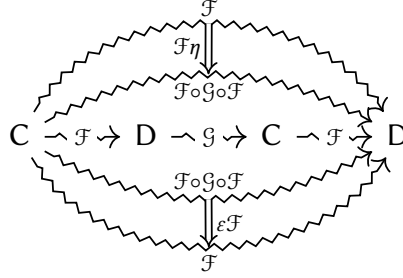
$$\begin{array}{ccc} & \text{F} \circ \text{G} & \\ & \Downarrow \varepsilon & \\ D & & D \\ & \text{id}_D & \end{array}$$

We can arrange these artfully like so.

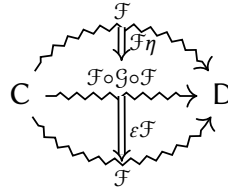
$$\begin{array}{c} \text{id}_C \\ \Downarrow \eta \\ C \rightsquigarrow \mathcal{F} \rightarrow D \rightsquigarrow \mathcal{G} \rightarrow C \rightsquigarrow \mathcal{F} \rightarrow D \\ \Downarrow \varepsilon \\ \text{id}_D \end{array}$$

Notice that we haven't actually *done* anything; this diagram is just the diagrams for the unit and counit, plus some extraneous information.

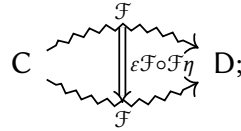
We can whisker the  $\eta$  on top from the right, and the  $\varepsilon$  below from the left, to get the following diagram,



then consolidate to get this:



We can then take the composition  $\varepsilon F \circ F\eta$  to get a natural transformation  $F \Rightarrow F$



the first triangle diagram says that this must be the same as the identity natural transformation  $\text{id}_F$ .

The second triangle diagram is analogous.

**Lemma 155.** *The functors  $F$  and  $G$  form a unit-counit adjunction if and only if they form a hom-set adjunction.*

*Proof.* Suppose  $F$  and  $G$  form a hom-set adjunction with natural isomorphism  $\Phi$ . Then for any  $A \in \text{Obj}(C)$ , we have  $F(A) \in \text{Obj}(D)$ , so  $\Phi$  give us a bijection

$$\Phi_{A, F(A)}: \text{Hom}_D(F(A), F(A)) \rightarrow \text{Hom}_C(A, (G \circ F)(A)).$$

We don't know much in general about  $\text{Hom}_D(F(A), F(A))$ , but the category axioms tell us that it always contains  $\text{id}_{F(A)}$ . We can use  $\Phi_{A, F(A)}$  to map this to

$$\Phi_{A, F(A)}(\text{id}_{F(A)}) \in \text{Hom}_C(A, (G \circ F)(A)).$$

Let's call  $\Phi_{A, F(A)}(\text{id}_{F(A)}) = \eta_A$ .

Similarly, if  $B \in \text{Obj}(D)$ , then  $G(B) \in \text{Obj}(C)$ , so  $\Phi$  gives us a bijection

$$\Phi_{G(B), B}: \text{Hom}_D((F \circ G)(B), B) \rightarrow \text{Hom}_C(G(B), G(B)).$$

Since  $\Phi_{G(B), B}$  is a bijection, it is invertible, and we can evaluate the inverse on  $\text{id}_{G(B)}$ . Let's call

$$\Phi_{G(B), B}^{-1}(\text{id}_{G(B)}) = \varepsilon_B.$$

Clearly,  $\eta_A$  and  $\varepsilon_B$  are completely determined by  $\Phi$  and  $\Phi^{-1}$  respectively. It turns out that the converse is also true; in a manner reminiscent of the proof of the Yoneda lemma, we can express  $\Phi_{A,B}$  in terms of  $\eta$ , and  $\Phi_{A,B}^{-1}$  in terms of  $\varepsilon$ , for *any*  $A$  and  $B$ . Here's how this is done.

We use the naturality of  $\Phi$ . We know that for any  $A \in \text{Obj}(\mathcal{C})$ ,  $B \in \text{Obj}(\mathcal{D})$ , and  $g: \mathcal{F}(A) \rightarrow B$ , the following diagram has to commute.

$$\begin{array}{ccc} \text{Hom}_{\mathcal{D}}(\mathcal{F}(A), \mathcal{F}(A)) & \xrightarrow{g \circ (-)} & \text{Hom}_{\mathcal{D}}(\mathcal{F}(A), B) \\ \downarrow \Phi_{A, \mathcal{F}(A)} & & \downarrow \Phi_{A, B} \\ \text{Hom}_{\mathcal{C}}(A, (\mathcal{G} \circ \mathcal{F})(A)) & \xrightarrow{\mathcal{G}(g) \circ (-)} & \text{Hom}_{\mathcal{C}}(A, \mathcal{G}(B)). \end{array}$$

Let's start at the top left with  $\text{id}_{\mathcal{F}(A)}$  and see what happens. Taking the top road to the bottom right, we have  $\Phi_{A,B}(g)$ , and from the bottom road we have  $\mathcal{G}(g) \circ \eta_A$ . The diagram commutes, so we have

$$\Phi_{A,B}(g) = \mathcal{G}(g) \circ \eta_A.$$

Similarly, the commutativity of the diagram

$$\begin{array}{ccc} \text{Hom}_{\mathcal{D}}((\mathcal{F} \circ \mathcal{G})(B), B) & \xrightarrow{(-) \circ \mathcal{F}(f)} & \text{Hom}_{\mathcal{D}}(\mathcal{F}(A), B) \\ \uparrow \Phi_{\mathcal{G}(B), B}^{-1} & & \uparrow \Phi_{A, B}^{-1} \\ \text{Hom}_{\mathcal{C}}(\mathcal{G}(B), \mathcal{G}(B)) & \xrightarrow{(-) \circ f} & \text{Hom}_{\mathcal{C}}(A, \mathcal{G}(B)) \end{array}$$

means that, for any  $f: A \rightarrow \mathcal{G}(B)$ ,

$$\Phi_{A,B}^{-1}(f) = \varepsilon_B \circ \mathcal{F}(f)$$

To show that  $\eta$  and  $\varepsilon$  as defined here satisfy the triangle identities, we need to show that for all  $A \in \text{Obj}(\mathcal{C})$  and all  $B \in \text{Obj}(\mathcal{D})$ ,

$$(\varepsilon \mathcal{F})_A \circ (\mathcal{F} \eta)_A = (\text{id}_{\mathcal{F}})_A \quad \text{and} \quad (\mathcal{G} \varepsilon)_B \circ (\eta \mathcal{G})_B = (\text{id}_{\mathcal{G}})_B.$$

We have

$$(\varepsilon \mathcal{F})_A \circ (\mathcal{F} \eta)_A = \varepsilon_{\mathcal{F}(A)} \circ \mathcal{F}(\eta_A) = \Phi_{A, \mathcal{F}(A)}^{-1}(\eta_A) = \text{id}_A = (\text{id}_{\mathcal{F}})_A$$

and

$$(\mathcal{G} \varepsilon)_B \circ (\eta \mathcal{G})_B = \mathcal{G}(\varepsilon_B) \circ \eta_{\mathcal{G}(B)} = \Phi_{\mathcal{G}(B), B}(\varepsilon_B) = \text{id}_B = (\text{id}_{\mathcal{G}})_B.$$

□

**Definition 156** (adjunct). Let  $\mathcal{F} \dashv \mathcal{G}$  be an adjunction as follows.

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

Then for each  $A \in \text{Obj}(\mathcal{C})$   $B \in \text{Obj}(\mathcal{D})$ , we have a natural isomorphism (i.e. a bijection)

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

Thus, for each  $f \in \text{Hom}_{\mathcal{D}}(\mathcal{F}(A), B)$  there is a corresponding element  $\tilde{f} \in \text{Hom}_{\mathcal{C}}(A, \mathcal{G}(B))$ , and vice versa. The morphism  $\tilde{f}$  is called the adjunct of  $f$ , and  $f$  is called the adjunct of  $\tilde{f}$ .

**Lemma 157.** Let  $C$  and  $D$  be categories,  $\mathcal{F}: C \rightsquigarrow D$  and  $\mathcal{G}, \mathcal{G}': D \rightsquigarrow C$  functors,

$$\begin{array}{ccc} & \mathcal{G} & \\ \swarrow & \text{---} & \searrow \\ C & \xrightarrow{\mathcal{F}} & D \\ \swarrow & \text{---} & \searrow \\ & \mathcal{G}' & \end{array}$$

and suppose that  $\mathcal{G}$  and  $\mathcal{G}'$  are both right-adjoint to  $\mathcal{F}$ . Then there is a natural isomorphism  $\mathcal{G} \Rightarrow \mathcal{G}'$ .

*Proof.* Since any adjunction is a hom-set adjunction, we have two isomorphisms

$$\Phi_{C,D}: \text{Hom}_D(\mathcal{F}(C), D) \Rightarrow \text{Hom}_C(C, \mathcal{G}(D)) \quad \text{and} \quad \Psi_{C,D}: \text{Hom}_D(\mathcal{F}(C), D) \Rightarrow \text{Hom}_C(C, \mathcal{G}'(D))$$

which are natural in both  $C$  and  $D$ . By [Lemma 40](#), we can construct the inverse natural isomorphism

$$\Phi_{C,D}^{-1}: \text{Hom}_C(C, \mathcal{G}(D)) \Rightarrow \text{Hom}_D(\mathcal{F}(C), D),$$

and compose it with  $\Psi$  to get a natural isomorphism

$$(\Psi \circ \Phi^{-1})_{C,D}: \text{Hom}_C(C, \mathcal{G}(D)) \Rightarrow \text{Hom}_C(C, \mathcal{G}'(D)).$$

Thus for any morphism  $f: D \rightarrow E$ , the following diagram commutes.

$$\begin{array}{ccc} \text{Hom}_C(C, \mathcal{G}(D)) & \xrightarrow{\text{Hom}_C(C, \mathcal{G}(f))} & \text{Hom}_C(C, \mathcal{G}(E)) \\ \downarrow (\Psi \circ \Phi^{-1})_{C,D} & & \downarrow (\Psi \circ \Phi^{-1})_{C,E} \\ \text{Hom}_C(C, \mathcal{G}'(D)) & \xrightarrow{\text{Hom}_C(C, \mathcal{G}'(f))} & \text{Hom}_C(C, \mathcal{G}'(E)) \end{array}$$

But the full faithfulness of the Yoneda embedding tells us that there exist isomorphisms  $\mu_D$  and  $\mu_E$  making the following diagram commute,

$$\begin{array}{ccc} \mathcal{G}(D) & \xrightarrow{\mathcal{G}(f)} & \mathcal{G}(E) \\ \mu_D \downarrow & & \downarrow \mu_E \\ \mathcal{G}'(D) & \xrightarrow{\mathcal{G}'(f)} & \mathcal{G}'(E) \end{array}$$

and taking the collection of all such  $\mu_{(-)}$  gives us a natural isomorphism  $\mu: \mathcal{G} \Rightarrow \mathcal{G}'$ . □

*Note 158.* We do not give very many examples of adjunctions now because of the frequency with which category theory graces us with them. However, it is worth mentioning a specific class of adjunctions: the so-called *free-forgetful adjunctions*. There are many *free* objects in mathematics: free groups, free modules, free vector spaces, free categories, etc. These are all unified by the following property: the functors defining them are all left adjoints.

Let us take a specific example: the free vector space over a set. This takes a set  $S$  and constructs a vector space which has as a basis the elements of  $S$ .

There is a forgetful functor  $\mathcal{U}: \text{Vect}_k \rightsquigarrow \text{Set}$  which takes any set and returns the set underlying it. There is a functor  $\mathcal{F}: \text{Set} \rightsquigarrow \text{Vect}_k$ , which takes a set and returns the free vector space on it. It turns out that there is an adjunction  $\mathcal{F} \dashv \mathcal{U}$ .

And this is true of any free object! (In fact by definition.) In each case, the functor giving the free object is left adjoint to a forgetful functor.

**Theorem 159.** Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories and  $\mathcal{F}$  and  $\mathcal{G}$  functors as follows.

$$\begin{array}{ccc} & \mathcal{F} & \\ & \rightsquigarrow & \\ \mathcal{C} & & \mathcal{D} \\ & \stackrel{\sim}{\leftarrow} & \\ & \mathcal{G} & \end{array}$$

Let  $\mathcal{F} \dashv \mathcal{G}$  be an adjunction. Then  $\mathcal{G}$  preserves limits, i.e. if  $\mathcal{D}: \mathbf{J} \rightarrow \mathcal{C}$  is a diagram and  $\lim_{\leftarrow i} \mathcal{D}_i$  exists in  $\mathcal{C}$ , then

$$\mathcal{G}(\lim_{\leftarrow i} \mathcal{D}_i) \simeq \lim_{\leftarrow i} (\mathcal{G} \circ \mathcal{D}_i).$$

*Proof.* We have the following chain of isomorphisms, natural in  $Y \in \text{Obj}(\mathcal{D})$ .

$$\begin{aligned} \text{Hom}_{\mathcal{D}}(Y, \mathcal{G}(\lim_{\leftarrow i} \mathcal{D}_i)) &\simeq \text{Hom}_{\mathcal{C}}(\mathcal{F}(Y), \lim_{\leftarrow i} \mathcal{D}_i) \\ &\simeq \lim_{\leftarrow i} \text{Hom}_{\mathcal{C}}(\mathcal{F}(Y), \mathcal{D}_i) && \left( \begin{array}{l} \text{Hom functor commutes with} \\ \text{limits: Theorem 144} \end{array} \right) \\ &\simeq \lim_{\leftarrow i} \text{Hom}_{\mathcal{D}}(Y, \mathcal{G} \circ \mathcal{D}_i) \\ &\simeq \text{Hom}_{\mathcal{C}}(Y, \lim_{\leftarrow i} (\mathcal{G} \circ \mathcal{D}_i)). \end{aligned}$$

By the Yoneda lemma, specifically [Corollary 105](#), we have a natural isomorphism

$$\mathcal{G}(\lim_{\leftarrow i} \mathcal{D}_i) \simeq \lim_{\leftarrow i} (\mathcal{G} \circ \mathcal{D}_i).$$

□

**Corollary 160.** Any functor  $\mathcal{F}$  which is a left-adjoint preserves colimits.

*Proof.* Dual to the proof of [Theorem 159](#).

□



# 6 Monoidal categories

## 6.1 Structure

### 6.1.1 Basic definitions

Many types of mathematical structures can be combined to form new ones. For example:

- The tensor product allows us to use two vector spaces to produce a new one, as does the direct sum.
- The Cartesian product and the disjoint union of sets produce a new set out of two given ones.

In each of these cases, there is a natural isomorphisms making this combination associative, and an identity object which acts, up to natural isomorphism, as a left and right identity. This means that each of these operations gives the collection of all objects the structure of a monoid.

A monoidal category will be a category in which the objects have the structure of a monoid, i.e. there is a suitably defined ‘multiplication’ (usually written  $\otimes$ ) which is unital (with unit 1) and associative. The prototypical example of categorical multiplication is the product (see [Example 68](#)), although it is far from the only one.

When put like this, monoidal categories don’t sound like complicated entities, and indeed in practice they are not. However, there is a lot of subtlety in making associativity play well with multiplication by units. Since we are in a category, demanding that our multiplication be associative ‘on the nose,’ i.e. that, for example,

$$(V \otimes 1) \otimes (W \otimes T) \quad \text{and} \quad (V \otimes W) \otimes T$$

should be literally equal, is too draconian, not to mention difficult to interpret. The natural weakening of this is to demand that these be merely isomorphic, but this is far too weak: for vector spaces, for example, this requires only that the dimension be the same. Even natural isomorphism is not quite strong enough.

The correct way of solving this problem is by demanding that certain diagrams, called *coherenece diagrams*, commute. These diagrams then force other diagrams to commute in a way that solves our problem, as Mac Lane showed in the so-called *Mac Lane’s Coherence Theorem*.

**Definition 161** (monoidal category). A monoidal category is a category  $C$  equipped with a monoidal structure. A monoidal structure is the following:

- A bifunctor ([Definition 28](#))  $\otimes: C \times C \rightarrow C$  called the *tensor product*,
- An object  $I$  called the *unit object*, and
- Three natural isomorphisms ([Definition 38](#)) subject to coherence conditions expressing the fact that the tensor product

- is associative: there is a natural isomorphism  $\alpha$  called the *associator*, with components

$$\alpha_{A,B,C}: (A \otimes B) \otimes C \xrightarrow{\sim} A \otimes (B \otimes C)$$

- has left and right identity: there are two natural isomorphisms  $\lambda$  and  $\rho$  respectively called the *left unitor* and *right unitor* with components

$$\lambda_A: I \otimes A \xrightarrow{\sim} A$$

and

$$\rho_A: A \otimes I \xrightarrow{\sim} A.$$

The coherence conditions are that the following diagrams commute for all  $A, B, C$ , and  $D \in \text{Obj}(\mathcal{C})$ .

- The *triangle diagram*

$$\begin{array}{ccc} (A \otimes I) \otimes B & \xrightarrow{\alpha_{A,I,B}} & A \otimes (I \otimes B) \\ \searrow \rho_A \otimes \text{id}_B & & \swarrow \text{id}_A \otimes \lambda_B \\ & A \otimes B & \end{array}$$

- The *home plate diagram*<sup>1</sup> (usually the *pentagon diagram*)

$$\begin{array}{ccccc} & & (A \otimes (B \otimes C)) \otimes D & & \\ & \nearrow \alpha_{A,B,C} \otimes \text{id}_D & & \searrow \alpha_{A,B \otimes C,D} & \\ ((A \otimes B) \otimes C) \otimes D & & & & A \otimes ((B \otimes C) \otimes D) \\ \downarrow \alpha_{A \otimes B,C,D} & & & & \downarrow \text{id}_A \otimes \alpha_{B,C,D} \\ (A \otimes B) \otimes (C \otimes D) & \xrightarrow{\alpha_{A,B,C \otimes D}} & & & A \otimes (B \otimes (C \otimes D)) \end{array}$$

More succinctly, a monoidal structure on a category  $\mathcal{C}$  is a quintuple  $(\otimes, 1, \alpha, \lambda, \rho)$ .

*Notation 162.* The notation  $(\otimes, 1, \alpha, \lambda, \rho)$  is prone to change. If the associator and unitors are not important, or understood from context, they are often left out. We will often say “Let  $(\mathcal{C}, \otimes, 1)$  be a monoidal category.”

**Example 163.** The simplest (though not the prototypical) example of a monoidal category is  $\text{Set}$  with the Cartesian product. We have already studied this structure in some detail in [Section 2.1](#). We check that it satisfies the axioms in [Definition 161](#).

<sup>1</sup>Unfortunately, the home plate, as drawn, is actually upside down.

- The Cartesian product on  $\mathbf{Set}$  is a set-theoretic product, and can be naturally viewed, thanks to [Theorem 71](#), as the bifunctor.
- Any set with one element  $I = \{*\}$  functions as the unit object.
- For all sets  $A, B, C$

- The universal property of products gives us a natural isomorphism with components

$$\alpha_{A,B,C}: (A \times B) \times C \rightarrow A \times (B \times C); \quad ((a, b), c) \mapsto (a, (b, c)).$$

- Since  $\{*\}$  is terminal, we get an isomorphism  $\lambda_A: \{*\} \times A \rightarrow A$  which sends  $(*, a) \mapsto a$ .
- Similarly, we get a map  $\rho_A: A \times \{*\} \rightarrow A$  which sends  $(a, *) \mapsto a$ .

The pentagon and triangle diagram commute vacuously since the cartesian product is associative.

**Lemma 164.** *The tensor product  $\otimes$  of vector spaces is a bifunctor  $\mathbf{Vect}_k \times \mathbf{Vect}_k \rightsquigarrow \mathbf{Vect}_k$ .*

*Proof.* It is clear what the domain and codomain of the tensor product is, and how it behaves on objects and morphisms. The only non-trivial aspect is showing that the standard definition of the tensor product of morphisms respects composition, which is not difficult.  $\square$

**Example 165.** The category  $\mathbf{Vect}_k$  is a monoidal category with

1. The bifunctor  $\otimes$  is given by the tensor product.
2. The unit  $1$  is given by the field  $k$  regarded as a 1-dimensional vector space over itself.
3. The associator is the map which sends  $(v_1 \otimes v_2) \otimes v_3$  to  $v_1 \otimes (v_2 \otimes v_3)$ . It is not *a priori* obvious that this is well-defined, but it is also not difficult to check.
4. The left unitor is the map which sends  $(x, v) \in k \times V$  to  $xv \in V$ .
5. The right unitor is the map which sends

$$(v, x) \mapsto xv.$$

**Definition 166** (monoidal subcategory). Let  $(C, \otimes, 1)$  be a monoidal category. A monoidal subcategory of  $C$  is a subcategory ([Definition 10](#))  $S \subseteq C$  which is closed under the tensor product, and which contains  $1$ .

**Example 167.** Recall that  $\mathbf{FinVect}_k$  is the category of finite dimensional vector spaces over a field  $k$ . We saw in [Example 12](#) that  $\mathbf{FinVect}_k$  was a full subcategory of  $\mathbf{Vect}_k$ .

We have just seen that  $\mathbf{Vect}_k$  is a monoidal category with unit object  $1 = k$ . Since  $k$  is a one-dimensional vector space over itself,  $k \in \mathbf{Obj}(\mathbf{FinVect}_k)$ , and since the dimension of the tensor product of two finite-dimensional vector spaces is the product of their dimensions, the tensor product is closed in  $\mathbf{FinVect}_k$ . Hence  $\mathbf{FinVect}_k$  is a monoidal subcategory of  $\mathbf{Vect}_k$ .

**Lemma 168.** *Let  $C$  be a category with monoidal structure  $(\otimes, 1, \alpha, \lambda, \rho)$ . Then the maps  $\lambda_1$  and  $\rho_1: 1 \otimes 1 \rightarrow 1$  agree.*

*Proof.* See [\[11\]](#), Lemma 3.9.  $\square$

*Note 169.* The triangle and pentagon diagram are the first in a long list of coherence diagrams designed to make categorical structures behave like their algebraic counterparts. For a monoid, multiplication is associative by fiat, and the extension of this to  $n$ -fold products follows by induction. In monoidal categories, associators are isomorphisms rather than equalities, and we have no a priori guarantee that different ways of composing associators give the same isomorphism.

Mac Lane's coherence theorem shows us that this is exactly what the coherence diagrams guarantee.

**Theorem 170** (Mac Lane's coherence theorem). *Any two ways of freely composing unitors and associators to go from one expression to another coincide.*

The following definition was taken *mutatis mutandis* from [13].

**Definition 171** (monoidal functor). Let  $C$  and  $C'$  be monoidal categories. A functor  $\mathcal{F}: C \rightsquigarrow C'$  is lax monoidal if it is equipped with

- a natural transformation  $\Phi_{X,Y}: \mathcal{F}(X) \otimes \mathcal{F}(Y) \rightarrow \mathcal{F}(X \otimes Y)$ , and
- a morphism  $\varphi: \text{id}_{C'} \rightarrow \mathcal{F}(\text{id}_C)$  such that
- the following diagrams commute for any  $X, Y, Z \in \text{Obj}(C)$ .

$$\begin{array}{ccccc}
 (\mathcal{F}(X) \otimes \mathcal{F}(Y)) \otimes \mathcal{F}(Z) & \xrightarrow{\Phi_{X,Y} \otimes \text{id}_{\mathcal{F}(Z)}} & \mathcal{F}(X \otimes Y) \otimes \mathcal{F}(Z) & \xrightarrow{\Phi_{X \otimes Y, Z}} & \mathcal{F}((X \otimes Y) \otimes Z) \\
 \downarrow \alpha_{\mathcal{F}(X), \mathcal{F}(Y), \mathcal{F}(Z)} & & & & \downarrow \mathcal{F}(\alpha_{X,Y,Z}) \\
 \mathcal{F}(X) \otimes (\mathcal{F}(Y) \otimes \mathcal{F}(Z)) & \xrightarrow{\text{id}_{\mathcal{F}(X)} \otimes \Phi_{Y,Z}} & \mathcal{F}(X) \otimes \mathcal{F}(Y \otimes Z) & \xrightarrow{\Phi_{X, Y \otimes Z}} & \mathcal{F}(X \otimes (Y \otimes Z))
 \end{array}$$
  

$$\begin{array}{ccc}
 1 \otimes \mathcal{F}(X) & \xrightarrow{\lambda_{\mathcal{F}(X)}} & \mathcal{F}(X) \\
 \downarrow \varphi \otimes \text{id}_{\mathcal{F}(X)} & & \uparrow \mathcal{F}(\lambda_X) \\
 \mathcal{F}(1) \otimes \mathcal{F}(X) & \xrightarrow{\Phi_{1,X}} & \mathcal{F}(1 \otimes X) \\
 \\ 
 \mathcal{F}(X) \otimes 1 & \xrightarrow{\rho_{\mathcal{F}(X)}} & \mathcal{F}(X) \\
 \downarrow \text{id}_{\mathcal{F}(X)} \otimes \varphi & & \uparrow \mathcal{F}(\rho_X) \\
 \mathcal{F}(X) \otimes \mathcal{F}(1) & \xrightarrow{\Phi_{X,1}} & \mathcal{F}(X \otimes 1)
 \end{array}$$

If  $\Phi$  is a natural isomorphism and  $\varphi$  is an isomorphism, then  $\mathcal{F}$  is called a strong monoidal functor.

We will denote the above monoidal functor by  $(\mathcal{F}, \Phi, \varphi)$ .

*Note 172.* The above diagrams above are exactly those necessary to ensure that the monoidal structure is preserved. They do this by demanding that the associator and the unitors be  $\mathcal{F}$ -equivariant.

*Note 173.* In much of the literature, a strong monoidal functor is simply called a monoidal functor.

**Definition 174** (monoidal natural transformation). Let  $(F, \Phi, \varphi)$  and  $(G, \Gamma, \gamma)$  be monoidal functors. A natural transformation  $\eta : \mathcal{F} \Rightarrow \mathcal{G}$  is monoidal if the following diagrams commute.

$$\begin{array}{ccc} \mathcal{F}(X) \otimes \mathcal{F}(Y) & \xrightarrow{\eta_X \otimes \eta_Y} & \mathcal{G}(X) \otimes \mathcal{G}(Y) \\ \Phi_{X,Y} \downarrow & & \downarrow \Gamma_{X,Y} \\ \mathcal{F}(X \otimes Y) & \xrightarrow{\eta_{X \otimes Y}} & \mathcal{G}(X \otimes Y) \end{array} \quad \begin{array}{ccc} 1 & & \\ \varphi \downarrow & \searrow \gamma & \\ \mathcal{F}(1) & \xrightarrow{\eta_1} & \mathcal{G}(1) \end{array}$$

### 6.1.2 Line objects

**Definition 175** (invertible object). Let  $(C, \otimes, 1)$  be a monoidal category. An invertible object (sometimes called a *line object*) is an object  $L \in \text{Obj}(C)$  such that both of the functors  $C \rightsquigarrow C$

- $\ell_L : A \mapsto L \otimes A$
- $r_L : A \mapsto A \otimes L$

are categorical equivalences.

**Lemma 176.** *If  $(C, \otimes, 1)$  is a monoidal category and  $L$  is an invertible object, then there is an object  $L^{-1} \in \text{Obj}(C)$ , unique up to isomorphism, such that  $L \otimes L^{-1} \simeq L^{-1} \otimes L \simeq 1$ . Furthermore,  $L$  is invertible only if there exists such an  $L^{-1}$ .*

*Proof.* Suppose  $L$  is invertible. Then the functor  $\ell_L : A \mapsto L \otimes A$  is bijective up to isomorphism, i.e. for any  $A \in \text{Obj}(C)$ , there is an object  $A' \in \text{Obj}(C)$ , unique up to isomorphism, such that

$$\ell_L(A') = L \otimes A' \simeq A.$$

If this is true for *any*  $A$ , it must also be true for  $1$ , so there exists an object  $L^{-1}$ , unique up to isomorphism, such that

$$\ell_L(L^{-1}) = L \otimes L^{-1} \simeq 1.$$

The same logic tells us that there exists some other element  $L'^{-1}$ , such that

$$r_L(L'^{-1}) = L'^{-1} \otimes L \simeq 1.$$

Now

$$1 \simeq L'^{-1} \otimes L \simeq L'^{-1} \otimes (L \otimes L^{-1}) \otimes L \simeq (L'^{-1} \otimes L) \otimes (L^{-1} \otimes L) \simeq (L'^{-1} \otimes L) \otimes 1 \simeq L'^{-1} \otimes L,$$

so  $L'^{-1}$  is also a left inverse for  $L$ . But since  $\ell_L$  is an equivalence of categories,  $L$  only has one left inverse up to isomorphism, so  $L^{-1}$  and  $L'^{-1}$  must be isomorphic.  $\square$

**Definition 177.** Let  $(C, \otimes, 1)$  be a monoidal category. Then the full subcategory (Definition 11)  $(\text{Line}(C), \otimes, 1) \subseteq (C, \otimes, 1)$  whose objects are the line objects in  $C$  is called the line subcategory of  $(C, \otimes, 1)$ . Since invertibility is closed under the tensor product and  $1$  is invertible ( $1^{-1} \simeq 1$ ),  $\text{Line}(C)$  is a monoidal subcategory of  $C$ .

### 6.1.3 Braided monoidal categories

Braided monoidal categories capture the idea that we should think of morphisms between tensor products spatially, as diagrams embedded in 3-space. This sounds odd, but it turns out to be the correct way of looking at a wide class of problems.

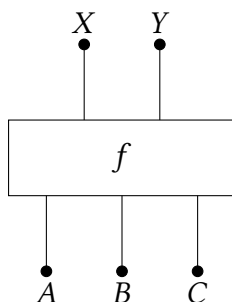
To be slightly more precise, we can think of the objects  $X$ ,  $Y$ , etc. in any monoidal category as little dots.



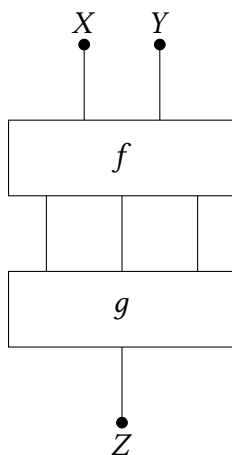
We can express the tensor product  $X \otimes Y$  by putting the dots representing  $X$  and  $Y$  next to each other.



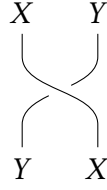
A morphism  $f$  between, say,  $X \otimes Y$  and  $A \otimes B \otimes C$  can be drawn as a diagram consisting of some lines and boxes.



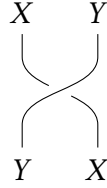
We can compose morphisms by concatenating their diagrams.



In a braided monoidal category, we require that for any two objects  $X$  and  $Y$  we have an isomorphism  $\gamma_{XY}: X \otimes Y \rightarrow Y \otimes X$ , which we draw like this.



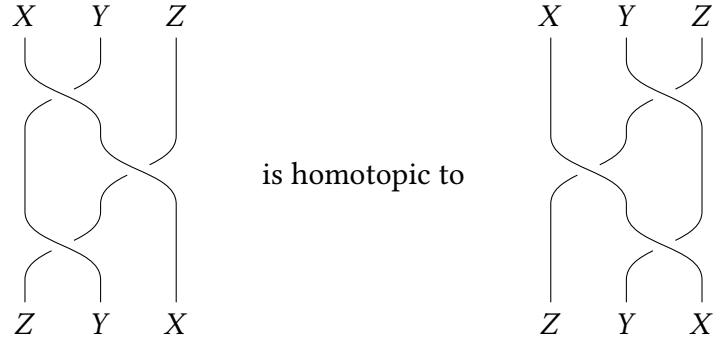
Since  $\gamma_{AB}$  is an isomorphism, it has an inverse  $\gamma_{AB}^{-1}$  (not necessarily equal to  $\gamma_{BA}$ !) which we draw like this.



The idea of a braided monoidal category is that we want to take these pictures seriously: we want two expressions involving repeated applications of the  $\gamma$ .. and their inverses to be equivalent if and only if the braid diagrams representing them are homotopic. Thus we want, for example,

$$\gamma_{XY} \circ \gamma_{YZ} \circ \gamma_{XY} = \gamma_{YZ} \circ \gamma_{XY} \circ \gamma_{YZ}$$

since



A digression into the theory of braid groups would take us too far afield. The punchline is that to guarantee that all such compositions involving the  $\gamma$  are identified in the correct way, we must define braided monoidal categories as follows.

**Definition 178** (braided monoidal category). A category  $\mathcal{C}$  with monoidal structure  $(\otimes, 1, \alpha, \lambda, \rho)$  is braided if for every two objects  $A$  and  $B \in \text{Obj}(\mathcal{C})$ , there is an isomorphism  $\gamma_{A,B}: A \otimes B \rightarrow B \otimes A$  such that the following *hexagon diagrams* commute.

$$\begin{array}{ccccc}
 & A \otimes (B \otimes C) & \xrightarrow{\gamma_{A,B \otimes C}} & (B \otimes C) \otimes A & \\
 \nearrow \alpha_{ABC} & & & & \searrow \alpha_{BCA} \\
 (A \otimes B) \otimes C & & & & B \otimes (C \otimes A) \\
 \searrow \gamma_{AB} \otimes 1 & & & & \nearrow 1 \otimes \gamma \\
 & (B \otimes A) \otimes C & \xrightarrow{\alpha_{BAC}} & B \otimes (A \otimes C) &
 \end{array}$$

$$\begin{array}{ccccc}
& & (A \otimes B) \otimes C & \xrightarrow{\gamma_{A \otimes B, C}} & C \otimes (A \otimes B) \\
& \nearrow \alpha_{ABC}^{-1} & & & \searrow \alpha_{CAB}^{-1} \\
A \otimes (B \otimes C) & & & & (C \otimes A) \otimes B \\
& \searrow 1 \otimes \gamma_{BC} & & & \nearrow \gamma_{AC} \otimes 1 \\
& & A \otimes (C \otimes B) & \xrightarrow{\alpha_{ACB}^{-1}} & (A \otimes C) \otimes B
\end{array}$$

The collection of such  $\gamma$  form a natural isomorphism between the bifunctors

$$(A, B) \mapsto A \otimes B \quad \text{and} \quad (A, B) \mapsto B \otimes A,$$

and is called a braiding.

**Definition 179** (braided monoidal functor). A lax monoidal functor  $(\mathcal{F}, \Phi, \phi)$  (Definition 171) is braided monoidal if it makes the following diagram commute.

$$\begin{array}{ccc}
\mathcal{F}(x) \otimes \mathcal{F}(y) & \xrightarrow{\gamma_{\mathcal{F}(x), \mathcal{F}(y)}} & \mathcal{F}(y) \otimes \mathcal{F}(x) \\
\downarrow \Phi_{x,y} & & \downarrow \Phi_{x,y} \\
\mathcal{F}(x \otimes y) & \xrightarrow{\mathcal{F}(\gamma_{x,y})} & \mathcal{F}(y \otimes x)
\end{array}$$

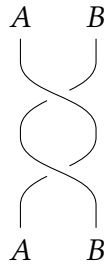
*Note 180.* There are no extra conditions imposed on a monoidal natural transformation to turn it into a braided natural transformation.

### 6.1.4 Symmetric monoidal categories

Until now, we have been calling the bifunctor  $\otimes$  in Definition 161 a tensor product. This has been an abuse of terminology: in general, one defines tensor products not to be those bifunctors which come from any monoidal category, but only those which come from *symmetric* monoidal categories. We will define these shortly.

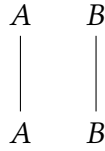
Conceptually, passing from the definition of a braided monoidal category to that of a symmetric monoidal category is rather simple. One only requires that for any two objects  $A$  and  $B$ ,  $\gamma_{BA} = \gamma_{AB}^{-1}$ , i.e.  $\gamma_{BA} \circ \gamma_{AB} = \text{id}_{A \otimes B}$ .

We can interpret this nicely in terms of our braid diagrams. We can draw  $\gamma_{BA} \circ \gamma_{AB}$  like this.

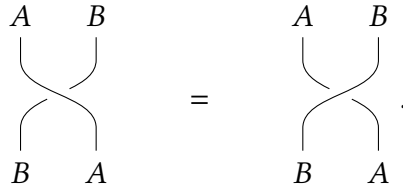


The requirement that this must be homotopic to the identity transformation

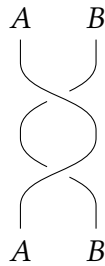




can be expressed by making the following rule: in a *symmetric* monoidal category, we don't care about the difference between undercrossings and overcrossings:



Then we can exchange the diagram representing  $\gamma_{BA} \circ \gamma_{AB}$  for



which is clearly homotopic to the identity transformation on  $A \otimes B$ .

**Definition 181** (symmetric monoidal category). Let  $C$  be a braided monoidal category with braiding  $\gamma$ . We say that  $C$  is a symmetric monoidal category if for all  $A, B \in \text{Obj}(C)$ ,  $\gamma_{BA} \circ \gamma_{AB} = \text{id}_{A \otimes B}$ . A braiding  $\gamma$  which satisfies such a condition is called symmetric.

*Note 182.* There are no extra conditions imposed on a monoidal natural transformation to turn it into a symmetric natural transformation.

## 6.2 Internal hom functors

We can now generalize the notion of an exponential object ([Definition 90](#)) to any monoidal category.

### 6.2.1 The internal hom functor

Recall the definition of the hom functor on a locally small category  $C$  ([Definition 94](#)): it is the functor which maps two objects to the set of morphisms between them, so it is a functor

$$C^{\text{op}} \times C \rightsquigarrow \text{Set}.$$

If we take  $\mathbf{C} = \mathbf{Set}$ , then our hom functor never really leaves  $\mathbf{Set}$ ; it is *internal* to  $\mathbf{Set}$ . This is our first example of an *internal hom functor*. In fact, it is the prototypical internal hom functor, and we can learn a lot by studying its properties.

Let  $X$  and  $Y$  be sets. Denote the set of all functions  $X \rightarrow Y$  by  $[X, Y]$ .

Let  $S$  be any other set, and consider a function  $f: S \rightarrow [X, Y]$ . For each element  $s \in S$ ,  $f$  picks out a function  $h_s: X \rightarrow Y$ . But this is just a curried version of a function  $S \times X \rightarrow Y$ ! So as we saw in [Section 3.1](#), we have a bijection between the sets  $[S, [X, Y]]$  and  $[S \times X, Y]$ . In fact, this is even a *natural* bijection, i.e. a natural transformation between the functors

$$[-, [-, -]] \quad \text{and} \quad [- \times -, -]: \mathbf{Set}^{\text{op}} \times \mathbf{Set}^{\text{op}} \times \mathbf{Set} \rightsquigarrow \mathbf{Set}.$$

Let's check this. First, we need to figure out how our functors act on functions. Suppose we have sets and functions like so.

$$\begin{array}{ccc} A'' & \xleftarrow{f''} & B'' \\ A' & \xleftarrow{f'} & B' \\ A & \xrightarrow{f} & B \end{array}$$

Our functor maps

$$(A'', A', A) \mapsto [A'', [A', A]] = \text{Hom}_{\mathbf{Set}}(A'', \text{Hom}_{\mathbf{Set}}(A', A)),$$

so it should map  $(f'', f', f)$  to a function

$$[f'', [f', f]]: [A'', [A', A]] \rightarrow [B'', [B', B]].$$

The way to do that is by sending  $m \in [A'', [A', A]]$  to

$$[f', f] \circ m \circ f''.$$

You can check that this works as advertised.

The other one's not so tough. Our functor maps an object  $(A'', A', A)$  to  $[A'' \times A', A]$ . We need to map  $(f'', f', f)$  to a function

$$[f'' \times f', f]: [A'' \times A', A] \rightarrow [B'' \times B', B].$$

We do that by sending  $m \in [A'' \times A', A]$  to

$$f \circ m \circ (f'', f') \in [B'' \times B', B].$$

Checking that  $[-, [-, -]]$  and  $[- \times -, -]$  really *are* functorial would be a bit much; each is just the composition of hom functor and the Cartesian product. We will however check that there is a natural isomorphism between them, which amounts to checking that the following diagram

commutes.

$$\begin{array}{ccc}
[A'' \times A', A] & \xrightarrow{[f'' \times f', f]} & [B'' \times B', B] \\
\downarrow \Phi_{[A'' \times A', A]} & & \downarrow \Phi_{[B'' \times B', B]} \\
[A'', [A', A]] & \xrightarrow{[f'', [f', f]]} & [B'', [B', B]]
\end{array}$$

$$\begin{array}{ccc}
m & \xrightarrow{\quad} & f \circ m \circ (f', f'') \\
\downarrow & & \downarrow \\
\Phi(m) \circ [f', f] & \xrightarrow{\quad} & \Phi(f \circ m \circ (f', f''))
\end{array}$$

In other words, we have to show that

$$\Phi_{[A'' \times A', A]}(f \circ m \circ (f', f'')) = [f', f] \circ \Phi_{[B'' \times B', B]}(m) \circ f''.$$

So what is each of these? Well,  $f \circ m \circ (f', f'')$  is a map  $B'' \times B' \rightarrow B$ , which maps (say)  $(b'', b') \mapsto b$ .

The natural transformation  $\Phi$  tells us to curry this, i.e. turn it into a map  $B'' \rightarrow [B', B]$ . Not just any map, though: a map which when evaluated on  $b''$  turns into a map which, when evaluated on  $b'$ , yields  $b$ .

We know that  $f \circ m \circ (f', f'') : (b'', b') \mapsto b$ , i.e.

$$f(m(f''(b''), f'(b'))) = b.$$

If we can show that this is *also* what  $[f', f] \circ \Phi_{[B'' \times B', B]}(m) \circ f''$  is equal to when evaluated on  $b''$  and then  $b'$ , we are done, since two functions are equal if they take the same value for all inputs.

Well, let's go through what this definition means. First, we take  $b''$  and feed it to  $f''$ . Next, we let  $\Phi_{[B'' \times B', B]}(m)$  act on the result, i.e. we fill the first argument of  $m$  with  $f''(b'')$ . What we get is the following:

$$m(f''(b''), -).$$

Then we are to precompose this with  $f'$  and stick the result into  $f$ :

$$f(m(f''(b''), f'(-))).$$

Finally, we are to evaluate this on  $b'$  to get

$$f(m(f''(b''), f'(b'))).$$

Indeed, this is equal to  $b$ , so the diagram commutes.

In other words,  $\Phi$  is a natural bijection between the hom-sets  $[-, [-, -]]$  and  $[- \times -, -]$ .

We picked this example because the collection  $[A, B]$  of all functions between two sets  $A$  and  $B$  is itself a set. Therefore it makes sense to think of the hom-sets  $\text{Hom}_{\mathcal{C}}(A, B)$  as living within the same category as  $A$  and  $B$ . We saw in [Section 2.1](#) that in a category with products, we could sometimes view hom-sets as exponential objects. However, we now have the technology to be even more general.

**Definition 183** (internal hom functor). Let  $(C, \otimes)$  be a monoidal category. An internal hom functor is a functor

$$[-, -]_C : C^{\text{op}} \times C \rightsquigarrow C$$

such that for every  $X \in \text{Obj}(C)$  we have a pair of adjoint functors

$$(-) \otimes X \dashv [X, -]_C.$$

The objects  $[A, B]_C$  are called internal hom objects.

*Note 184.* The reason for the long introduction to this section was that the pair of adjoint functors in [Definition 183](#) really matches the one in  $\text{Set}$ . Recall, in  $\text{Set}$  there was a natural transformation

$$\text{Hom}_{\text{Set}}(S \times X, Y) \simeq \text{Hom}_{\text{Set}}(S, [X, Y]).$$

This means that for any set  $X$ , there is a pair of adjoint functors

$$(-) \times X \dashv [X, -],$$

which is in agreement with the statement of [Definition 183](#).

*Notation 185.* The convention at the nLab is to denote the internal hom by square braces  $[A, B]$ , and this is for the most part what we will do. Unfortunately, we have already used this notation for the *regular* hom functor. To remedy this, we will add a subscript if the category to which the hom functor belongs is not clear:  $[-, -]_C$  for a hom functor internal to  $C$ ,  $[-, -]_{\text{Set}}$  for the standard hom functor (or the hom functor internal to  $\text{Set}$ , which amounts to the same).

There is no universally accepted notation for the internal hom functor. One often sees it denoted by a lower-case hom:  $\text{hom}_C(A, B)$ . Many sources (for example DMOS [16]) distinguish the internal hom with an underline:  $\underline{\text{Hom}}_C(A, B)$ . Deligne typesets it with a script H:  $\mathcal{H}om_C(A, B)$ .

**Definition 186** (closed monoidal category). A monoidal category equipped with an internal hom functor is called a closed monoidal category.

*Note 187.* Here is another (clearly equivalent) definition of  $[X, Y]_C$ : it is the object representing ([Definition 97](#)) the functor

$$T \mapsto \text{Hom}_C(T \otimes X, Y).$$

**Example 188.** In many locally small categories whose objects can be thought of as “sets with extra structure,” it is possible to pile structure on top of the hom sets until they themselves can be viewed as bona fide objects in their categories. It often (*but not always!*) happens that these beefed-up hom sets coincide (up to isomorphism) with the internal hom objects.

Take for example  $\text{Vect}_k$ . For any vector spaces  $V$  and  $W$ , we can turn  $\text{Hom}_{\text{Vect}_k}(V, W)$  into a vector space by defining addition and scalar multiplication pointwise; we can then view  $\text{Hom}_{\text{Vect}_k}(V, W)$  as belonging to  $\text{Obj}(\text{Vect}_k)$ . It turns out that this is precisely (up to isomorphism) the internal hom object  $[V, W]_{\text{Vect}_k}$ .

To see this, we need to show that there is a natural bijection

$$\text{Hom}_{\text{Vect}_k}(A, \text{Hom}_{\text{Vect}_k}(B, C)) \simeq \text{Hom}_{\text{Vect}_k}(A \otimes B, C).$$

Suppose we are given a linear map  $f : A \rightarrow \text{Hom}_{\text{Vect}_k}(B, C)$ . If we act with this on an element of  $A$ , we get a linear map  $B \rightarrow C$ . If we evaluate this on an element of  $B$ , we get an element of  $C$ . Thus, we can view  $f$  as a bilinear map  $A \times B \rightarrow C$ , hence as a linear map  $A \otimes B \rightarrow C$ .

Now suppose we are given a linear map  $g: A \otimes B \rightarrow C$ . By pre-composing this with the tensor product we can view this as a bilinear map  $A \times B \rightarrow C$ , and by currying this we get a linear map  $A \rightarrow \text{Hom}_{\text{Vect}_k}(B, C)$ .

For the remainder of this chapter, let  $(C, \otimes, 1)$  be a closed monoidal category with internal hom functor  $[-, -]_C$ .

In a closed monoidal category, the adjunction between the internal hom and the tensor product even holds internally.

**Lemma 189.** *For any  $X, Y, Z \in \text{Obj}(C)$  there is a natural isomorphism*

$$[X \otimes Y, Z]_C \xrightarrow{\sim} [X, [Y, Z]_C]_C.$$

*Proof.* Let  $A \in \text{Obj}(C)$ . We have the following string of natural isomorphisms.

$$\begin{aligned} \text{Hom}_C(A, [X \otimes Y, Z]_C) &\simeq \text{Hom}_C(A \otimes (X \otimes Y), Z) \\ &\simeq \text{Hom}_C((A \otimes X) \otimes Y, Z) \\ &\simeq \text{Hom}_C(A \otimes X, [Y, Z]_C) \\ &\simeq \text{Hom}_C(A, [X, [Y, Z]_C]_C). \end{aligned}$$

Since this is true for each  $A$  we have, by [Corollary 105](#),

$$[X \otimes Y, Z]_C \xrightarrow{\sim} [X, [Y, Z]_C]_C.$$

□

**Lemma 190.** *Let  $(C, \otimes, 1)$  be a closed symmetric monoidal category. For any  $A, B, R \in \text{Obj}(C)$ , there is a natural transformation*

$$[A, B]_C \rightarrow [R \otimes A, R \otimes B]_C,$$

*natural in  $A$  and  $B$ .*

*Proof.* The assignment  $R \otimes (-)$  is a functor, and induces a transformation of the regular hom functor

$$\text{Hom}_C(A, B) \mapsto \text{Hom}_C(R \otimes A, R \otimes B)$$

which is natural in  $A$  and  $B$ . We would like to show that the internal hom functor also has this property.

The following string of natural transformations guarantees it by the Yoneda lemma.

$$\begin{aligned} \text{Hom}_C(X, [A, B]_C) &\simeq \text{Hom}_C(X \otimes A, \otimes B) \\ &\simeq \text{Hom}_C(R \otimes X \otimes A, R \otimes B) \\ &\simeq \text{Hom}_C(X \otimes (R \otimes A), R \otimes B) \\ &\simeq \text{Hom}_C(X, [R \otimes A, R \otimes B]_C). \end{aligned}$$

□

### 6.2.2 The evaluation map

The internal hom functor gives us a way to talk about evaluating morphisms  $f: X \rightarrow Y$  without mentioning elements of  $X$ .

**Definition 191** (evaluation map). Let  $X \in \text{Obj}(\mathcal{C})$ . We have seen that the adjunction

$$(-) \otimes X \dashv [X, -]_{\mathcal{C}}$$

gives us, for any  $A, X, Y \in \text{Obj}(\mathcal{C})$ , a natural bijection

$$\text{Hom}_{\mathcal{C}}(A \otimes X, Y) \xrightarrow{\sim} \text{Hom}_{\mathcal{C}}(A, [X, Y]_{\mathcal{C}}).$$

In particular, with  $A = [X, Y]_{\mathcal{C}}$ , we have a bijection

$$\text{Hom}_{\mathcal{C}}([X, Y]_{\mathcal{C}} \otimes X, Y) \xrightarrow{\sim} \text{Hom}_{\mathcal{C}}([X, Y]_{\mathcal{C}}, [X, Y]_{\mathcal{C}}).$$

The adjunct ([Definition 156](#)) of  $\text{id}_{[X, Y]_{\mathcal{C}}} \in \text{Hom}_{\mathcal{C}}([X, Y]_{\mathcal{C}}, [X, Y]_{\mathcal{C}})$  is an object in  $\text{Hom}_{\mathcal{C}}([X, Y]_{\mathcal{C}} \otimes X, Y)$ , denoted

$$\text{eval}_{X, Y}: [X, Y]_{\mathcal{C}} \otimes X \rightarrow Y,$$

and called the evaluation map.

**Example 192.** As we saw in [Example 163](#), the category  $\text{Set}$  is a monoidal category with a bifunctor given by the cartesian product. The internal hom is simply the regular hom functor

$$\text{Hom}_{\text{Set}}(-, -) = [-, -].$$

Let us explore the evaluation map on  $\text{Set}$ . It is the adjunct of the identity map  $\text{id}_{[X, Y]}$  under the adjunction

$$[[X, Y] \times X, Y] \dashv [[X, Y], [X, Y]].$$

Thus, it is a function

$$\text{eval}_{X, Y}: [X, Y] \times X \rightarrow Y; \quad (f, x) \mapsto \text{eval}_{X, Y}(f, x).$$

So far, we don't know what  $\text{eval}_{X, Y}$  sends  $(f, x)$  to; we just know that we'd *like it* if it sent it to  $f(x)$ .

The above adjunction is given by currying: we start on the LHS with a map  $\text{eval}_{X, Y}$  with two arguments, and we turn it into a map which fills in only the first argument. Thus the map on the RHS adjunct to  $\text{eval}_{X, Y}$  is given by

$$f \mapsto \text{eval}_{X, Y}(f, -).$$

If we want the map  $f \mapsto \text{eval}_{X, Y}(f, -)$  to be the identity map,  $f$  and  $\text{eval}_{X, Y}(f, -)$  must agree on all elements  $x$ , i.e.

$$f(x) = \text{eval}_{X, Y}(f, x) \quad \text{for all } x \in X.$$

Thus, the evaluation map is the map which sends  $(f, x) \mapsto f(x)$ .

### 6.2.3 The composition morphism

The evaluation map allows us to define composition of morphisms without talking about internal hom objects as if they have elements.

**Definition 193** (composition morphism). For  $X, Y, Z \in \text{Obj}(\mathcal{C})$ , the composition morphism

$$\circ_{X,Y,Z}: [Y, Z]_{\mathcal{C}} \otimes [X, Y]_{\mathcal{C}} \rightarrow [X, Z]_{\mathcal{C}}$$

is the  $(-) \otimes X \vdash [X, -]_{\mathcal{C}}$ -adjunct of the composition

$$[Y, Z]_{\mathcal{C}} \otimes [X, Y]_{\mathcal{C}} \otimes X \xrightarrow{(\text{id}_{[Y,Z]_{\mathcal{C}}}, \text{eval}_{X,Y})} [Y, Z]_{\mathcal{C}} \otimes Y \xrightarrow{\text{eval}_{Y,Z}} Z .$$

**Example 194.** In  $\text{Set}$ , the composition morphism  $\circ_{X,Y,Z}$  lives up to its name. Let  $f: X \rightarrow Y$ ,  $g: Y \rightarrow Z$ , and  $x \in X$ . The above composition goes as follows.

1. The map  $(\text{id}_{[Y,Z]}, \text{eval}_{X,Y})$  turns the triple  $(g, f, x)$  into the pair  $(g, f(x))$ .
2. The map  $\text{eval}_{Y,Z}$  turns  $(g, f(x))$  into  $g(f(x)) = (g \circ f)(x)$ .

The evaluation morphism  $\circ_{X,Y,Z}$  is the currying of this, i.e. it sends

$$(f, g) \mapsto (f \circ g)(-).$$

### 6.2.4 Dual objects

Recall that for any  $k$ -vector space  $V$ , there is a dual vector space

$$V^* = \{L: V \rightarrow k\} .$$

This definition generalizes to any closed monoidal category.

**Definition 195** (dual object). Let  $X \in \text{Obj}(\mathcal{C})$ . The dual object to  $X$ , denoted  $X^*$ , is defined to be the object

$$[X, 1]_{\mathcal{C}} .$$

That is to say,  $X^*$  is the internal hom object modelling the hom set of morphisms from  $X$  to the identity object  $1$ .

*Notation 196.* The evaluation morphism (Definition 191) has a component

$$\text{eval}_{X^*,X}: X^* \otimes X \rightarrow 1.$$

To clean things up a bit, we will write  $\text{eval}_X$  instead of  $\text{eval}_{X^*,X}$ .

*Notation 197.* In many sources, e.g. DMOS ([16]), the dual object to  $X$  is denoted  $X^\vee$  instead of  $X^*$ .

**Lemma 198.** *There is a natural isomorphism between the functors*

$$\text{Hom}_{\mathcal{C}}(-, X^*) \quad \text{and} \quad \text{Hom}_{\mathcal{C}}((-) \otimes X, 1).$$

*Proof.* For any  $X, T \in \text{Obj}(\mathcal{C})$ , the definition of the internal hom  $[-, -]_{\mathcal{C}}$  gives us a natural isomorphism

$$\text{Hom}_{\mathcal{C}}(T \otimes X, 1) \simeq \text{Hom}_{\mathcal{C}}(T, [X, 1]_{\mathcal{C}}) = \text{Hom}_{\mathcal{C}}(T, X^*).$$

□

**Theorem 199.** *The map  $X \mapsto X^*$  can be extended to a contravariant functor.*

*Proof.* We need to figure out how our functor should act on morphisms. We define this by analogy with the familiar setting of vector spaces. Recall that for a linear map  $L: V \rightarrow W$ , the dual map  $L^t: W^* \rightarrow V^*$  is defined by

$$(L^t(w))(v) = w(L(v)).$$

By analogy, for  $f \in \text{Hom}_{\mathcal{C}}(X, Y)$ , we should define the dual morphism  $f^t \in \text{Hom}_{\mathcal{C}}(Y^*, X^*)$  by demanding that the following diagram commutes.

$$\begin{array}{ccc} h^* \otimes X & \xrightarrow{f^t \otimes \text{id}_X} & X^* \otimes X \\ \text{id}_Y \otimes f \downarrow & & \downarrow \text{eval}_X \\ h^* \otimes Y & \xrightarrow{\text{eval}_Y} & 1 \end{array}$$

To check that this is functorial, we must check that it respects compositions, i.e. that the following diagram commutes.

$$\begin{array}{ccc} Z^* \otimes X & \xrightarrow{(f^t \circ g^t) \otimes \text{id}_X} & X^* \otimes X \\ \text{id}_Z \otimes (g \circ f) \downarrow & & \downarrow \text{eval}_X \\ Z^* \otimes Z & \xrightarrow{\text{eval}_Z} & 1 \end{array}$$

Let's add in some more objects and morphisms.

$$\begin{array}{ccccc} Z^* \otimes X & \xrightarrow{g^t \otimes \text{id}_X} & h^* \otimes X & \xrightarrow{f^t \otimes \text{id}_X} & X^* \otimes X \\ \text{id}_{Z^*} \otimes f \downarrow & & \text{id}_{h^*} \otimes f \downarrow & & \downarrow \text{eval}_X \\ Z^* \otimes Y & \xrightarrow{g^t \otimes \text{id}_Y} & h^* \otimes Y & & \\ \text{id}_{Z^*} \otimes g \downarrow & & \searrow \text{eval}_Y & & \\ Z^* \otimes Z & \xrightarrow{\text{eval}_Z} & & & 1 \end{array}$$

We want to show that the outer square commutes. But it clearly does: that the top left square commutes is trivial, and the right and bottom 'squares' are the commutativity conditions defining  $f^t$  and  $g^t$ . □



*Note 200.* It's not clear to me why  $f^t$  as defined above exists and is unique.

The above is one, but not the only, way to define dual objects. We can be more general.

**Definition 201** (right duality). Let  $\mathcal{C}$  be a category with monoidal structure  $(\otimes, 1, \alpha, \lambda, \rho)$ . Right duality of two objects  $A$  and  $A^* \in \text{Obj}(\mathcal{C})$  consists of

1. A morphism of the form

$$\text{eval}_A: A^* \otimes A \rightarrow 1,$$

called the *evaluation map* (or *counit* if you're into Hopf algebras)

2. A morphism of the form

$$i_A: 1 \rightarrow A \otimes A^*,$$

called the *coevaluation map* (or *unit*)

such that the compositions

$$\begin{aligned} X &\xrightarrow{i_A \otimes \text{id}_X} (X \otimes X^*) \otimes X \xrightarrow{\alpha_{X, X^*, X}} X \otimes (X^* \otimes X) \xrightarrow{\text{id}_X \otimes \text{eval}_X} X \\ X^* &\xrightarrow{\text{id}_{X^*} \otimes \text{eval}_X} X^* \otimes (X \otimes X^*) \xrightarrow{\alpha_{X^*, X, X^*}^{-1}} (X^* \otimes X) \otimes X^* \xrightarrow{\text{eval}_X \otimes \text{id}_{X^*}} X^* \end{aligned}$$

are the identity morphism.

**Definition 202** (rigid monoidal category). A monoidal category  $(\mathcal{C}, \otimes, 1)$  is rigid if every object has a left and right dual.

**Theorem 203.** Every rigid monoidal category is a closed monoidal category (i.e. has an internal hom functor, see [Definition 186](#)) with internal hom object

$$[A, B]_{\mathcal{C}} \simeq B \otimes A^*.$$

*Proof.* We can prove the existence of this isomorphism by showing, thanks to [Corollary 105](#), that for any  $X \in \text{Obj}(\mathcal{C})$  there is an isomorphism

$$\text{Hom}_{\mathcal{C}}(X, [A, B]_{\mathcal{C}}) \simeq \text{Hom}_{\mathcal{C}}(X, B \otimes A^*).$$

The defining adjunction of the internal hom gives us

$$\text{Hom}_{\mathcal{C}}(X, [A, B]_{\mathcal{C}}) \simeq \text{Hom}_{\mathcal{C}}(X \otimes A, B).$$

Now we can map any  $f \in \text{Hom}_{\mathcal{C}}(X \otimes A, B)$  to

$$(f \otimes \text{id}_A) \circ (\text{id}_X \otimes i_A) \in \text{Hom}_{\mathcal{C}}(X, B \otimes A^*).$$

We will be done if we can show that the assignment

$$f \mapsto (f \otimes \text{id}_A) \circ (\text{id}_X \otimes i_A)$$

is an isomorphism. We'll do this by exhibiting an inverse:

$$\text{Hom}_{\mathcal{C}}(X, B \otimes A^*) \ni g \mapsto (\text{id}_W \otimes \text{eval}_V) \circ (g \otimes \text{id}_V) \in \text{Hom}_{\mathcal{C}}(X \otimes A, B).$$

Of course, first we should show that  $(f \otimes \text{id}_A) \circ (\text{id}_X \otimes i_A)$  really does map  $X \rightarrow B \otimes A^*$ . But it does; it does this by first acting on  $X$  with  $i_A$ :

$$X \rightarrow X \otimes A \otimes A^*$$

and then acting on the  $X \otimes A$  with  $f$  and letting the  $A^*$  hang around:

$$X \otimes A \otimes A^* \rightarrow B \otimes A^*.$$

To show that

$$g \mapsto (\text{id}_B \otimes \text{eval}_A) \circ (g \otimes \text{id}_A)$$

really is an inverse, we can shove the assignment

$$f \mapsto (f \otimes \text{id}_A) \circ (\text{id}_X \otimes i_A)$$

into it and show that we get  $f$  right back out. That is to say, we need to show that

$$(\text{id}_B \otimes \text{eval}_A) \circ [(f \otimes \text{id}_A) \circ (\text{id}_X \otimes i_A)] \otimes \text{id}_A = f.$$

This is easy to see but hard to type. Write it out. You'll need to use first of the two composition identities.

To show that the other composition yields  $g$ , you have to use the other. □

# 7 Abelian categories

This section draws heavily from [22].

## 7.1 Additive categories

Recall that  $\mathbf{Ab}$  is the category of abelian groups.

**Definition 204** (Ab-enriched category). A category  $\mathbf{C}$  is Ab-enriched if

1. for all objects  $A, B \in \mathbf{Obj}(\mathbf{C})$ , the hom-set  $\mathrm{Hom}_{\mathbf{C}}(A, B)$  has the structure of an abelian group (i.e. one can add morphisms), such that
2. the composition

$$\circ: \mathrm{Hom}_{\mathbf{C}}(B, C) \times \mathrm{Hom}_{\mathbf{C}}(A, B) \rightarrow \mathrm{Hom}_{\mathbf{C}}(A, C)$$

is additive in each slot: for any  $f_1, f_2 \in \mathrm{Hom}_{\mathbf{C}}(B, C)$  and  $g \in \mathrm{Hom}_{\mathbf{C}}(A, B)$ , we must have

$$(f_1 + f_2) \circ g = f_1 \circ g + f_2 \circ g,$$

and similarly in the second slot.

*Note 205.* In any Ab-enriched category, every hom-set has at least one element—the identity element of the hom-set taken as an abelian group.

**Definition 206** (endomorphism ring). Let  $\mathbf{C}$  be an Ab-enriched category, and let  $A \in \mathbf{Obj}(\mathbf{C})$ . The endomorphism ring of  $A$ , denoted  $\mathrm{End}(A)$ , is  $\mathrm{Hom}_{\mathbf{C}}(A, A)$ , with addition given by the abelian structure and multiplication given by composition.

**Lemma 207.** *In an Ab-enriched category  $\mathbf{C}$ , a finite product is also a coproduct, and vice versa. In particular, initial objects and terminal objects coincide.*

*Proof.* See [39], Proposition 2.1 for details. □

**Definition 208** (additive category). A category  $\mathbf{C}$  is additive if it has biproducts (Definition 84) and is Ab-enriched.

**Example 209.** The category  $\mathbf{Ab}$  of Abelian groups is an additive category. We have already seen that it has the direct sum  $\oplus$  as biproduct. Given any two abelian groups  $A$  and  $B$  and morphisms  $f, g: A \rightarrow B$ , we can define the sum  $f + g$  via

$$(f + g)(a) = f(a) + g(a) \quad \text{for all } a \in A.$$

Then for another abelian group  $C$  and a morphism  $h: B \rightarrow C$ , we have

$$[h \circ (f + g)](a) = h(f(a) + g(a)) = h(f(a)) + h(g(a)) = [h \circ f + h \circ g](a),$$

so

$$h \circ (f + g) = h \circ f + h \circ g,$$

and similarly in the other slot.

**Example 210.** The category  $\text{Vect}_k$  is additive. Since vector spaces are in particular abelian groups under addition, it is naturally  $\text{Ab}$ -enriched,

**Definition 211** (additive functor). Let  $\mathcal{F}: C \rightsquigarrow D$  be a functor between additive categories. We say that  $\mathcal{F}$  is additive if for each  $X, Y \in \text{Obj}(C)$  the map

$$\text{Hom}_C(X, Y) \rightarrow \text{Hom}_D(\mathcal{F}(X), \mathcal{F}(Y))$$

is a homomorphism of abelian groups.

**Lemma 212.** For any additive functor  $\mathcal{F}: C \rightsquigarrow D$ , there exists a natural isomorphism

$$\Phi: \mathcal{F}(-) \oplus \mathcal{F}(-) \Rightarrow \mathcal{F}(- \oplus -).$$

*Proof.* The commutativity of the following diagram is immediate.

$$\begin{array}{ccc} \mathcal{F}(X \oplus Y) & \xrightarrow{\mathcal{F}(f \oplus g)} & \mathcal{F}(X' \oplus Y') \\ \Phi_{X,Y} \downarrow & & \downarrow \Phi_{X',Y'} \\ \mathcal{F}(X) \oplus \mathcal{F}(Y) & \xrightarrow{\mathcal{F}(f) \oplus \mathcal{F}(g)} & \mathcal{F}(X') \oplus \mathcal{F}(Y') \end{array}$$

The  $(X, Y)$ -component  $\Phi_{X,Y}$  is an isomorphism because

□

## 7.2 Pre-abelian categories

**Definition 213** (pre-abelian category). A category  $C$  is pre-abelian if it is additive and every morphism has a kernel ([Definition 126](#)) and a cokernel ([Definition 133](#)).

**Lemma 214.** Pre-abelian categories have equalizers ([Definition 121](#)).

*Proof.* We show that in an pre-abelian category, the equalizer of  $f$  and  $g$  coincides with the kernel of  $f - g$ . It suffices to show that the kernel of  $f - g$  satisfies the universal property for the equalizer of  $f$  and  $g$ .

Here is the diagram for the universal property of the kernel of  $f - g$ .

$$\begin{array}{ccccc} Z & & & & \\ & \searrow \exists! i & & \searrow & \\ & \text{ker}(f - g) & \longrightarrow & 0 & \\ & \downarrow \iota_{f-g} & & \downarrow & \\ & A & \xrightarrow{f-g} & B & \end{array}$$

(Note: A curved arrow labeled  $i$  goes from  $Z$  to  $A$ , and a curved arrow goes from  $Z$  to  $0$ .)

The universal property tells us that for any object  $Z \in \text{Obj}(\mathcal{C})$  and any morphism  $i: Z \rightarrow A$  with  $i \circ (f - g) = 0$  (i.e.  $i \circ f = i \circ g$ ), there exists a unique morphism  $\bar{i}: Z \rightarrow \ker(f - g)$  such that  $i = \bar{i} \circ \iota_{f-g}$ .  $\square$

**Corollary 215.** *Every pre-abelian category has all finite limits.*

*Proof.* By [Theorem 143](#), a category has finite limits if and only if it has finite products and equalizers. Pre-abelian categories have finite products by definition, and equalizers by [Lemma 214](#).  $\square$

Recall from [Section 2.4](#) the following definition.

**Definition 216** (zero morphism). Let  $\mathcal{C}$  be a category with zero object  $0$ . For any two objects  $A, B \in \text{Obj}(\mathcal{C})$ , the zero morphism  $0_{A,B}$  is the unique morphism  $A \rightarrow B$  which factors through  $0$ .

$$\begin{array}{ccccc} & & 0_{A,B} & & \\ & \searrow & & \nearrow & \\ A & \longrightarrow & 0 & \longrightarrow & B \end{array}$$

*Notation 217.* It will often be clear what the source and destination of the zero morphism are; in this case we will drop the subscripts, writing  $0$  instead of  $0_{AB}$ .

It is easy to see that the left- or right-composition of the zero morphism with any other morphism results in the zero morphism:  $f \circ 0 = 0$  and  $0 \circ g = 0$ .

**Lemma 218.** *Every morphism  $f: A \rightarrow B$  in a pre-abelian category has a canonical decomposition*

$$A \xrightarrow{p} \text{coker}(\ker(f)) \xrightarrow{\tilde{f}} \ker(\text{coker}(f)) \xrightarrow{i} B ,$$

where  $p$  is an epimorphism ([Definition 18](#)) and  $i$  is a monomorphism ([Definition 14](#)).

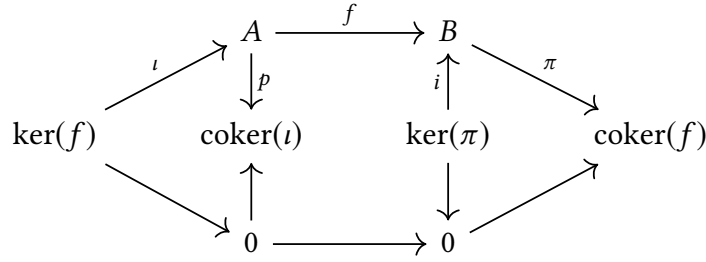
*Proof.* We start with a map

$$A \xrightarrow{f} B .$$

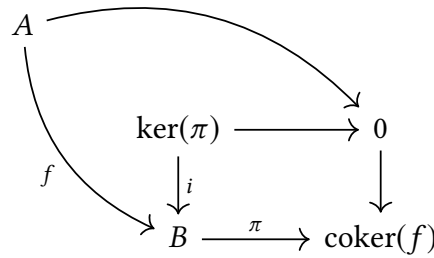
Since we are in a pre-abelian category, we are guaranteed that  $f$  has a kernel  $(\ker(f), \iota)$  and a cokernel  $(\text{coker}(f), \pi)$ . From the universality squares it is immediate that  $f \circ \iota = 0$  and  $\pi \circ f = 0$ . This tells us that the composition  $\pi \circ f \circ \iota = 0$ , so the following commutes.

$$\begin{array}{ccccc} & & A & \xrightarrow{f} & B \\ & \nearrow \iota & & & \searrow \pi \\ \ker(f) & & & & \text{coker}(f) \\ & \searrow & & \nearrow & \\ & & 0 & \longrightarrow & 0 \end{array}$$

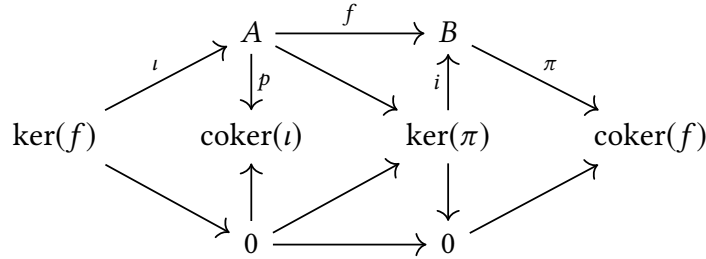
We know that  $\pi$  has a kernel  $(\ker(\pi), i)$  and  $\iota$  has a cokernel  $(\operatorname{coker}(\iota), p)$ , so we can add their commutativity squares as well.



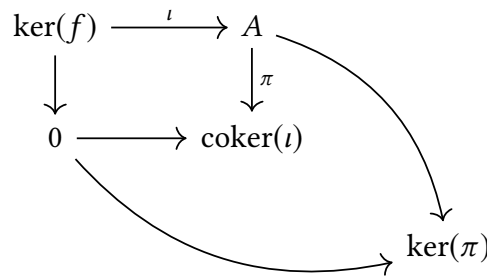
If we squint hard enough, we can see the following diagram.



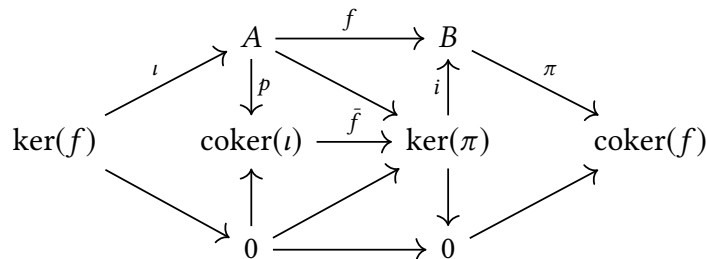
The outer square commutes because  $\pi \circ f = 0$ , so the universal property for  $\ker(\pi)$  gives us a unique morphism  $A \rightarrow \ker(\pi)$ . Let's add this to our diagram, along with a morphism  $0 \rightarrow \ker(\pi)$  which trivially keeps everything commutative.



Again, buried in the bowels of our new diagram, we find the following.



And again, the universal property of cokernels gives us a unique morphism  $\bar{f}: \operatorname{coker}(\iota) \rightarrow \ker(\pi)$ .



The fruit of our laborious construction is the following commuting square.

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ p \downarrow & & \downarrow i \\ \text{coker}(\iota) & \xrightarrow{\bar{f}} & \ker(\pi) \end{array}$$

We have seen (Lemma 129) that  $i$  is mono, and (Lemma 135) that  $p$  is epi.

Now we abuse terminology by calling  $\iota = \ker(f)$  and  $\pi = \text{coker}(f)$ . Then we have the required decomposition.  $\square$

*Note 219.* The abuse of notation above is ubiquitous in the literature.

## 7.3 Abelian categories

This section is under very heavy construction. Don't trust anything you read here.

**Definition 220** (abelian category). A pre-abelian category  $\mathcal{C}$  is abelian if for each morphism  $f$ , the canonical morphism guaranteed by Lemma 218

$$\bar{f}: \text{coker}(\ker(f)) \rightarrow \ker(\text{coker}(f))$$

is an isomorphism.

*Note 221.* The above piecemeal definition is equivalent to the following.

A category  $\mathcal{C}$  is *abelian* if

1. it is Ab-enriched Definition 208, i.e. each hom-set has the structure of an abelian group and composition is bilinear;
2. it admits finite coproducts, hence (by Lemma 207) biproducts and zero objects;
3. every morphism has a kernel and a cokernel;
4. for every morphism,  $f$ , the canonical morphism  $\bar{f}: \text{coker}(\ker(f)) \rightarrow \ker(\text{coker}(f))$  is an isomorphism.

For the remainder of the section, let  $\mathcal{C}$  be an abelian category.

**Lemma 222.** *In an abelian category, every morphism decomposes into the composition of an epimorphism and a monomorphism.*

*Proof.* For any morphism  $f$ , bracketing the decomposition  $f = i \circ \bar{f} \circ p$  as

$$i \circ (\bar{f} \circ p).$$

gives such a composition.  $\square$

*Note 223.* The above decomposition is unique up to unique isomorphism.

**Definition 224** (image of a morphism). Let  $f: A \rightarrow B$  be a morphism. The object  $\ker(\text{coker}(f))$  is called the image of  $f$ , and is denoted  $\text{im}(f)$ .

**Lemma 225.**

1. A morphism  $f: A \rightarrow B$  is mono iff for all  $Z \in \text{Obj}(\mathcal{C})$  and for all  $g: Z \rightarrow A$ ,  $f \circ g = 0$  implies  $g = 0$ .
2. A morphism  $f: A \rightarrow B$  is epi iff for all  $Z \in \text{Obj}(\mathcal{C})$  and for all  $g: B \rightarrow Z$ ,  $g \circ f = 0$  implies  $g = 0$ .

*Proof.*

1. First, suppose  $f$  is mono. Consider the following diagram.

$$Z \xrightarrow[\underset{0}{\rightrightarrows}]{g} A \xrightarrow{f} B$$

If the above diagram commutes, i.e. if  $f \circ g = 0$ , then  $g = 0$ , so  $1 \implies 2$ .

Now suppose that for all  $Z \in \text{Obj}(\mathcal{C})$  and all  $g: Z \rightarrow A$ ,  $f \circ g = 0$  implies  $g = 0$ .

Let  $g, g': Z \rightarrow A$ , and suppose that  $f \circ g = f \circ g'$ . Then  $f \circ (g - g') = 0$ . But that means that  $g - g' = 0$ , i.e.  $g = g'$ . Thus,  $2 \implies 1$ .

2. Dual to the proof above.

□

**Lemma 226.** Let  $f: A \rightarrow B$ . We have the following.

1. The morphism  $f$  is mono iff  $\ker(f) = 0$
2. The morphism  $f$  is epi iff  $\text{coker}(f) = 0$ .

*Proof.*

1. We first show that if  $\ker(f) = 0$ , then  $f$  is mono. Suppose  $\ker(f) = 0$ . By the universal property of kernels, we know that for any  $Z \in \text{Obj}(\mathcal{C})$  and any  $g: Z \rightarrow A$  with  $f \circ g = 0$  there exists a unique map  $\bar{g}: Z \rightarrow \ker(f)$  such that  $g = \iota \circ \bar{g}$ .

$$\begin{array}{ccccc} Z & & \xrightarrow{\exists! \bar{g}} & \ker(f) = 0 & \longrightarrow & 0 \\ & \searrow g & & \downarrow \iota & & \downarrow \\ & & A & \xrightarrow{f} & B \end{array}$$

But then  $g$  factors through the zero object, so we must have  $g = 0$ . This shows that  $f \circ g = 0 \implies g = 0$ , and by [Lemma 225](#)  $f$  must be mono.

Next, we show that if  $f$  is mono, then  $\ker(f) = 0$ . To do this, it suffices to show that  $\ker(f)$  is final, i.e. that there exists a unique morphism from every object to  $\ker(f)$ .

Since  $\text{Hom}_{\mathcal{C}}(Z, \ker(f))$  has the structure of an abelian group, it must contain at least



one element. Suppose it contains two morphisms  $h_1$  and  $h_2$ .

$$\begin{array}{ccc}
 Z & \begin{array}{c} \searrow h_1 \\ \searrow h_2 \end{array} & \text{ker}(f) \longrightarrow 0 \\
 & & \downarrow \iota \quad \downarrow \\
 & & A \xrightarrow{f} B
 \end{array}$$

Our aim is to show that  $h_1 = h_2$ . To this end, compose each with  $\iota$ .

$$\begin{array}{ccc}
 Z & \begin{array}{c} \searrow h_1 \\ \searrow h_2 \end{array} & \text{ker}(f) \longrightarrow 0 \\
 \searrow \iota \circ h_1 & \searrow \iota \circ h_2 & \downarrow \iota \quad \downarrow \\
 & & A \xrightarrow{f} B
 \end{array}$$

Since  $f \circ \iota = 0$ , we have  $f \circ (\iota \circ h_1) = 0$  and  $f \circ (\iota \circ h_2) = 0$ . But since  $f$  is mono, by [Lemma 225](#), we must have  $\iota \circ h_1 = 0 = \iota \circ h_2$ . But by [Lemma 129](#),  $\iota$  is mono, so again we have

$$h_1 = h_2 = 0,$$

and we are done.

2. Dual to the proof above.

□

**Lemma 227.** *We have the following.*

1. *The kernel of the zero morphism  $0 : A \rightarrow B$  is the pair  $(A, \text{id}_A)$ .*
2. *The cokernel of the zero morphism  $0 : A \rightarrow B$  is the pair  $(B, \text{id}_B)$ .*

*Proof.*

1. We need only verify that the universal property is satisfied. That is, for any object  $Z \in \text{Obj}(\mathcal{C})$  and any morphism  $h : Z \rightarrow A$  such that  $0 \circ h = 0$ , there exists a unique morphism  $\bar{g} : Z \rightarrow \text{ker}(0)$  such that the following diagram commutes.

$$\begin{array}{ccccc}
 Z & \xrightarrow{\bar{g}=g} & \text{ker}(0) = A & \xrightarrow{0} & 0 \\
 & \searrow g & \downarrow \iota = \text{id}_A & & \downarrow \\
 & & A & \xrightarrow{0} & B
 \end{array}$$

But this is pretty trivial:  $\bar{g} = g$ .

2. Dual to above.

□

**Theorem 228.** All abelian categories are binormal (Definition 141). That is to say:

1. all monomorphisms are kernels
2. all epimorphisms are cokernels.

*Proof.*

1. Consider the following diagram taken Lemma 218, which shows the canonical factorization of any morphism  $f$ .

$$\begin{array}{ccccc}
 & & A & \xrightarrow{f} & B \\
 & \nearrow \iota & \downarrow p & \searrow & \uparrow i \\
 \ker(f) & & \text{coker}(\iota) & \xrightarrow{\bar{f}} & \ker(\pi) \\
 & \searrow & \uparrow & \nearrow & \searrow \pi \\
 & & 0 & \xrightarrow{\quad} & 0 \\
 & & & & \uparrow \\
 & & & & \text{coker}(f)
 \end{array}$$

By definition of a pre-abelian category, we know that  $\bar{f}$  is an isomorphism.

□

*Note 229.* The above theorem is actually an equivalent definition of an abelian category, but the proof of equivalence is far from trivial. See e.g. [40] for details.

**Definition 230** (subobject, quotient object, subquotient object). Let  $Y \in \text{Obj}(\mathcal{C})$ .

1. A subobject of  $Y$  is an object  $X \in \text{Obj}(\mathcal{C})$  together with a monomorphism  $i: X \hookrightarrow Y$ . If  $X$  is a subobject of  $Y$  we will write  $X \subseteq Y$ .
2. A quotient object of  $Y$  is an object  $Z$  together with an epimorphism  $p: Y \twoheadrightarrow Z$ .
3. A subquotient object of  $Y$  is a quotient object of a subobject of  $Y$ .

**Definition 231** (quotient). Let  $X \subseteq Y$ , i.e. let there exist a monomorphism  $f: X \hookrightarrow Y$ . The quotient  $Y/X$  is the cokernel  $(\text{coker}(f), \pi_f)$ .

**Example 232.** Let  $V$  be a vector space,  $W \subseteq V$  a subspace. Then we have the canonical inclusion map  $\iota: W \hookrightarrow V$ , so  $W$  is a subobject of  $V$  in the sense of Definition 230.

According to Definition 231, the quotient  $V/W$  is the cokernel  $(\text{coker}(\iota), \pi_\iota)$  of  $\iota$ . We saw in Example 134 that the cokernel of  $\iota$  was  $V/\text{im}(\iota)$ . However,  $\text{im}(\iota)$  is exactly  $W$ ! So the categorical notion of the quotient  $V/W$  agrees with the linear algebra notion.

**Definition 233** ( $k$ -linear category). An abelian category Definition 220  $\mathcal{C}$  is  $k$ -linear if for all  $A, B \in \text{Obj}(\mathcal{C})$  the hom-set  $\text{Hom}_{\mathcal{C}}(A, B)$  has the structure of a  $k$ -vector space whose additive structure is the abelian structure, and for which the composition of morphisms is  $k$ -linear.

**Example 234.** The category  $\text{Vect}_k$  is  $k$ -linear.

**Definition 235** ( $k$ -linear functor). let  $\mathcal{C}$  and  $\mathcal{D}$  be two  $k$ -linear categories, and  $\mathcal{F}: \mathcal{C} \rightsquigarrow \mathcal{D}$  a functor. Suppose that for all objects  $C, D \in \text{Obj}(\mathcal{C})$  all morphisms  $f, g: C \rightarrow D$ , and all  $\alpha, \beta \in k$ , we have

$$\mathcal{F}(\alpha f + \beta g) = \alpha \mathcal{F}(f) + \beta \mathcal{F}(g).$$

Then we say that  $\mathcal{F}$  is  $k$ -linear.

## 7.4 Exact sequences

**Definition 236** (exact sequence). A sequence of morphisms

$$\cdots \longrightarrow X_{i-1} \xrightarrow{f_{i-1}} X_i \xrightarrow{f_i} X_{i+1} \longrightarrow \cdots$$

is called exact in degree  $i$  if the image (Definition 224) of  $f_{i-1}$  is equal to the kernel (Definition 126) of  $f_i$ . A sequence is exact if it is exact in every degree.

**Lemma 237.** *If a sequence*

$$\cdots \longrightarrow X_{i-1} \xrightarrow{f_{i-1}} X_i \xrightarrow{f_i} X_{i+1} \longrightarrow \cdots$$

*is exact in degree  $i$ , then  $f_i \circ f_{i-1} = 0$ .*

**Definition 238** (short exact sequence). A short exact sequence is an exact sequence of the following form.

$$0 \longrightarrow X \longrightarrow Y \longrightarrow Z \longrightarrow 0$$

**Definition 239** (exact functor). Let  $C, D$  be abelian categories,  $\mathcal{F}: C \rightsquigarrow D$  a functor. We say that  $\mathcal{F}$  is

- left exact if it preserves biproducts and kernels
- right exact if it preserves biproducts and cokernels
- exact if it is both left exact and right exact.

## 7.5 Length of objects

**Definition 240** (simple object). A nonzero object  $X \in \text{Obj}(C)$  is called simple if  $0$  and  $X$  are its only subobjects.

**Example 241.** In  $\text{Vect}_k$ , the only simple object (up to isomorphism) is  $k$ , taken as a one-dimensional vector space over itself.

**Definition 242** (semisimple object). An object  $Y \in \text{Obj}(C)$  is semisimple if it is isomorphic to a direct sum of simple objects.

**Example 243.** In  $\text{Vect}_k$ , all finite-dimensional vector spaces are semisimple.

**Definition 244** (semisimple category). An abelian category  $C$  is semisimple if every object of  $C$  is semisimple.

**Example 245.** The category  $\text{FinVect}_k$  is semisimple.

**Definition 246** (Jordan-Hölder series). Let  $X \in \text{Obj}(C)$ . A filtration

$$0 = X_0 \subset X_1 \subset \cdots \subset X_{n-1} \subset X_n = X$$

of  $X$  such that  $X_i/X_{i-1}$  is simple for all  $i$  is called a Jordan Hölder series for  $X$ . The integer  $n$  is called the length of the series  $X_i$ .

The importance of Jordan-Hölder series is the following.

**Theorem 247** (Jordan-Hölder). *Let  $X_i$  and  $Y_i$  be two Jordan-Hölder series for some object  $X \in \text{Obj}(\mathcal{C})$ . Then the length of  $X_i$  is equal to the length of  $Y_i$ , and the objects  $Y_i/Y_{i-1}$  are a reordering of  $X_i/X_{i-1}$ .*

*Proof.* See [22], pg. 5, Theorem 1.5.4. □

**Definition 248** (length). The length of an object  $X$  is defined to be the length of any of its Jordan-Hölder series. This is well-defined by [Theorem 247](#).

# 8 Tensor Categories

The following definition is taken almost verbatim from [11].

**Definition 249** (tensor category). Let  $k$  be a field. A  $k$ -tensor category  $A$  (as considered by Deligne in [30]) is an

1. essentially small (Definition 51)
2.  $k$ -linear<sup>1</sup> (Definition 233)
3. rigid (Definition 202)
4. symmetric (Definition 181)
5. monoidal category (Definition 161)

such that

1. the tensor product functor  $\otimes: A \times A \rightsquigarrow A$  is, in both arguments separately,
  - a)  $k$ -linear (Definition 235)
  - b) exact (Definition 239)
2.  $\text{End}(1) \simeq k$ , where  $\text{End}$  denotes the endomorphism ring (Definition 206).

**Example 250.**  $\text{Vect}_k$  is *not* a tensor category because it is not essentially small; there is one isomorphism class of vector spaces for each cardinal, and there is no set of all cardinals. However, its subcategory  $\text{FinVect}_k$  is a tensor category.

**Definition 251** (finite tensor category). A  $k$ -tensor category  $A$  is called finite (over  $k$ ) if

1. There are only finitely many simple objects in  $A$ , and each of them admits a projective presentation.
2. Each object  $A$  of  $A$  is of finite length.
3. For any two objects  $A, B$  of  $A$ , the hom-object (i.e.  $k$ -vector space)  $\text{Hom}_A(A, B)$  is finite-dimensional.

**Example 252.** The category  $\text{FinVect}_k$  is finite.

1. The only simple object is  $k$  taken as a one-dimensional vector space over itself.
2. The length of a finite-dimensional vector space is simply its dimension.
3. The vector space  $\text{Hom}_{\text{FinVect}}(V, W)$  has dimension  $\dim(V) \dim(W)$ .

**Definition 253** (finitely  $\otimes$ -generated). A  $k$ -tensor category  $A$  is called finitely  $\otimes$ -generated if there exists an object  $E \in \text{Obj}(A)$  such that every other object  $X \in A$  is a subquotient

---

<sup>1</sup>Hence abelian.

([Definition 230](#)) of a finite direct sum of tensor products of  $E$ ; that is to say, if there exists a finite collection of integers  $n_i$  such that  $X$  is a subquotient of  $\bigoplus_i E^{\otimes n_i}$ .

$$\begin{array}{c} \bigoplus_i E^{\otimes n_i} \\ \downarrow \pi \\ X \hookrightarrow (\bigoplus_i E^{\otimes n_i}) / Q \end{array}$$

**Example 254.** The category  $\text{FinVect}_k$  is finitely generated since any finite-dimensional vector space is isomorphic to  $k^n = k \oplus \cdots \oplus k$  for some  $n$ .

**Definition 255** (subexponential growth). A tensor category  $A$  has subexponential growth if, for each object  $X$  there exists a natural number  $N_X$  such that

$$\text{len}(X^{\otimes n}) \leq (N_X)^n.$$

**Example 256.** The category  $\text{FinVect}_k$  has subexponential growth. For any finite-dimensional vector space  $V$ , we always have

$$\dim(V^{\otimes n}) = (\dim(V))^n,$$

so we can take  $N_V = \dim(V)$ .

**Theorem 257.** Let  $A$  be a tensor category, and suppose that

1. every object  $A \in \text{Obj}(A)$  has a finite length
2. the dimension of every hom space  $\text{Hom}_A(A, B)$  is finite over  $k$ .

Then the category  $\text{Ind}(A)$  of ind-objects of  $A$  ([Definition 149](#)) has the following properties.

1.  $\text{Ind}(A)$  is abelian ([Definition 220](#)).
2.  $A \hookrightarrow \text{Ind}(A)$  is a full subcategory (cf. [Note 150](#)).
3. The tensor product on  $A$  extends to  $\text{Ind}(A)$  via

$$\begin{aligned} X \otimes Y &\simeq (\lim_{\rightarrow i} X_i) \otimes (\lim_{\rightarrow j} Y_j) \\ &\simeq \lim_{\rightarrow i, j} (X_i \otimes Y_j). \end{aligned}$$

4. The category  $\text{Ind}(A)$  fails to be a tensor category only because it is not necessarily essentially small and rigid. More specifically, an object  $A \in \text{Ind}(A)$  is dualizable if and only if it is in  $A$ .

*Proof.* Proposition 3.38 in [11]. □

**Definition 258** (tensor functor). Let  $(\mathcal{A}, \otimes_A, \text{id}_A)$  and  $(\mathcal{B}, \otimes_B, \text{id}_B)$  be  $k$ -tensor categories. A functor  $\mathcal{F}: \mathcal{A} \rightarrow \mathcal{B}$  is called a tensor functor if it is

1. braided ([Definition 179](#)) and
2. strong monoidal ([Definition 171](#)).

# 9 Internalization

One of the reasons that category theory is so useful is that it makes generalizing concepts very easy. One of the most powerful ways of doing this is known as *internalization*.

## 9.1 Internal groups

**Definition 259** (group object). Let  $\mathcal{C}$  be a category with binary products  $\times$  and a terminal object  $*$ . A group object in  $\mathcal{C}$  (or a *group internal to  $\mathcal{C}$* ) is an object  $G \in \text{Obj}(\mathcal{C})$  together with

- a map  $e: * \rightarrow G$ , called the *unit map*;
- a map  $(-)^{-1}: G \rightarrow G$ , called the *inverse map*; and
- a map  $m: G \times G \rightarrow G$ , called the *multiplication map*

such that

- Multiplication is associative, i.e. the following diagram commutes.

$$\begin{array}{ccc} G \times G \times G & \xrightarrow{\text{id}_G \times m} & G \times G \\ m \times \text{id}_G \downarrow & & \downarrow m \\ G \times G & \xrightarrow{m} & G \end{array}$$

- The unit picks out the ‘identity element,’ i.e. the following diagram commutes.

$$\begin{array}{ccc} G & \xrightarrow{e \times \text{id}_G} & G \times G \\ \text{id}_G \times e \downarrow & & \downarrow m \\ G \times G & \xrightarrow{m} & G \end{array}$$

- The inverse map behaves as an inverse, i.e. the following diagram commutes.

$$\begin{array}{ccccc} & G \times G & \xrightarrow{(-)^{-1} \times \text{id}} & G \times G & \\ \delta \nearrow & & & & \searrow m \\ G & \xrightarrow{\exists!} & * & \xrightarrow{e} & G \\ \delta \searrow & & & & \nearrow m \\ & G \times G & \xrightarrow{\text{id} \times (-)^{-1}} & G \times G & \end{array}$$

Here,  $\delta: G \rightarrow G \times G$  is the diagonal map defined uniquely by the universal property of the product

$$\begin{array}{ccccc} & & G & & \\ & \swarrow \text{id}_G & \downarrow \delta & \searrow \text{id}_G & \\ G & \xleftarrow{\pi_1} & G \times G & \xrightarrow{\pi_2} & G \end{array} .$$

It will be convenient to represent the above data in the following way.

$$\begin{array}{c} G \times G \\ \downarrow m \\ G \curvearrowright i \\ \uparrow e \\ * \end{array}$$



# Bibliography

- [1] M.-L. Michelson and H.B. Lawson. *Spin Geometry*. Princeton University Press, Princeton, NJ, 1989.
- [2] R. Vakil, *The Rising Sea*. <http://www.math216.wordpress.com/>
- [3] S. B. Sontz. *Principal Bundles: The Classical Case*. Springer International Publishing, Switzerland, 2015.
- [4] T. Hungerford. *Algebra*. Springer-Verlag New York, NY, 1974.
- [5] J. Figueroa-O’Farril. *PG Course on Spin Geometry*. <https://empg.maths.ed.ac.uk/Activities/Spin/>
- [6] P. Deligne et al. *Quantum Fields and Strings: a Course for Mathematicians*. American Mathematical Society, 1999.
- [7] V. S. Varadarajan. *Supersymmetry for Mathematicians: An Introduction*. American Mathematical Society, 2004.
- [8] The Catsters. <https://www.youtube.com/channel/UC5Y9H2KDRHZZTWZJt1H4VbA>
- [9] A. Connes and M. Marcolli. *Noncommutative Geometry, Quantum Fields and Motives*. <http://www.alainconnes.org/docs/bookwebfinal.pdf>
- [10] P. Aluffi. *Algebra: Chapter 0*. American Mathematical Society, 2009.
- [11] Nlab—Deligne’s Theorem on Tensor Categories. <https://ncatlab.org/nlab/show/Deligne’s+theorem+on+tensor+categories>
- [12] J. Baez. *This Week’s Finds in Mathematical Physics (Week 137)*. <http://math.ucr.edu/home/baez/week137.html>
- [13] J. Baez. *Some Definitions Everyone Should Know*. <http://math.ucr.edu/home/baez/qg-fall2004/definitions.pdf>
- [14] *The Unapologetic Mathematician: Mac Lane’s Coherence Theorem*. <https://unapologetic.wordpress.com/2007/06/29/mac-lanes-coherence-theorem/>
- [15] D. Montgomery and L. Zippin. *Topological Transformation Groups*. University of Chicago Press, Chicago, 1955.
- [16] P. Deligne, J.S. Milne, A. Ogus, and K. Shih. *Hodge Cycles, Motives, and Shimura Varieties*. Springer Verlag, 1982
- [17] S. Mac Lane. *Categories for the Working Mathematician*. Springer-Verlag New York, New York, 1998.
- [18] J. Baez. *An introduction to n-Categories*. <https://arxiv.org/pdf/q-alg/>

9705009.pdf

- [19] <https://groups.google.com/forum/#!topic/sci.math/7LqPFfmWGOA>
- [20] <https://www.ncatlab.org/>
- [21] Wikipedia - Product (Category Theory). [https://en.wikipedia.org/wiki/Product\\_\(category\\_theory\)](https://en.wikipedia.org/wiki/Product_(category_theory))
- [22] P. Etingof, S. Gelaki, D. Nikshych, and V. Ostrik. *Tensor Categories*. American Mathematical Society, 2015.
- [23] S. Awodey and A. Bauer. *Lecture Notes: Introduction to Categorical Logic*
- [24] S. Awodey. *Category Theory Foundations*. [https://www.youtube.com/watch?v=BF6kHD1DAeU&index=1&list=PLGCr8P\\_YncjVjwAxrifKgcQYtbZ3zuPlb](https://www.youtube.com/watch?v=BF6kHD1DAeU&index=1&list=PLGCr8P_YncjVjwAxrifKgcQYtbZ3zuPlb)
- [25] S. Awodey. *Category Theory*. Oxford University Press, 2006.
- [26] R. Haag. *Local Quantum Physics: Fields, Particles, Algebras*. Springer-Verlag Berlin Heidelberg New York, 1996
- [27] R. Sexl and H. Urbantke. *Relativity, Groups, Particles: Special Relativity and Relativistic Symmetry in Field and Particle Physics*. Springer-Verlag Wein, 1992
- [28] J. Wess and J. Bagger. *Supersymmetry and Supergravity*. Princeton University Press, Princeton NJ, 1992
- [29] H J W Müller-Kirschen and Armin Wiedemann *Introduction to Supersymmetry (Second edition)*. World Scientific, 2010.
- [30] Pierre Deligne. *Catégories Tensorielle*, Moscow Math. Journal 2 (2002) no. 2, 227-228 <https://www.math.ias.edu/files/deligne/Tensorielles.pdf>
- [31] I. Kolář, P. Michor, and J. Slovák. *Natural Operations in Differential Geometry*. Springer-Verlag, Berlin Heidelberg, 1993.
- [32] R. Hartshorne. *Algebraic Geometry*. Springer-Verlag, New York, 1977.
- [33] Q. Yuan. *Annoying Precision: A meditation on semiadditive categories*. <https://qchu.wordpress.com/2012/09/14/a-meditation-on-semiadditive-categories/>
- [34] J. Nestruev. *Smooth Manifolds and Observables*. Springer-Verlag, New York, 2002.
- [35] J. Baez and A. Lauda. *A prehistory of n-categorical physics*. <https://arxiv.org/pdf/0908.2469.pdf>
- [36] A. Neumaier. *Elementary particles as irreducible representations*. <https://www.physicsoverflow.org/21960>.
- [37] U. Schreiber. *Why Supersymmetry? Because of Deligne's theorem* <https://www.physicsforums.com/insights/supersymmetry-delignes-theorem/>
- [38] G. W. Mackey. *Induced representations*. W.A. Benjamin, Inc., and Editore Boringhieri, New York, 1968.

- [39] nLab: Additive category. <https://ncatlab.org/nlab/show/additive+category#ProductsAreBiproducts>
- [40] P. Freyd. *Abelian Categories* Harper and Row, New York, 1964.
- [41] J. Milne, *Basic Theory of Affine Group Schemes*, 2012. Available at [www.jmilne.org/math/](http://www.jmilne.org/math/)
- [42] E. Wigner. *On Unitary Representations of the Inhomogeneous Lorentz Group*. Annals of Mathematics. Second Series, Vol. 40, No. 1 (Jan., 1939), pp. 149-204
- [43] J. P. M. dos Santos. *Representation theory of symmetric groups*. <https://www.math.tecnico.ulisboa.pt/~ggranja/joaopedro.pdf>
- [44] U. Manin. *Gauge Fields and Complex Geometry*, Springer-Verlag Berlin Heidelberg New York, 1988.
- [45] Valter Moretti (<https://physics.stackexchange.com/users/35354/valter-moretti>). *Euler-Lagrange equations and friction forces*, URL (version: 2014-02-02): <https://physics.stackexchange.com/q/96470>
- [46] J.S. Milne. *Lie Algebras, Algebraic Groups, and Lie Groups*. Available at [www.jmilne.org/math/](http://www.jmilne.org/math/)
- [47] J. Fröhlich and F. Gabbiani. *Braid statistics in Local Quantum Theory*. Rev. Math. Phys. 02, 251 (1990).
- [48] J. Binney and D. Skinner. *The Physics of Quantum Mechanics*. Available at <https://www-thphys.physics.ox.ac.uk/people/JamesBinney/qb.pdf>
- [49] R. Feynman. *Spacetime Approach to Non-Relativistic Quantum Mechanics*. Rev. Mod. Phys. 20, 367 – Published 1 April 1948
- [50] F. A. Berezin. *The Method of Second Quantization*. Nauka, Moscow, 1965. Translation: Academic Press, New York, 1966. (Second edition, expanded: M. K. Polivanov, ed., Nauka, Moscow, 1986.)
- [51] S. Coleman and J. Mandula. *All Possible Symmetries of the S Matrix*. Physical Review, 159(5), 1967, pp. 1251–1256.
- [52] R. Haag, M. Sohnius, and J. T. Łopuszański. *All possible generators of supersymmetries of the S-matrix*. Nuclear Physics B, 88: 257–274 (1975)