Part III Category Theory

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Contents

1 Definitions and Examples

Definition 1.1 (Category). *A category $\mathcal{C}$ consists of*

a. *a collection* $\mathrm{ob}\,\mathcal{C}$ *of* ***objects*** A, B, C, ...

b. *a collection* $\mathrm{mor}\,\mathcal{C}$ *of* ***morphisms*** f, g, h, ...

c. *two operations* dom , cod *from morphisms to objects. We write* $f : A \to B$ *or* $A \xrightarrow{f} B$ *to mean 'f is a morphism and* $\mathrm{dom}\, f = A$ *and* $\mathrm{cod}\, f = B$*'*

d. *an operation assigning to each object A a morphism* $1_A : A \to A$

e. *a partial binary operation* $(f, g) \mapsto gf$*, s.t.* gf *is defined* $\iff$ $\mathrm{dom}\, g = \mathrm{cod}\, f$*, and then* $gf : \mathrm{dom}\, f \to \mathrm{cod}\, g$

satisfying

f. $f1_A = f$ *and* $1_B f = f$ $\forall f : A \to B$

g. $h(fg) = (hg)f$ *whenever* gf *and* hg *are defined*

Definition 1.2 (Functor). *Let $\mathcal{C}$ and $\mathcal{D}$ be categories. A* ***functor*** $\mathcal{C} \to \mathcal{D}$ *consists of* *a. a mapping* $A \to FA$ *from* $\operatorname{ob}\mathcal{C}$ *to* $\operatorname{ob}\mathcal{D}$

b. a mapping $f \to Ff$ *from* $\operatorname{mor}\mathcal{C}$ *to* $\operatorname{mor}\mathcal{D}$

satisfying $\operatorname{dom} Ff = F\operatorname{dom} f$, $\operatorname{cod} Ff = F\operatorname{cod} f$ *for all* f, $F(1_A) = 1_{FA}$ *for all* A, *and* $F(gf) = (Fg)(Ff)$ *whenever* gf *is defined.*

Definition 1.3. *By a* ***contravariant functor*** $\mathcal{C} \to \mathcal{D}$ *we mean a functor* $\mathcal{C} \to \mathcal{D}^{op}$ *(or equivalently* $\mathcal{C}^{op} \to \mathcal{D}$*). A functor* $\mathcal{C} \to \mathcal{D}$ *is sometimes said to be* ***covariant****.*

Definition 1.4 (Natural transformation)**.** *Let* $\mathcal{C}$ *and* $\mathcal{D}$ *be two categories and* $F, G : \mathcal{C} \rightrightarrows \mathcal{D}$ *two functors. A* ***natural transformation*** $\alpha : F \to G$ *assigns to each* $A \in \operatorname{ob}\mathcal{C}$ *a morphism* $\alpha_A : FA \to GA$ *in* $\mathcal{D}$*, such that*

$$\begin{tikzcd} FA \arrow[r, "Ff"] \arrow[d, "\alpha_A"] & FB \arrow[d, "\alpha_B"] \\ GA \arrow[r, "Gf"] & GB \end{tikzcd}$$

commutes.

We can compose natural transformations: given $\alpha : F \to G$ and $\beta : G \to H$, the mapping $A \mapsto \beta_A \alpha_A$ is the A-component of a natural transformation $\beta\alpha : F \to H$.

Definition 1.5. *Given categories* $\mathcal{C}, \mathcal{D}$*, we write* $[\mathcal{C}, \mathcal{D}]$ *for the category of all functors* $\mathcal{C} \to \mathcal{D}$ *and natural transformations between them.*

Lemma 1.6. *Given* $F, G : \mathcal{C} \to \mathcal{D}$ *and* $\alpha : F \to G$*,* α *is an isomorphism in* $[\mathcal{C}, \mathcal{D}] \iff$ *each* α_A *is an isomorphism in* $\mathcal{D}$*.*

Definition 1.7 (Faithful and full)**.** *Let* $F : \mathcal{C} \to \mathcal{D}$ *be a functor.*

a. We say that F *is* ***faithful*** *if, given* $f, g \in \operatorname{mor}\mathcal{C}$*, the equations* $\operatorname{dom} f = \operatorname{dom} g$*,* $\operatorname{cod} f = \operatorname{cod} g$ *and* $Ff = Fg$ *imply* $f = g$*.*

b. F *is* ***full*** *if, given any* $g : FA \to FB$ *in* $\mathcal{D}$*, there exists* $f : A \to B$ *in* $\mathcal{C}$ *with* $Ff = g$*.*

c. We say a subcategory $\mathcal{C}'$ *of* $\mathcal{C}$ *is* ***full*** *if the inclusion* $\mathcal{C}' \hookrightarrow \mathcal{C}$ *is a full functor.*

For example, **Gp** is a full subcategory of the category **Mon** of monoids, but **Mon** is a non-full subcategory of the category **Sgp** of semigroups.

Definition 1.8 (Equivalence of categories)**.** *Let $\mathcal{C}$ and $\mathcal{D}$ be categories. An **equivalence** between $\mathcal{C}$ and $\mathcal{D}$ is a pair of functors $F : \mathcal{C} \to \mathcal{D}$, $G : \mathcal{D} \to \mathcal{C}$ together with natural isomorphisms $\alpha : 1_{\mathcal{C}} \to GF$, $\beta : FG \to 1_{\mathcal{D}}$. We write $\mathcal{C} \simeq \mathcal{D}$ to mean that $\mathcal{C}$ and $\mathcal{D}$ are equivalent.*

*We say a property P of categories is **categorical** if whenever $\mathcal{C}$ has P and $\mathcal{C} \simeq \mathcal{D}$ then $\mathcal{D}$ has P.*

For example, being a groupoid is a categorical property, but being a group is not.

Definition 1.9 (Slice category)**.** *Given an object B of a category $\mathcal{C}$, define the **slice category** $\mathcal{C}/B$ to have morphisms $A \xrightarrow{f} B$ as objects, and morphisms $(A \xrightarrow{f} B) \to (A' \xrightarrow{f'} B)$ are morphisms $h : A \to A'$ making*

$$\begin{tikzcd} A \arrow[rr, "h"] \arrow[dr, "f"'] & & A' \arrow[dl, "f'"] \\ & B & \end{tikzcd}$$

commute.

Lemma 1.10. *Let $F : \mathcal{C} \to \mathcal{D}$ be a functor. Then F is part of an equivalence $\mathcal{C} \simeq \mathcal{D} \iff F$ is full, faithful and **essentially surjective**, i.e. for every $B \in \operatorname{ob} \mathcal{D}$, there exists $A \in \operatorname{ob} \mathcal{C}$ s.t. $FA \cong B$.*

Definition 1.11.

*a. A **skeleton** of a category $\mathcal{C}$ is a full subcategory $\mathcal{C}'$ containing exactly one object from each isomorphism class of objects of $\mathcal{C}$.*

*b. We say $\mathcal{C}$ is **skeletal** if it's a skeleton of itself. Equivalently, any isomorphism f in $\mathcal{C}$ satisfies $\operatorname{dom} f = \operatorname{cod} f$.*

For example, $\mathbf{Mat}_K$ is skeletal. The full subgategory of standard vector spaces K^n is a skeleton of $\mathbf{fd\ Mod}_K$.

Remark 1.12. *The following statements are each equivalent to the Axiom of Choice:*

1. *Every small category has a skeleton*
2. *Any small category is equivalent to each of its skeletons*
3. *Any two skeletons of a given small category are isomorphic*

Definition 1.13. *Let $f : A \to B$ be a morphism in a category $\mathcal{C}$.*

*a. f is a **monomorphism** if, given $g, h : D \rightrightarrows A$, the equation $fg = fh$ implies $g = h$. We write $A \rightarrowtail B$ if f is monic.*

b. *Dually, f is an **epimorphism** if, given $k, l : B \rightrightarrows C$, $kf = lf$ implies $k = l$. We write $A \twoheadrightarrow B$ if f is epic.*

c. *$\mathcal{C}$ is a **balanced** category if every $f \in \operatorname{mor} \mathcal{C}$ which is both monic and epic is an isomorphism.*

2 The Yoneda Lemma

Definition 2.1. *A category $\mathcal{C}$ is **locally small** if, for any two objects A, B of $\mathcal{C}$, the morphism $A \to B$ are parametrised by a set $\mathcal{C}(A, B)$.*

Given local smallness, $B \mapsto \mathcal{C}(A, B)$ becomes a functor $\mathcal{C}(A, -) : \mathcal{C} \to \mathbf{Set}$: if $g : B \to B'$, the mapping $f \mapsto gf : \mathcal{C}(A, B) \to \mathcal{C}(A, B')$ is functorial since $h(gf) = (hg)f$ for any $h : B' \to B''$.

Similarly, $A \mapsto \mathcal{C}(A, B)$ becomes a functor $\mathcal{C}^{op} \to \mathbf{Set}$.

Lemma 2.2 (Yoneda)**.** *Let $\mathcal{C}$ be a locally small category, $A \in \operatorname{ob} \mathcal{C}$ and $F : \mathcal{C} \to$ **Set**. Then*

i. *There is a bijection between natural transformations $\mathcal{C}(A, -) \to F$ and elements of FA.*

ii. *Moreover, this bijection is natural in both A and F.*

Proof. Bijection: given $\alpha : \mathcal{C}(A, -) \to F$, define $\Phi(\alpha) = \alpha_A(1_A) \in FA$.

Given $x \in FA$, define $\Psi(x) : \mathcal{C}(A, -) \to F$ by

$$\Psi(x)_B(A \xrightarrow{f} B) = (Ff)(x) \in FB$$

$\Psi(x)$ is natural: given $g : B \to C$, we have

$$\begin{aligned} \Psi(x)_C(\mathcal{C}(A, g)(f)) &= \Psi(x)_C(gf) \\ &= F(gf)(x) \\ &= (Fg)(Ff)(x) \\ &= (Fg)\Psi(x)_B(f) \end{aligned}$$

$\Phi\Psi(x) = x$ since $F(1_A)(x) = x$, and $\Psi\Phi(\alpha) = \alpha$ since, for any $f : A \to B$,

$$\begin{aligned} \Psi\Phi(\alpha)_B(f) &= Ff(\Phi(\alpha)) \\ &= Ff(\alpha_A(1_A)) \\ &= \alpha_B(\mathcal{C}(A, f)(1_A)) \\ &= \alpha_B(f) \end{aligned}$$

□

Corollary 2.3. *The mapping $A \to \mathcal{C}(A, -)$ is a full and faithful functor $\mathcal{C}^{op} \to [\mathcal{C}, \textbf{\textit{Set}}]$.*

Proof. Given two objects A, B, 2.2(i) gives us a bijection from $\mathcal{C}(B, A)$ to the collection of natural transformations $\mathcal{C}(A, -) \to \mathcal{C}(B, -)$ (by taking $F : C \mapsto \mathcal{C}(B, C)$). We need to show this is functorial, but given $f \in \mathcal{C}(B, A)$, $\Psi(F)_A$ sends 1_A to $\mathcal{C}(B, f)(1_A) = f$, so it's the natural transformation $g \mapsto gf$.

Hence, given $e : C \to B$, $\Psi(fe)(g) = g(fe) = (gf)(e) = \Psi(e)\Psi(f)g$ $\square$

We call this functor the **Yoneda embedding**. Hence any locally small category $\mathcal{C}$ is equivalent to a full subcategory of $[\mathcal{C}^{op}, \mathbf{Set}]$.

Definition 2.4. *A functor $\mathcal{C} \to$ **Set** is **representable** if it's isomorphic to $\mathcal{C}(A, -)$ for some A.*

*A **representation** of $F : \mathcal{C} \to$ **Set** is a pair (A, x) where $A \in \operatorname{ob}\mathcal{C}$, $x \in FA$ and $\Psi(x) : \mathcal{C}(A, -) \to F$ is an isomorphism. We also call x a **universal element** of F.*

Corollary 2.5 ('Representations are unique up to unique isomorphism')**.** *If (A, x) and (B, y) are both representations of $F : \mathcal{C} \to$ **Set**, then there's a unique isomorphism $f : A \to B$ s.t $Ff(x) = y$.*

Definition 2.6 (Product and coproduct)**.** *Given two objects A, B of a locally small category $\mathcal{C}$, we define their **product** to be a representation of the functor*

$$\mathcal{C}(-, A) \times \mathcal{C}(-, B) : \mathcal{C}^{op} \to \textbf{\textit{Set}}$$

i.e. an object $A \times B$ equipped with morphisms $\pi_1 : A \times B \to A$, $\pi_2 : A \times B \to B$ s.t. given any pair $(f : C \to A, g : C \to B)$, there exists a unique $h : C \to A \times B$ s.t. $\pi_1 h = f$ and $\pi_2 h = g$.

*More generally, we can define the product $\prod_{i \in I} A_i$ of a family $\{A_i \mid i \in I\}$ of objects, or the product of the empty family, i.e. a **terminal object** 1 s.t. for every A there's a unique $A \to 1$.*

*Dualizing, we get the notion of **coproduct** or **sum**.*

Definition 2.7 (Equaliser and coequaliser)**.** *Given a parallel pair $f, g : A \rightrightarrows B$ in a locally small category $\mathcal{C}$, the assignment $C \mapsto FC = \{h : C \to A \mid fh = gh\}$ is a subfunctor F of $\mathcal{C}(-, A)$. A representation of F is called an **equaliser** of (f, g).*

In elementary terms, it's an object E equipped with $e : E \to A$ s.t. $fe = ge$, s.t. any h with $fh = gh$ factors uniquely as $h = ek$

*Dually, we have the notion of **coequaliser**, i.e. a morphism $q : B \to Q$ satisfying $qf = qg$, and universal among such.*

Definition 2.8. *a. We say a monomorphism is **regular** if it occurs as an equaliser (dually, regular epimorphism).*

*b. We say $f : A \to B$ is a **split monomorphism** if there exists $g : B \to A$ with $gf = 1_A$.*

Every split monomorphism is regular: if $gf = 1_A$, f is an equaliser of $(1_B, fg)$ [see sheet 1, q2].

Definition 2.9. *Let $\mathcal{C}$ be a (locally small) category, $\mathcal{G}$ a collection of objects of $\mathcal{C}$.*

*a. Say $\mathcal{G}$ is a **separating family** if the functors $\mathcal{C}(G, -)$, $G \in \mathcal{G}$ are jointly faithful, i.e. if given $f, g : A \rightrightarrows B$ with $f \neq g$, there exists $G \in \mathcal{G}$ and $h : G \to A$ with $fh \neq gh$.*

*b. Say $\mathcal{G}$ is a **detecting family** if the $\mathcal{C}(G, -)$, $G \in \mathcal{G}$ jointly reflect isomorphisms, i.e. if given $f : A \to B$ s.t. every $g : G \to B$ with $G \in \mathcal{G}$ factors uniquely through f, f is an isomorphism.*

Lemma 2.10. *i. If $\mathcal{C}$ is balanced, then any separating family is detecting*

ii. If $\mathcal{C}$ has equalisers, then every detecting family is separating

Definition 2.11. *An object P is **projective** if $\mathcal{C}(P, -)$ preserves epimorphisms, i.e. if given*

$$\begin{tikzcd} & P \arrow[d, "f"] \\ A \arrow[r, two heads, "e"] & B \end{tikzcd}$$

there exists $g : P \to A$ with $eg = f$.

*Dually, P is **injective** in $\mathcal{C}$ if it's projective in $\mathcal{C}^{op}$.*

If P satisfies this property $\forall e$ in some class $\mathcal{E}$ of epimorphisms, we call it $\mathcal{E}$-projective.

Corollary 2.12. *Representable functors are (pointwise) projective in $[\mathcal{C}, \textbf{Set}]$*

Proof. Given

$$\begin{tikzcd} & \mathcal{C}(A, -) \arrow[d, "\beta"] \\ F \arrow[r, two heads, "\alpha"] & G \end{tikzcd}$$

β corresponds to some $y \in GA$. α_A is surjective, so $\exists x \in FA$ with $\alpha_A(x) = y$. x corresponds to $\gamma : \mathcal{C}(A, -) \to F$ with $\alpha\gamma = \beta$. $\square$

3 Adjunctions

Definition 3.1 (D.M. Khan, 1958)**.** *Let $\mathcal{C}$ and $\mathcal{D}$ be categories and $F : \mathcal{C} \to \mathcal{D}$, $G : \mathcal{D} \to \mathcal{C}$ be two functors. An* ***adjunction*** *between F and G is a bijection between morphisms $FA \to B$ in $\mathcal{D}$ and morphisms $A \to GB$ in $\mathcal{C}$, which is natural in A and B.*

*(If $\mathcal{C}$ and $\mathcal{D}$ are locally small, this says that $(A, B) \to \mathcal{D}(FA, B)$ and $(A, B) \to \mathcal{C}(A, GB)$ are naturally isomorphic functors $\mathcal{C}^{op} \times \mathcal{D} \to$ **Set**).*

We say F is ***left adjoint*** *to G, or G is* ***right adjoint*** *to F, and write $F \dashv G$.*

Theorem 3.2. *Let $G : \mathcal{D} \to \mathcal{C}$ be a functor. Given $A \in \operatorname{ob}\mathcal{C}$, let $(A \downarrow G)$ be the category whose objects are pairs (B, f) with $B \in \operatorname{ob}\mathcal{D}$, $f : A \to GB$ and whose morphisms $(B, f) \to (B', f')$ are morphisms $g : B \to B'$ in $\mathcal{D}$ such that*

$$\begin{tikzcd} A \arrow[r, "f"] \arrow[dr, "f'"'] & GB \arrow[d, "Gg"] \\ & GB' \end{tikzcd}$$

commutes. Then specifying a left adjoint for G is equivalent to specifying an initial object of $(A \downarrow G)$ for each A.

Proof. First suppose G has a left adjoint F. Let $\eta_A : A \to GFA$ be the morphism corresponding to $1_{FA} : FA \to FA$. The pair (FA, η_A) is an object of $(A \downarrow G)$. We'll show it's initial.

Given $g : FA \to B$, the composite $A \xrightarrow{\eta_A} GFA \xrightarrow{Gg} GB$ must correspond to $FA \xrightarrow{1} FA \xrightarrow{g} B$ under the adjunction.

So, for any object (B, f) of $(A \downarrow G)$, the unique morphism $(FA, \eta_A) \to (B, f)$ in $(A \downarrow G)$ is the morphism $FA \to B$ corresponding to f.

Conversely, suppose we're given an initial object (FA, η_A) of $(A \downarrow G)$ for each G. Given $f : A \to A'$, the composite $A \xrightarrow{f} A' \xrightarrow{\eta_{A'}} GFA'$ is an object of $(A \downarrow G)$, so there's a unique morphism $Ff : FA \to FA'$ making

$$\begin{tikzcd} A \arrow[r, "\eta_A"] \arrow[d, "f"] & GFA \arrow[d, "GFf"] \\ A' \arrow[r, "\eta_{a'}"] & GFA' \end{tikzcd}$$

commute.

$f \mapsto Ff$ is functorial: given $f' : A' \to A''$, then $(Ff')(Ff)$ and $F(f'f)$ are both morphisms $(FA, \eta_A) \to (FA'', \eta_{A''} f'f)$ in $(A \downarrow G)$, so they're equal.

Finally, given $f : A \to GB$, the morphism $g : FA \to B$ corresponding to it is the unique morphism $(FA, \eta_A) \to (B, f)$ in $(A \downarrow G)$.

The naturality of this bijection is given by naturality of η, and naturality in B is immediate. $\square$

Corollary 3.3. *If F, F' are both left-adjoint to G, then there's a canonical natural isomorphism $F \to F'$.*

Proof. For each A, (FA, η_A) and $(F'A, \eta'_A)$ are both initial in $(A \downarrow G)$, so there's a unique isomorphism $\alpha_A : (FA, \eta_A) \to (F'A, \eta'_A)$.

α is natural: given $f : A \to A'$, $\alpha_{A'} f$ and $(Ff)\alpha_A$ are both morphisms $(FA, \eta_A) \to (F'A', \eta'_{A'} f)$ in $(A \downarrow G)$. So they're equal. $\square$

Lemma 3.4. *Given $\mathcal{C} \underset{G}{\overset{F}{\rightleftarrows}} \mathcal{D} \underset{K}{\overset{H}{\rightleftarrows}} \mathcal{E}$, if $F \dashv G$ and $H \dashv K$ then $HF \dashv GK$.*

Proof. We have bijections

$$\mathcal{E}(HFA, C) \cong \mathcal{D}(FA, KC) \cong \mathcal{C}(A, GKC)$$

which are natural in A and C. $\square$

Corollary 3.5. *Given a commutative square* $\begin{array}{ccc} \mathcal{C} & \xrightarrow{F} & \mathcal{D} \\ \downarrow{\scriptstyle G} & & \downarrow{\scriptstyle H} \\ \mathcal{E} & \xrightarrow{K} & \mathcal{F} \end{array}$ *of categories and functors, suppose all the functors in the diagram have left adjoints. Then the diagram* $\begin{array}{ccc} \mathcal{F} & \longrightarrow & \mathcal{E} \\ \downarrow & & \downarrow \\ \mathcal{D} & \longrightarrow & \mathcal{C} \end{array}$ *of left adjoints commutes up to natural isomorphism.*

Given $F \dashv G$, we have a natural transformation $\eta : 1_\mathcal{C} \to GF$ defined as in 3.2. We call η the **unit** of the adjunction.

Dually, we have $\epsilon : FG \to 1_\mathcal{D}$, the **counit**. $\epsilon_B : FGB \to B$ corresponds to $1_{GB} : GB \to GB$.

Theorem 3.6. *Suppose we're given $F : \mathcal{C} \to \mathcal{D}$ and $G : \mathcal{D} \to \mathcal{C}$. Specifying an adjunction $F \dashv G$ is equivalent to specifying natural transformations $\eta : 1_\mathcal{C} \to GF$ and $\epsilon : FG \to 1_\mathcal{D}$ such that*

$$\begin{tikzcd} F \arrow[r, "F\eta"] \arrow[dr, "1_F"'] & FGF \arrow[d, "\epsilon_F"] \\ & F \end{tikzcd} \quad \text{and} \quad \begin{tikzcd} G \arrow[r, "\eta_G"] \arrow[dr, "1_G"'] & GFG \arrow[d, "G\epsilon"] \\ & G \end{tikzcd}$$

commute. (We say η and ϵ satisfy the ***triangular identities****).*