1 Categories

Definiton 1.1 (Category)**.** A category, $\mathcal{A}$ is defined to have each of the following,

(i) A collection of objects, denoted by ob($\mathcal{A}$) and written A,B,C $\in \mathcal{A}$.
Such that each object has an 'identity', $1_A \in \mathcal{A}(A, A), 1_B \in \mathcal{A}(B, B), 1_C \in \mathcal{A}(C, C)$

(ii) For each pair of objects, a collection of 'links'/morphisms between them, denoted by $\mathcal{A}(A, B)$ and written as f $\in \mathcal{A}(A, B)$ $g \in \mathcal{A}(B, C)$. Such that,

  (a) morphisms with matching domain,co-domain can be 'chained'/composed $(g, f) = g \circ f$

  (b) with this composition being associative, $(h \circ g) \circ f = h \circ (g \circ f)$

  (c) and they are 'fixed' by the identity $f \circ 1_A = f = 1_B \circ f$

Example 1.1. Non-trivial Identity Consider the objects to be groups, and morphisms to be direct product between them:

i ob $(\mathcal{A}) = \{G|$ G is a group$\}$

ii $\mathcal{A}(A, B) := A \times B$

iii $\mathcal{A}(B, C) \ \circ \mathcal{A}(A, B) \mapsto \mathcal{A}(A, C)$

So, there's a unique morphism between any two objects i.e groups. And the identity morphism,

$\forall A, B \in \mathcal{A}$, if f $\in \mathcal{A}(A, B)$, then $f \circ 1_A \in \mathcal{A}(A, B) \times \mathcal{A}(A, A) \mapsto \mathcal{A}(A, B)$ and $1_B \circ f \in \mathcal{A}(B, B) \times \mathcal{A}(A, B) \mapsto \mathcal{A}(A, B)$

Thus, $ob(\mathcal{A})$ along with $\circ$ is actually a group. And hence has a unique inverse. But how exactly?

Example 1.2. Set The objects are defined to be sets, and morphisms are the functions between them, with the usual composition law:

i ob $(\mathcal{A}) = \{S|$ S is a set$\}$

ii $(f : A \mapsto B) \in \mathcal{A}(A, B)$

iii $(g \in \mathcal{A}(B, C)) \circ (f \in \mathcal{A}(A, B)) \mapsto g(f) \in \mathcal{A}(A, C)$

Example 1.3. Pre-ordered Set A pre-ordered , can be made into a category via the binary operation, so that the morphism $a \mapsto b$ is defined iff $a \leq b$ where $\leq$ is the preorder. The interesting part about this category is that there's at most one morphism between any two objects.

Example 1.4. Grp Objects are groups,with homomorphisms between them being the morphisms, and composition being as usual:

i $ob(\mathcal{A}) = \{G|G$ is a group $\}$

ii $\mathcal{A}(A, B) = Hom(A, B)$ i.e. all f such that $\forall x, y \in A f((x) \cdot_A (y)) = (f(x)) \cdot_B (f(y))$

iii composition is defined as that between two group homomorphisms

In this example, the set of all morphisms along with composition forms a group.

Example 1.5. Ring Objects are rings, and arrows are ring homomorphisms between them.

i $ob(\mathcal{A}) = \{G|G$ is a ring $\}$

ii $\mathcal{A}(A, B) = Hom(A, B)$

iii composition is defined as that between two ring homomorphisms

Definiton 1.2 (Dual Category)**.** Given a category $\mathcal{A}$, it's opposite/dual, $\mathcal{A}^{op}$ is a category with the same objects, but reversed arrows, while keeping the composition :

$$ob(\mathcal{A}^{op}) = ob(\mathcal{A}) \text{ and } \forall A, B \in ob(\mathcal{A}) \ , \ \mathcal{A}^{op}(A, B) = \mathcal{A}(B, A)$$

Example 1.6. Vect$_k$ Objects are vector spaces *over field k* , and the morphisms between them are linear transformations

i $ob(\mathcal{A}) = \{A|A$ is a vector space$\}$

ii $\mathcal{A}(A, B) = \mathcal{L}(A, B)$

iii composition is defined as that of linear transformations

Definiton 1.3 (Isomorphism)**.** An isomorphism, between objects, is a morphism between them such that it's 'inverse' is also a morphism. So,

$$f : A \mapsto B \text{ is an isomorphism } \iff \exists g \in \mathcal{A}(B, A) : gf = 1_A \text{ and } fg = 1_B$$

Definiton 1.4 (Product Category)**.** Somewhat like a cartesian product of categories. Given categories $\mathcal{A}$ and $\mathcal{B}$, $\mathcal{A} \times \mathcal{B}$ is defined as:

i $ob(\mathcal{A} \times \mathcal{B}) := ob(\mathcal{A}) \times ob(\mathcal{B})$

ii $(\mathcal{A} \times \mathcal{B})((A, B), (A', B')) := \mathcal{A}(A, A') \times \mathcal{B}(B, B')$

iii $(f, g) \in \mathcal{A} \times \mathcal{B}((A, B), (C, D))$, $(a, b) \in \mathcal{A} \times \mathcal{B}((C, D), (E, F)) \implies (a, b) \circ (f, g) := (a \circ f, b \circ g)$

iv $\forall (A, B) \in ob(\mathcal{A} \times \mathcal{B})$, $1_{(A,B)} := (1_A, 1_B)$

Example 1.7 (CAT)**.** The category of all categories with morphisms being functors.

i $ob(\mathcal{A}) = \{A|A$ is a category$\}$

ii $\mathcal{A}(A, B) = F(A, B)$

iii $F : \mathcal{A} \mapsto \mathcal{B}$, $G : \mathcal{B} \mapsto \mathcal{C} \implies G \circ F := H : \mathcal{A} \mapsto \mathcal{C}$

And thus, the identity of $\mathcal{A}$ is the functor, $1_{\mathcal{A}} : \mathcal{A} \mapsto \mathcal{A}$

2 Functors

Definiton 2.1 ((Covariant)Functor)**.** A functor is a map between categories, written $F : \mathcal{A} \mapsto \mathcal{B}$, consists :

(i) function taking objects of $\mathcal{A}$ to those of $\mathcal{B}$ i.e. $ob(\mathcal{A}) \mapsto ob(\mathcal{B})$. Written as $A \mapsto F(A)$.

(ii) associative, identity-preserving function taking links between objects of $\mathcal{A}$ to those for $\mathcal{B}$, $f \mapsto F(f)$, i.e.

$$\forall A, B \in \mathcal{A},\ \mathcal{A}(A, B) \mapsto \mathcal{B}(F(A), F(B)) \text{ such that } (a)\ f \in \mathcal{A}(A, B), g \in \mathcal{A}(B, C) \implies F(g \circ f) = F(g) \circ F(f) = F(g \circ f)$$
$$(b) A \in \mathcal{A} \implies F(1_A) = 1_{F(A)}$$

Example 2.1. Forgetful Functors They essentially ignore some of the structure of the 'domain'.

(a) $U : Grp \mapsto Set$ takes groups to their underlying set, and homomorphisms to maps between the sets.Similarly, $Ring \mapsto Set$ and $Vect_k \mapsto Set$

(b) Let Ab be the category of abelian groups, then, $U : Ring \mapsto Ab$ takes rings to their additive group, 'forgetting' the multiplicative group. And if Mon is the category of monoids, $U : Ring \mapsto Mon$ 'forgets' the additive group.

(c) $U : Ab \mapsto Grp$ just takes each abelian group to itself, and does the same for (homo)morphisms.

Example 2.2. Free Functors

(a) let $F(S)$ denote the free group on a set S. Then, $F : Set \mapsto Grp$ is a 'free' functor taking sets to their free group, and thus the maps between them become homomorphisms between their free groups. As,

$$f \in Set(S, S') \mapsto F(f) \in Grp(F(S), F(S')) \text{ i.e. } f : s \mapsto s' \text{ goes to } F(f) : F(s) := g \mapsto f(g)$$

(b) Similarly, there's a 'free' functor $F : Set \mapsto CRing$ to the category of commutative rings. Defined as taking sets to polynomial rings having each element as a commuting variable, and coefficients from $\mathbb{Z}$.

(c) To construct a free functor to$Vect_k$, take $Set \mapsto CRing \xrightarrow{\text{(a)}} Field$, the category of fields by using part (a). Thus,

Example 2.3. Let $\mathcal{G}, \mathcal{H}$ be the one object categories of monoids G,H respectively. Then, due to composition being associative and identity preserving, possible functors are precisely the homomorphisms.

Example 2.4. Let monoid G be regarded as a one-object category, $\mathcal{G}$. Then, functor $F : \mathcal{G} \mapsto Set$ has one object, a set S. And, $\forall g \in G,\ F(g) : S \mapsto S$ is defined as $(F(g))(s) = g * s$ where * is an associative identity-preserving function.Thus, $(g, s) \mapsto g.s$ i.e. S is a left G-set.

Definiton 2.2 (Contravariant Functor)**.** For categories $\mathcal{A}$ and $\mathcal{B}$, $\mathcal{A}^{op} \mapsto \mathcal{B}$ is a contravariant functor from $\mathcal{A}$ to $\mathcal{B}$.

Example 2.5. Let k be a field and V, V', W be vector spaces over it. Then fixing W,

$$\forall f \in Hom(V, V`), \exists f^* : Hom(V', W) \mapsto Hom(V, W) \text{ as } g \in Hom(V', W) \implies V \xrightarrow{f} V' \xrightarrow{g} W$$

recheck the following argument So, for each $V \in ob(Vect_k)$, $Hom(V, W)$ defines a contravariant functor (by putting $V' =$) from $Vect_k^{op}$ to $Vect_k$

3 Natural Isomorphisms

Example 3.1.

To be continued.