

# Category theory in context

Siddharth Bhat

Monsoon, second year of the plague

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# CATEGORIES, FUNCTORS, NATURAL TRANSFORMATIONS

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## 1.1 ABSTRACT AND CONCRETE CATEGORIES

## 1.2 DUALITY

### 1.2.1 *Musing*

How does one remember mono is  $gk = gl \implies k = l$  and vice versa?

### 1.2.2 *Solutions*

**Question: Lemma 1.2.3.**  $f : x \rightarrow y$  is an isomorphism iff it defines a bijection  $f_* : C(c, x) \rightarrow C(c, y)$ .

**Proof** [ $f$  is iso  $\implies$  post composition with  $f$  induces bijection] Let  $f : x \rightarrow y$  be an isomorphism. Thus we have an inverse arrow  $g : y \rightarrow x$  such that  $fg = id_y, gf = id_x$ . The map:

$$C(c, x) \xrightarrow{f_*} C(c, y) : (\alpha : c \rightarrow x) \mapsto (f\alpha : c \rightarrow y)$$

has a two sided inverse:

$$C(c, y) \xrightarrow{g_*} C(c, x) : (\beta : c \rightarrow y) \mapsto (g\beta : c \rightarrow x)$$

which can be checked as  $g_*(f_*(\alpha)) = g_*(f\alpha) = gf\alpha = id_x\alpha = \alpha$ , and similarly for  $f_*(g_*(\beta))$ . Hence we are done, as the iso induces a bijection of hom-sets.  $\square$

**Proof** [(post-composition with  $f$  is bijection implies  $f$  is iso)] We are given that the post composition by  $f, f_* : C(c, x) \rightarrow C(c, y)$  is a bijection. We need to show that  $f$  is an isomorphism, which means that there exists a function  $g$  such that  $fg = id_y$  and  $gf = id_x$ . Since post-composition is a bijection for all  $c$ , pick  $c = y$ . This tells us that the post-composition  $f_* : C(y, x) \rightarrow C(y, y)$  is a bijection. Since  $id_y \in C(y, y)$ ,  $id_y$  an inverse image  $g \equiv f_*^{-1}(id_y)$ . [We choose to call this map  $g$ ]. By definition of  $f_*^{-1}$ , we have that  $f_*(f_*^{-1}(id_y)) = id_y$ , which means that  $fg = id_y$ . We also need to show that  $gf = id_x$ . To show this, consider  $f_*(gf) = fgf = (fg)f = (1_y)f = f$ . We also have that  $f_*(id_x) = fid_x = f$ . Since  $f_*$  is a bijection, we have that  $id_x = gf$  and we are done.  $\square$

$$\begin{array}{ccc}
 C(y, x) & \xrightarrow{f_*} & C(y, y) \\
 \downarrow \psi & & \downarrow \text{id}_y \\
 g = f_*^{-1}(id_y) & \xleftarrow{f_*^{-1}} & id_y \\
 & \uparrow f_* & \\
 & f_* & \\
 & \text{is bijective.} &
 \end{array}$$

by defn:

$$\textcircled{a} \quad f_* (f_*^{-1}(id_y)) = id_y \Rightarrow f_* g = id_y$$

$$\textcircled{b} \quad f_* (g b) = f_* g b = (f_* g) b = id_y b = b = f_* id_x = f_* (id_x)$$

$$f_* (g b) = f_* (id_x) \Rightarrow g b = id_x$$

$f_*$  is injective

Iso is bijection of hom-sets

**Question: Q 1.2.ii.** Show that  $f : x \rightarrow y$  is split epi iff for all  $c \in C$ , post composition  $f \circ - : C(c, x) \rightarrow C(c, y)$  is a surjection.

**Proof** [(split epi implies post composition is surjective)] Let  $f : e \rightarrow b$  be split epi, and thus possess a section  $s : b \rightarrow e$  such that  $fs = id_b$ . We wish to show that post composition  $C(c, e) \xrightarrow{f_*} C(c, b)$  is surjective. So pick any  $g \in C(c, b)$ . Define  $sg \in C(c, e)$ . See:

$$f_*(sg) = fsg = (fs)g = id_b g = g$$

. Hence, for all  $g \in C(c, b)$  there exists a pre-image under  $f_*$ ,  $sg \in C(c, e)$ . Thus,  $f_*$  is surjective since every element of codomain has a pre-image.  $\square$

**Proof** [(post composition is surjective implies split epi)] Let  $f : e \rightarrow b$  be a morphism such that for all  $c \in C$ , we have  $C(c, e) \xrightarrow{f_*} C(c, b)$  is surjective. We need to show that there exists a morphism  $s : b \rightarrow e$  such that  $fs = id_b$ . Set  $c = b$ . This gives us a surjection  $C(b, e) \xrightarrow{f_*} C(b, b)$ . Pick an inverse image of  $id_b \in C(b, b)$ . That is, pick any function  $s \in f_*^{-1}(id_b)$ . By definition, of  $s$  being in the fiber of  $id_b$ , we have that  $f_*(s) = fs = id_b$ . Thus means that we have found a function  $s$  such that  $fs = id_b$ . Thus we are done.  $\square$

**Question: Q 1.2.iii.** Mono is closed under composition, and if  $gf$  is monic then so is  $f$ .

**Proof** [(Mono is closed under composition)] Let  $f : x \rightarrow y, g : y \rightarrow z$  be monomorphisms (Recall that  $f$  is a monomorphism iff for any  $\alpha, \beta$ , if  $f\alpha = f\beta$  then  $\alpha = \beta$ ). We are to show that  $gf : x \rightarrow z$  is monic. Consider this diagram which shows that  $gfk = gfl$  for arbitrary  $k, l : a \rightarrow x$ . We wish to show that  $k = l$ .

$$\begin{array}{ccccc}
 a & \xrightarrow{k} & x & \xrightarrow{f} & y & \xrightarrow{g} & z \\
 a & \xrightarrow{l} & x & \xrightarrow{f} & y & \xrightarrow{g} & z
 \end{array}$$

Since  $g$  is mono, we can cancel it from  $gfk = gfl$ , giving us  $fk = fl$ . Since  $f$  is mono, we can once again cancel it, giving us  $k = l$  as desired. Hence, we are done.  $\square$ .

**Proof** [(If  $gf$  is monic then so is  $f$ )] Let us assume that  $fk = fl$  for arbitrary  $l$ . We wish to show that  $k = l$ . We show this by applying  $g$ , giving us  $fk = fl \implies gfk = gfl$ . As  $gf$  is monic, we can cancel, giving us  $gfk = gfl \implies k = l$ .  $\square$ .

**Question: Q 1.2.iv.** What are monomorphisms in category of fields?

**Proof** Claim: All morphisms are monomorphisms in the category of fields. Let  $f : K \rightarrow L$  be an arbitrary field morphism. Consider the kernel of  $f$ . It can either be  $\{0\}$  or  $K$ , since those are the only two ideals of  $K$ . However, the kernel can't be  $K$ , since that would send 1 to 0 which is an illegal ring map. Thus, the map  $f$  has trivial kernel, therefore is an injection, is left-cancellable, is a monomorphism.  $\square$

**Question: Q 1.2.v.** Show that the ring map  $i : \mathbb{Z} \rightarrow \mathbb{Q}$  is both monic and epic but not iso.

**Proof** [ $i$  is not iso] No ring map  $i : \mathbb{Z} \rightarrow \mathbb{Q}$  can be iso since the rings are different (eg.  $\mathbb{Q}$  is a field).  $\square$

**Proof** [ $i$  is epic] To show that it's epic, we must show that given for arbitrary  $f, g : \mathbb{Q} \rightarrow R$  that  $fi = gi$ :

$$\mathbb{Z} \xrightarrow{i} \mathbb{Q} \xrightarrow{f} R$$

$$\mathbb{Z} \xrightarrow{i} \mathbb{Q} \xrightarrow{g} R$$

implies that  $f = g$ . Let  $fi : \mathbb{Z} \rightarrow R = gi$ . Then, the functions  $f, g$  are uniquely determined since  $\mathbb{Q}$  is the field of fractions of  $\mathbb{Z}$ , thus a ring map  $\mathbb{Z} \rightarrow R$  extends uniquely to a ring map  $\mathbb{Q} \rightarrow R$ . Let's assume that  $f(i(z)) = g(i(z))$  for all  $z$ , and show that  $f = g$ . Consider arbitrary  $p/q \in \mathbb{Q}$  for  $p, q \in \mathbb{Z}$ . Let's evaluate:

$$f(p/q) = f(p)f(q)^{-1} = f(i(p)) \cdot f(i(q))^{-1} = g(i(p)) \cdot g(i(q))^{-1} = g(p/q)$$

which shows that  $f(p/q) = g(p/q)$  for all  $p, q$ . Thus, we can extend a ring function defined on the integers to rationals uniquely, hence  $fi = gi \implies f = g$  showing that  $i$  is epic.  $\square$

**Proof** [ $i$  is monic] given two arbitrary maps  $k, l : R \rightarrow \mathbb{Z}$ , if  $ik = il$  then we must have  $k = l$ . Given  $ik = il$ , since  $i$  is an injection of  $\mathbb{Z}$  into  $\mathbb{Q}$ , we must have  $k = l$ .

**Question: Q 1.2.vi.** Mono + split epi iff iso.

**Proof** [Iso is mono + split epi] Iso is both left and right cancellable. Hence it's mono and epi. It splits because the inverse of the iso splits it.  $\square$ .

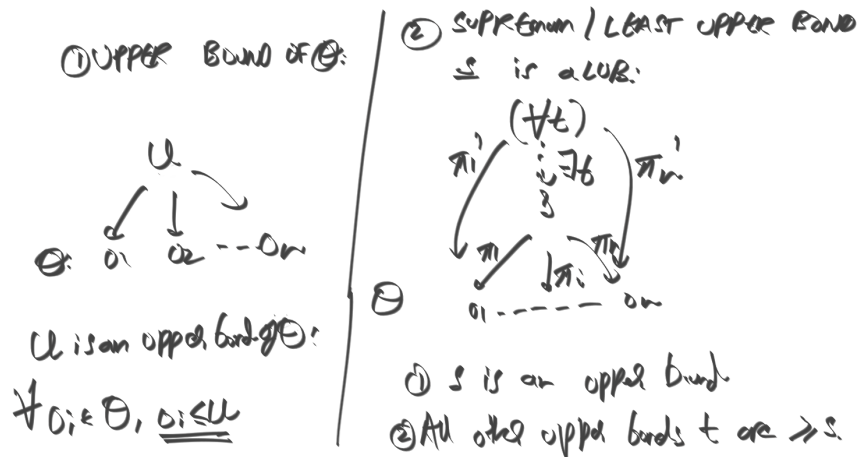
**Proof** [mono + split epi is iso] Let  $f : e \rightarrow b$  be mono (for all  $k, l : p \rightarrow e$ ,  $fk = fl \implies k = l$ ) and split epi (there exists  $s : b \rightarrow e$  such that  $fs : b \rightarrow b = id_b$ ). We need to show it's iso. That is, there exists a  $g : b \rightarrow e$  such that  $fg = id_b$  and  $gf = id_e$ . I claim that  $g \equiv s$ . We already know that  $fg = fs = id_b$  from  $f$  being split epi. We need to check that  $gf = sf = id_e$ . Consider:

$$f s f = (f s) f = id_b f = f = f id_e$$

Hence, we have that  $f(sf) = f(id_e)$ . Since  $f$  is mono, we conclude that  $sf = id_e$ . We are done since we have found a map  $s$  such that  $fs = id_b, sf = id_e$ .

**Question: 1.2.vii.** Regarding a poset a category, define the supremum of a subcollection, such that the dual gives the infimum.

**Proof** We regard an arrow  $a \rightarrow b$  as witnessing that  $a \leq b$ . First define an upper bound of a set  $O$  to be an object  $u$  such that for all  $o \in O$ , we have  $o \leq u$ . Now, the supremum of  $O$  is the least upper bound of  $O$ . That is,  $s$  is a supremum iff  $s$  is an upper bound, and for all other upper bounds  $t$  of  $O$ , we have that  $s \leq t$ . So we draw a diagram showing upper bounds and suprema:



Upper bound and supremum

### 1.3 FUNCTORS

**Question: Exercise 1.3.i.** What is a functor between groups, when regarded as one-object categories?

**Proof** It's going to be a group homomorphism. Since, a functor preserves composition, we have that a functor  $F : C \rightarrow D$  preserves the group structure; for elements of the group / isos  $f, g \in \text{Hom}(G, G)$ , we have that the functor obeys  $F(f \circ_G g) = (Ff) \circ_H (Fg)$ , which is exactly the equation we need to preserve group structure. For example, since a functor preserves isomorphisms, an element of the group  $f \in \text{Hom}(G, G)$  is mapped to an invertible element  $F(f) \in \text{Hom}(H, H)$ .  $\square$

**Question: Exercise 1.3.ii.** What is a functor between preorders, regarded as a category?

**Proof** Going to be a preorder morphism. I don't know what these are called; If we had a partial order, these would be called monotone maps. Recall that  $a \rightarrow b$  is the encoding of  $a \leq b$  within the category. Suppose we have a functors between preorders (encoded as categories)  $F : C \rightarrow D$ . Since  $F$  preserves identity arrows, and  $a \leq a$  is encoded as  $\text{id}_a$ , we have that  $F(a) \leq F(a)$  as:

$$F(a \leq a) = F(\text{id}_a) = \text{id}_{F(a)} = F(a) \leq F(a)$$

Similarly, since functors take arrows to arrows, the fact that  $a \leq b$  which is witnessed by an arrow  $a \xrightarrow{f} b$  translates to an arrow  $F(a) \xrightarrow{Ff} F(b)$ , which stands for the relation  $F(a) \leq F(b)$ . Thus, the map indeed preserves the preorder structure. Preservation of composition of arrows preserves transitivity of the order relation.  $\square$

**Question: Exercise 1.3.iii.** Objects and morphisms in the image of a functor  $F : C \rightarrow D$  do not necessarily define a subcategory of  $D$ .

**Proof** Recall that a morphism can *smoosh* objects, thereby creating coalescing the domains and codomains of arrows that used to be disjoint. Concretely, consider the diagram:

$$a \xrightarrow{f} b$$

$$c \xrightarrow{g} d$$

Where we have a category of four objects  $a, b, c, d$  with two disconnected arrow  $f : a \rightarrow b$ , and  $g : c \rightarrow d$ . This is the domain of the functor we will build. The codomain is a three object category:

$$\begin{array}{ccc} x & \xrightarrow{k} & y \\ l \circ k \downarrow & \swarrow l & \\ z & & \end{array}$$

The functor will smoosh the four objects into three with a functor, which sends  $a$  to  $x$ , both  $b, c$  to  $y$ , and  $d$  to  $z$ . Now the image of the functor only has the arrows  $k, l$ , but not the composite  $l \circ k$ , which makes the image NOT a subcategory.

$$\begin{array}{ccc} x : a & \xrightarrow{k:f} & y : b, c \\ l \circ k : \downarrow & \swarrow l:g & \\ z : d & & \end{array}$$

**Question: Exercise 1.3.iv.** Verify that the Hom-set construction is functorial.

**Question: Exercise 1.3.v.** What is the difference between a functor  $F : C^{\text{op}} \rightarrow D$  and a functor  $F : C \rightarrow D^{\text{op}}$ ?

**Proof** There is no difference. The functor  $C^{\text{op}} \rightarrow D$  looks like:

$$\begin{array}{ccc} a & & b \longrightarrow Fa \\ f \downarrow & \Downarrow f_{op} & \downarrow Ff_{op} \\ b & & a \longrightarrow Fb \end{array}$$

while the functor  $G : D \rightarrow C^{\text{op}}$  looks like:

$$\begin{array}{ccc} p \longrightarrow Gp & & Gp \\ \downarrow f & Gf \Downarrow & \uparrow Gf \\ q \longrightarrow Gq & & Gq \end{array}$$

Given a functor  $F : C^{op} \rightarrow D$ , we can build an associated functor  $G_F : C \rightarrow D^{op}$ . Consider an arrow  $x \rightarrow fy \in C$ . Dualize it, giving us an arrow  $y_{op} \xrightarrow{f_{op}} x_{op} \in C^{op}$ . Find its image under  $F$ , which gives us an arrow  $F(y_{op}) \xrightarrow{F(f_{op})} F(x_{op}) \in D$ . Dualize this in  $D$ , giving us  $F(x_{op})_{op} \xrightarrow{F(f_{op})_{op}} F(y_{op})_{op} \in D^{op}$ . See that the arrow direction coincides with the domain arrow direction  $x \rightarrow fy \in C$ . So we can build a functor  $H$  which sends the arrow  $x \rightarrow fy \in C$  to the arrow  $F(x_{op})_{op} \xrightarrow{F(f_{op})_{op}} F(y_{op})_{op} \in D^{op}$ . Hence,  $H : C \rightarrow D^{op}$ , defined by  $H(x) \equiv F(x_{op})_{op}$  and  $H(f) \equiv F(f_{op})_{op}$ . By duality, we get the other direction where we start from  $F' : C \rightarrow D^{op}$  and end at  $H' : C^{op} \rightarrow D$ . Thus, the two are equivalent.

In a nutshell, the diagram is:

$$\begin{array}{ccccc}
 a & b \longrightarrow Fb & \Longrightarrow & a \longrightarrow Fa & Fb \\
 f \downarrow & \downarrow f_{op} & & \downarrow f & \downarrow (Ff)_{op} \\
 b & a \longrightarrow Fa & \Longrightarrow & b \longrightarrow Fb & Fa
 \end{array}$$

**Question: Exercise 1.3.vi.** Given the comma category  $F \downarrow G$ , define the domain and codomain projection functors  $dom : F \downarrow G \rightarrow F$  and  $codom : F \downarrow G \rightarrow G$ .

Recall that an object in the comma category is a triple  $(d \in D, e \in E, F(d) \xrightarrow{f} F(e))$ , or diagrammatically:

$$\begin{array}{ccc}
 d \in D & & e \in E \\
 F \downarrow & & \downarrow G \\
 Fd \in C & \xrightarrow{f} & Ge \in C
 \end{array}$$

and a morphism in such a category is a diagram:

$$\begin{array}{ccc}
 (d, e, f) & & Fd \xrightarrow{f} Ge \\
 \downarrow (\alpha \downarrow \beta) & & \downarrow \alpha \quad \downarrow \beta \\
 (d', e', f') & & Fd' \xrightarrow{f'} Ge'
 \end{array}$$

We construct the domain functor  $dom$  as a functor that sends an object  $(d \in D, e \in E, F(d) \xrightarrow{f} F(e))$  to an object  $d \in D$ . It sends the morphism between  $(d, e, f)$  and  $(d', e', f')$ , given by  $(\alpha : Fd \rightarrow Fd', \beta : Ge \rightarrow Ge')$  to the arrow  $Fd \xrightarrow{\alpha} Fd' \in D$ .

In a diagram, this looks like:

$$\begin{array}{ccc}
 (d, e, f) & Fd \xrightarrow{f} Ge & Fd \\
 \downarrow (\alpha \downarrow \beta) & \downarrow \alpha \quad \downarrow \beta & \downarrow \alpha \\
 (d', e', f') & Fd' \xrightarrow{f'} Ge' & Fd'
 \end{array} \xrightarrow{dom}$$



*codom* will do the same thing, by stripping out the codomain of the comma instead of the domain.  $\square$

**Question: Exercise 1.3.vii.** Define slice category as special case of the comma category.

**Proof** To define the slice  $C/c$  whose objects are of the form  $d \rightarrow c$  for varying  $d \in C$ , we pick the category  $D = C, E = C$ , and functors  $F : C \rightarrow C = id$ ,  $G : C \rightarrow C = \delta_c$ , that is, the constant functor which smooshes the entire  $C$  category into the object  $c \in C$  by mapping all objects to  $c$  and all arrows to  $id_c$ .

This causes the diagram to collapse down to objects of the form  $d \rightarrow c$ , and the arrows to be what we'd expect  $\square$ .

**Question: Exercise 1.3.viii.** Show that functors need not reflect isomorphisms. for a functor  $F : C \rightarrow D$ , and a morphisms  $f \in C$  such that  $Ff$  is an isomorphism in  $D$  but  $f$  is not an isomorphism in  $C$ .

Pick a category  $C$  and an object  $o \in C$ . Build the constant functor  $\delta_o : C \rightarrow C$ . The image of every arrow  $c \xrightarrow{a} c'$  is the identity arrow  $id_o$  which is an iso. The arrow  $a$  need not be iso. The functor  $\delta_o$  does not reflect isos.  $\square$

**Question: Exercise 1.3.ix.** Consider the not-yet-functors  $Grp \rightarrow Grp$  that sends a group to its center, comutator subgroup, and automorphism group. Are these functors if we limit the category  $Grp$  to have (a) only isomorphisms? (b) only epimorphisms? (c) all homomorphisms?

**Proof [(isos)]** If we have (a) only isomorphisms, then these are indeed functors, since an isomorphism  $G \simeq H$  implies that their group theoretic properties are identical. Thus, we will have  $Z(G) \simeq Z(H)$ , ie, isomorphic centers. Thus, an iso arrow  $f : G \rightarrow H$  becomes an iso arrow  $Z(f) : Z(G) \rightarrow Z(H)$ . The exact same happens for commutator and automorphism.  $\square$

**Proof [(epis)]** If we only have epimorphisms, we first invoke given footnote 29, that all epis in Group are surjections. Thus, given an epi (surjection)  $\phi : G \rightarrow H$ , we identify  $im(\phi) \simeq G/ker(\phi)$  or  $H \simeq G/ker(\phi)$ , since  $H \simeq im(\phi)$  by  $\phi$  being a surjection. So we can choose to study only quotient maps  $\phi : G \rightarrow G/ker\phi$ .

For the center, consider the determinant map  $|\cdot| : GL(2, \mathbb{R}) \rightarrow \mathbb{R}^\times$ . This map is surjective since we can pick the matrix  $\begin{bmatrix} 1 & 0 \\ 0 & r \end{bmatrix}$  to get all possible determinants for arbitrary  $r \in \mathbb{R}$ . The center of the group of matrices is scalar multiples of the identity, thus  $Z(GL(2, \mathbb{R})) = \{kI : k \in \mathbb{R}\}$ . The center of the reals  $Z(\mathbb{R}^\times)$  is the reals themselves since it's an abelian group. Now see that the determinant of a matrix  $kI$  must be  $k^2$ , since we get two copies of  $k$  along the diagonal. Thus, the image  $\phi(Z(GL(2, \mathbb{R}))) = \{k^2 : k \in \mathbb{R}\} = \mathbb{R}_{\geq 0}$  which is smaller than the center of the image,  $Z(\phi(GL(2, \mathbb{R}))) = Z(\mathbb{R}^\times) = \mathbb{R}^\times$ . Thus, **the center not functorial on epis.**

## 1.4 NATURAL TRANSFORMATIONS

1.4.1 *Musing**Torsion decomposition*

Let  $TA$  be the subgroup of  $A$  that have finite order.

- The idea is to first show that any natural transformation of the identity functor  $\eta : 1 \Rightarrow 1$  is multiplication by some  $n \in \mathbb{Z}$  (recall that every abelian group is a  $\mathbb{Z}$ -module, so this is a sensible thing to say).
- Let's study the component of  $\eta$  at  $\mathbb{Z}$ . This means that we have an arrow at  $1(\mathbb{Z}) \xrightarrow{\eta(id)} 1(\mathbb{Z})$ , which is  $\mathbb{Z} \rightarrow \eta(id)\mathbb{Z}$  since identity functor leaves objects and arrow invariant. Any arrow  $\mathbb{Z} \xrightarrow{\eta(id)} \mathbb{Z}$  is a multiplication by some natural number.
- Now consider a homomorphism  $f : \mathbb{Z} \rightarrow A$ . This is determined entirely by  $f(1) \in A$ , so any such map is the same as picking an element  $a \in A$ .
- Let's now consider the isomorphism  $A \twoheadrightarrow A/TA \hookrightarrow TA \oplus (A/TA) \simeq A$ . If this isomorphism were natural, then we would have a natural endomorphism of the identity functor  $\alpha : 1 \rightarrow 1$ .
- Let's observe  $\alpha$  at  $\mathbb{Z}$ . We already know that such a transformation is given by  $\mathbb{Z} \xrightarrow{\alpha} \mathbb{Z}$ , which is multiplication by a number  $n \neq 0$  (can't be zero since we need an isomorphism).
- Now consider  $C \equiv \mathbb{Z}/2n\mathbb{Z}$  where  $n$  is the  $\alpha$  scale factor. See that  $T(\mathbb{Z}/2n\mathbb{Z}) = \mathbb{Z}/2n\mathbb{Z}$ . So we get the factoring as  $\mathbb{Z}/2n\mathbb{Z} \twoheadrightarrow 0 \hookrightarrow \mathbb{Z}/2n\mathbb{Z} \oplus 0 \simeq \mathbb{Z}/2n\mathbb{Z}$ . Since we factor through zero, the full map is the zero map. However, we know from the natural transformation that the natural transformation must scale all elements by  $n \neq 0$ . So we break naturality

The big thing I don't understand in this is why we need to factor *through* the epi. If I directly define  $A \rightarrow (A/TA) \oplus TA$ , given by the exact sequence  $0 \hookrightarrow TA \hookrightarrow A \twoheadrightarrow A/TA \rightarrow 0$ ? Ah I see, this sequence need not always split.

*Walking arrow for unnatural isomorphism*

Consider the category  $I \equiv (0 \rightarrow 1)$ . Consider functors  $F : I \rightarrow \text{Vec}(\mathbb{R})$ . The functor picks out morphisms between real vector spaces. If we consider endomorphisms, I could consider a functor  $F_{id}$  that picked out the identity map from  $\mathbb{R}$  to  $\mathbb{R}$ , and another  $F_0$  that picked out the constant linear function  $f(x) = 0$  from  $\mathbb{R}$  to  $\mathbb{R}$ . These have the same domain and range, but the actual action of the arrow is wildly different. So, for a natural transformation to be natural, it's not enough to have the same action on objects (clearly!)

*Permutations and total orderings for unnatural isomorphism*

Consider a subcategory of  $\text{Set}$  containing only bijections. Define the functor  $\text{Perm} : \text{Set} \rightarrow \text{Set}$  which takes a set  $S$  to its set of permutations, where a permutation is a bijection  $S \rightarrow S$ , and the functor  $\text{Ord} : \text{Set} \rightarrow \text{Set}$  which takes a set  $S$  to its total orderings, where a total ordering is a bijection  $\{1, 2, \dots, |S|\} \rightarrow S$ . We claim that there is no natural transformation between

these two functors. To see why, let us study the situation on the smallest non-trivial case, a two element set  $\{a, b\}$ .

With the chosen arrow as  $id : [a \mapsto a; b \mapsto b]$ , we get the commutative diagram for the naturality square as:

$$\begin{array}{ccc}
 [a \mapsto a; b \mapsto b][a \mapsto b; b \mapsto a] & \xrightarrow{Perm(id_A)(f)=id_A \circ f \circ id_A^{-1}=f} & [a \mapsto a; b \mapsto b][a \mapsto b; b \mapsto a] \\
 \downarrow \eta_A & & \downarrow \eta_A \\
 [1 \mapsto a; 2 \mapsto b][1 \mapsto b; 2 \mapsto a] & \xrightarrow{Ord(id_A)(f)=id_A \circ f=f} & [1 \mapsto a; 2 \mapsto b][1 \mapsto b; 2 \mapsto a] \\
 & & \downarrow \text{equal} \\
 & & [1 \mapsto a; 2 \mapsto b][1 \mapsto b; 2 \mapsto a]
 \end{array}$$

While with the chosen arrow as  $\sigma : [a \mapsto b; b \mapsto a]$  we get the non-commuting diagram for the naturality square as:

$$\begin{array}{ccc}
 [a \mapsto a; b \mapsto b][a \mapsto b; b \mapsto a] & \xrightarrow{Perm(\sigma)(f)=\sigma \circ f \circ \sigma^{-1}} & [b \mapsto b; a \mapsto a][b \mapsto a; a \mapsto b] \\
 \downarrow \eta_A & & \downarrow \eta_A \\
 [1 \mapsto a; 2 \mapsto b][1 \mapsto b; 2 \mapsto a] & \xrightarrow{Ord(\sigma)(f)=\sigma \circ f} & [2 \mapsto b; 1 \mapsto a][2 \mapsto a; 1 \mapsto b] \\
 & & \downarrow \text{not equal} \\
 & & [1 \mapsto b; 2 \mapsto a][1 \mapsto a; 2 \mapsto b]
 \end{array}$$

We see that we cannot define a single  $\eta_A$  that works in both cases.

#### Group as category v/s poset category

in poset as category, objects carry most of the structure, not many arrows. In group as category, only one object, many arrows.

#### 1.4.2 Exercises

**Question: Exercise 1.4.i.** Let  $\alpha : F \Rightarrow G$  be a natural isomorphism. Show that the inverses of the components define a natural isomorphism  $\alpha^{-1} : G \Rightarrow F$ .

We need to show that the square with ? in it commutes, given the square on top:

$$\begin{array}{ccccc}
x & & Fx & \xrightarrow{\eta(x)} & Gx \\
a \downarrow & & Fa \downarrow & & \downarrow Ga \\
y & & Fy & \xrightarrow{\eta(y)} & Gy
\end{array}$$
  

$$\begin{array}{ccccc}
Gx & \xrightarrow{\eta^{-1}(x)} & Fx \\
Ga \downarrow & & \downarrow Fa \\
& ? & \\
Gy & \xrightarrow{\eta^{-1}(y)} & Fy
\end{array}$$

From the square, we know that  $Ga \circ \eta(x) = \eta(y) \circ Fa$ . Using inverses, we derive:

$$\begin{aligned}
Ga \circ \eta(x) &= \eta(y) \circ Fa \\
Ga \circ \eta(x) \circ \eta^{-1}(x) &= \eta(y) \circ Fa \circ \eta^{-1}(x) \\
Ga \circ id_x &= \eta(y) \circ Fa \circ \eta^{-1}(x) \\
Ga &= \eta(y) \circ Fa \circ \eta^{-1}(x) \\
\eta^{-1}(y) \circ Ga &= \eta^{-1}(y) \circ \eta(y) \circ Fa \circ \eta^{-1}(x) \\
\eta^{-1}(y) \circ Ga &= id_y \circ Fa \circ \eta^{-1}(x) \\
\eta^{-1}(y) \circ Ga &= Fa \circ \eta^{-1}(x)
\end{aligned}$$

which is exactly the diagram:

$$\begin{array}{ccccc}
x & & Gx & \xrightarrow{\eta^{-1}(x)} & Fx \\
a \downarrow & & Ga \downarrow & & \downarrow Fa \\
y & & Gy & \xrightarrow{\eta^{-1}(y)} & Fy
\end{array}$$

$\eta^{-1}(y) \circ Ga = Fa \circ \eta^{-1}(x)$

**Question: Exercise 1.4.ii.** What is a natural transformation between a parallel pair of functors between groups regarded as one object categories?

**Proof** Let  $G, H$  be groups regarded as one object categories, so elements are arrows. A functor  $F : G \rightarrow H$  is a group homomorphism. Two functors  $F, F' : G \rightarrow H$  are two group homomorphisms. A natural transformation is a map  $\eta : G \rightarrow H$  which for every (the only) object  $*_G \in G$ , assigns an arrow  $\eta(*_G) : F(*_G) \xrightarrow{\eta(*_G)} G(*_G)$  which is compatible with all arrows:

$$\begin{array}{ccc}
F(*_G) \in H & \xrightarrow{\eta(*_G)} & F'(*_G) \in H \\
\downarrow F(g) & & \downarrow F'(g) \\
F(*_G) \in H & \xrightarrow{\eta(*_G)} & F'(*_G) \in H
\end{array}$$

Simplifying the diagram by substituting  $F(*) = F'(*) = *$ , and setting  $\alpha \equiv \eta(*_G) \in \text{Hom}(*_H, *_H)$ , we get:

$$\begin{array}{ccc}
*_H & \xrightarrow{\alpha \equiv \eta(*_G)} & *_H \\
F(g) \downarrow & & \downarrow F'(g) \\
*_H & \xrightarrow{\alpha \equiv \eta(*_G)} & *_H
\end{array}$$

So we are looking for an arrow (group element)  $\alpha \in H$  such that for all  $g \in G$ ,  $F'(g) \cdot \alpha = \alpha \cdot F(g)$ . On rearranging:  $\alpha^{-1} \cdot F'(g) \cdot \alpha = F(g)$ . So it gives a sort of “inner automorphism” from  $F$  to  $F'$ .  $\square$

**Question: Exercise 1.4.iii.** What is a natural transformation between a parallel pair of functors between preorders regarded as categories?

**Proof** We regard preorders as thin categories, where there is an most arrow from  $p \rightarrow p'$  if  $p \leq p'$ . A functor from  $(P, \leq)$  to  $(Q, \leq)$  is a monotone map. A pair of functors  $F, G : P \rightarrow Q$  is a pair of monotone maps. A natural transformation  $\eta : F \Rightarrow G$  makes for each  $p \in P$  the diagram commute:

$$\begin{array}{ccccc}
p & & F(p) & \xrightarrow{\eta(p)} & G(p) \\
\downarrow p < p' & & \downarrow F(p < p') & & \downarrow G(p < p') \\
p' & & F(p') & \xrightarrow{\eta(p')} & G(p')
\end{array}$$

So, for every  $p \leq p'$ , the functor  $F$  maps us to elements  $F(p) \leq F(p')$ , and  $G$  maps us to elements  $G(p) \leq G(p')$ . The natural transformation  $\eta$  asks to witness an arrow  $F(p) \xrightarrow{\eta(p)} G(p)$ , which means that we must have  $F(p) \leq G(p)$  within the category  $Q$ , and similarly for  $p'$ . Thus, it witnesses that  $G$  is always *above*  $F$ . For any element  $p \in P$ , we will always have  $F(p) \leq G(p)$ , in a way that is consistent with the monotonicity of  $F, G$ .

**Question: Exercise 1.4.iv.** Prove that distinct parallel morphisms  $f, g : c \rightrightarrows d$  define distinct natural transformations  $f_*, g_* : C(-, c) \Rightarrow C(-, d)$  by precomposition.

Recall that the natural transformation by  $f_*$  is given for a fixed  $o \xrightarrow{a} o'$  by  $\text{Hom}(o, c) \xrightarrow{f_* \equiv f \circ -} \text{Hom}(o, d)$ , and similarly for  $g_*$  by  $\text{Hom}(o, c) \xrightarrow{g_* \equiv g \circ -} \text{Hom}(o, d)$ . If we choose  $o = c$ , then we can consider  $\text{Hom}(c, c)$ . Let's then see where  $\text{id}_c \in \text{Hom}(c, c)$  gets mapped to:

$$\begin{aligned}
\text{Hom}(o, c) &\xrightarrow{f_* \equiv f \circ -} \text{Hom}(o, d) \\
\text{Hom}(o = c, c) &\xrightarrow{f_* \equiv f \circ -} \text{Hom}(o = c, d) \\
\text{Hom}(c, c) &\xrightarrow{f_* \equiv f \circ -} \text{Hom}(c, d) \\
id_c \in \text{Hom}(c, c) &\xrightarrow{f_* \equiv f \circ -} f \circ id_c \in \text{Hom}(c, d) \\
id_c \in \text{Hom}(c, c) &\xrightarrow{f_* \equiv f \circ -} f \in \text{Hom}(c, d)
\end{aligned}$$

So we map  $id \in \text{Hom}(c, c)$  into  $f \in \text{Hom}(c, d)$  by  $f_*$ . Since there was nothing special about  $f$ , we similarly map  $id \in \text{Hom}(c, c)$  into  $g \in \text{Hom}(c, d)$  by  $g_*$ . Since the two morphisms are distinct, we have  $f \neq g$ . Thus, the two distinct parallel morphisms  $f, g$  natural transformations  $f_*$  and  $g_*$  are inequivalent since they have different components on the element  $c$ :  $f_*(c) : \text{Hom}(c, c) \rightarrow \text{Hom}(c, d)$  is not the same action as  $g_*(c) : \text{Hom}(c, c) \rightarrow \text{Hom}(c, d)$ , since they act differently on  $id_c \in \text{Hom}(c, c)$ , as  $f_*(c)(id_c) = f \neq g = g_*(c)(id_c)$ .

**Question: Exercise 1.4.v.** Consider the comma category  $F \downarrow G$  for  $F : D \rightarrow C, G : E \rightarrow C$ . Construct a canonical natural transformation  $\alpha : F \circ \text{dom} \rightarrow G \circ \text{codom}$ :

$$\begin{array}{ccc}
F \downarrow G & \xrightarrow{\quad \text{codom} \quad} & E \\
\uparrow \text{dom} & \nearrow \eta & \downarrow G \\
D & \xleftarrow{\quad F \quad} & C
\end{array}$$

**Proof**

Recall that elements  $k, k' \in F \downarrow G$  and arrows  $k \xrightarrow{a} k'$  is given by:

$$\begin{array}{ccc}
k \equiv (d, e, Fd \xrightarrow{a_k} Ge) & & Fd \xrightarrow{a_k} Ge \\
\downarrow a \equiv (d \xrightarrow{a_d} d', e \xrightarrow{a_e} e') & & \begin{array}{ccc} F(a_d) \downarrow & & \downarrow G(a_e) \\ Fd' & \xrightarrow{a'_k} & Ge' \end{array} \\
k' \equiv (d', e', Fd' \xrightarrow{a'_k} Ge') & & 
\end{array}$$

We need to make this diagram commute for all  $k, k' \in F \downarrow G$

$$\begin{array}{ccc}
F \circ \text{dom}(k) & \xrightarrow{\eta(k)} & G \circ \text{codom}(k) \\
\downarrow F \circ \text{dom}(a) & & \downarrow G \circ \text{codom}(k) \\
F \circ \text{dom}(k') & \xrightarrow{\eta(k')} & G \circ \text{codom}(k')
\end{array} = \begin{array}{ccc}
d & \xrightarrow{\eta(k)} & e \\
\downarrow Fa_d & & \downarrow Ga_e \\
d' & \xrightarrow{\eta(k')} & e'
\end{array}$$

To show the equality between the left square and right square, we simplify using the definitions of  $k, k'$ :

- $k \equiv (d, e, Fd \xrightarrow{a_k} Ge), k' \equiv (d', e', Fd' \xrightarrow{a'_k} Ge')$ .
- $a : k \rightarrow k'$  is given by  $a \equiv (d \xrightarrow{a_d} d', e \xrightarrow{a_e} e')$  such that the diagram commutes.
- $\text{dom}(a) = a_d. F(\text{dom}(a)) = Fa_d.$  Similarly,  $\text{codom}(a) = a_e,$  and  $G(\text{codom}(a)) = Ga_e.$
- $\text{dom}(k) = d. F(\text{dom}(k)) = Fd. \text{codom}(k) = e. G(\text{codom}(k)) = Ge.$

By comparing the simplified naturality square to the square in the *definition of arrow in the comma category*, we find that we can pick  $\eta(k) \equiv a_k,$  and  $\eta(k') \equiv a'_k,$  the only data of  $k$  and  $k'$  we have not used so far! This causes the diagram to commute by definition of what it means to have a morphism in a comma category. To be crystal clear, we compare the two diagrams:

condition for $a$ in $C$	in $F \downarrow G$
$  \begin{array}{ccc}  Fd & \xrightarrow{\quad a_k \quad} & Ge \\  \downarrow Fa_d & & \downarrow Ga_e \\  Fd' & \xrightarrow{\quad a'_k \quad} & Ge'  \end{array}  $	$  \begin{array}{c}  k \equiv (d, e, Fd \xrightarrow{a_k} Ge) \\  \downarrow a \equiv (d \xrightarrow{a_d} d', e \xrightarrow{a_e} e') \\  k' \equiv (d', e', Fd' \xrightarrow{a'_k} Ge')  \end{array}  $
condition for $\eta$ in $C$	
$  \begin{array}{ccc}  Fd & \xrightarrow{\quad \eta(k) \quad} & Ge \\  \downarrow Fa_d & & \downarrow Ga_e \\  Fd' & \xrightarrow{\quad \eta(k') \quad} & Ge'  \end{array}  $	

**Question: Exercise 1.4.vi.** Why do extranatural transforms need a common target?

I don't understand the question. We need the same common target category to have a common space for the diagrams to live. But this feels too naive, so I'm not sure what it is I'm missing.

## 1.5 1.5: EQUIVALENCE OF CATEGORIES

### 1.5.1 Musings

**Proof: Equivalence of categories implies full, faithful, essentially surjective**

I reproduce the proof in a way that makes sense to me, since this feels like the first somewhat non-trivial theorem we have proven.

**Equivalence is faithful:** Let us have two arrows  $c \xrightarrow{p} d$  and  $c \xrightarrow{q} d$ . We wish to show that if  $Fc \xrightarrow{Fp} Fd$  equals  $Fc \xrightarrow{Fq} Fd$ , then  $p$  equals  $q$ . So  $Fp = Fq \implies p = q$ . The idea is to apply  $G$  to get  $GFp = GFq$ , at which point we can apply  $\eta : 1_C \rightarrow GF$  to convert from  $GFp, GFq$  into  $p, q$ . Witness the diagram:

$$\begin{array}{ccccc}
 & & c \xrightarrow{1p} d & & c \xrightarrow{p} d & & c \xrightarrow{p} d \\
 & & \eta_c \downarrow & & \uparrow \eta_c^{-1} & & \uparrow \text{id}_c \\
 Fc & \xrightarrow{Fp} & Fd & & GFc & & GFd \\
 = \downarrow & & & & \downarrow \eta_d & & \downarrow \eta_d^{-1} \\
 Fc & \xrightarrow{Fq} & Fd & & GFc & & GFd \\
 & & \uparrow \eta_c & & \uparrow \eta_c & & \uparrow \eta_d \\
 & & c \xrightarrow{q} d & & c \xrightarrow{q} d & & c \xrightarrow{q} d
 \end{array}$$

In text, the proof proceeds as:

- Start by  $Fc \xrightarrow{Fp} Fd = Fc \xrightarrow{Fq} Fd$
- Augment by applying  $\eta : 1 \Rightarrow FG$ ,  $\eta^{-1} : FG \Rightarrow 1$  to the left and the right, giving

$$(c \xrightarrow{p} d) \xRightarrow{\eta} (Fc \xrightarrow{Fp} Fd) = (Fc \xrightarrow{Fq} Fd) \xRightarrow{\eta^{-1}} (c \xrightarrow{q} d)$$

- Collapse along the equality, apply composition  $\eta^{-1} \circ \eta = \text{id}$  giving:

$$(c \xrightarrow{p} d) \xRightarrow{\text{id}} (c \xrightarrow{q} d)$$

- Thus, we derive  $p = q$  starting from  $Fp = Fq$ .  $\square$

**Equivalence is full:** Suppose we are given an arrow  $(Fc \xrightarrow{q} Fd)$  (Note that this **does not** give us an arrow  $(d \xrightarrow{q} d')$  — we know that the objects in question are in the image of the functor). We must show that there is a pre-image of the arrow  $q$ , so we expect an arrow  $(c \xrightarrow{p} d)$  such that  $Fp = q$ . Let's do the obvious thing, and pull back along  $G$  to get:

$$\begin{array}{ccc}
 Fc & \xrightarrow{q} & Fd \\
 \\ 
 c & \xrightarrow{?} & d \\
 \eta_c \downarrow & & \downarrow \eta_d \\
 GFc & \xrightarrow{Gq} & GFd
 \end{array}
 \qquad
 \begin{array}{ccc}
 c & \xrightarrow{p = \eta_d^{-1} \circ Gq \circ \eta_c} & d \\
 \eta_c \downarrow & & \uparrow \eta_d^{-1} \\
 GFc & \xrightarrow{GFp = Gq} & GFd
 \end{array}$$

So we define an arrow  $p \equiv \eta_d^{-1} \circ Gq \circ \eta_c$  since it seems to be the "right arrow" for our use case. By the commutativity of the diagram, we have that



$GFp = Gq$ . Since  $G$  is faithful (as proven above), we have  $Fp = q$  and so we are done, as we have established a pre-image arrow  $p$  for the given  $q$ .

**Equivalence is essentially surjective:** Let  $d \in D$ . We must find a  $c \in C$  such that  $F(c) \simeq d$ . Let's try the obvious candidate,  $G(d) \in C$ . We get  $F(G(d))$ , which we must show is isomorphic to  $d$ . Recall that we have a natural isomorphism  $\epsilon : FG \Rightarrow 1_D$ . We invoke  $\epsilon_d$  to get the isomorphism  $FGd \xrightarrow{\epsilon_d} d$ . It is invertible since the isomorphism  $\epsilon$  is invertible, with inverse arrow  $d \xrightarrow{\epsilon_d^{-1}} FGd$  such that they are inverses of each other.

### 1.5.2 Exercises 1.5

#### Question: Exercise 1.5.i.

First, let's recall the category  $\mathbf{2}$ :

$$0 \xrightarrow{(0 \rightarrow 1)} 1$$

Now when we take the product of some category  $C$  with  $\mathbf{2}$ , get as objects  $\cup_{c \in C} \{(c, 0), (c, 1)\}$  and as arrows we get three types:

- Cross arrows from  $(-, 0)$  to  $(-, 1)$ :  $\{(c, 0) \xrightarrow{(a, 0 \rightarrow 1)} (d, 1) : c, d \in C; a \in \text{Hom}(c, d)\}$
- Arrows within the component  $(-, 0)$ :  $\{(c, 0) \xrightarrow{(a, \text{id}_0)} (d, 0) : c, d \in C; a \in \text{Hom}(c, d)\}$
- Arrows within the component  $(-, 1)$ :  $\{(c, 1) \xrightarrow{(a, \text{id}_1)} (d, 1) : c, d \in C; a \in \text{Hom}(c, d)\}$

If we now have a functor  $H : C \times \mathbf{2} \rightarrow D$ , we can recover the functors  $F, G$  by considering the commutative square:

$$\begin{array}{ccc} H(c, 0) & \xrightarrow{H(f, \text{id}_0)} & H(d, 0) \\ \downarrow H(\text{id}_c, 0 \rightarrow 1) & & \downarrow H(\text{id}_d, 0 \rightarrow 1) \\ H(c, 1) & \xrightarrow{H(f, \text{id}_1)} & H(d, 1) \end{array}$$

Where the top row is  $F$ , bottom row is  $G$ , and top-to-bottom morphism is the natural transformation  $\eta$ :

$$\begin{array}{ccc} Fc \simeq H(c, 0) & \xrightarrow{Ff \simeq H(f, \text{id}_0)} & H(d, 0) \simeq Fd \\ \downarrow \eta_c \simeq H(\text{id}_c, 0 \rightarrow 1) & & \downarrow H(\text{id}_d, 0 \rightarrow 1) \simeq \eta_d \\ Gc \simeq H(c, 1) & \xrightarrow{Gf \simeq H(f, \text{id}_1)} & H(d, 1) \simeq Gd \end{array}$$

I haven't drawn one arrow, that of  $H(f, 0 \rightarrow 1)$ . The diagram we have above only tells us that the arrows have the right shape. It does not tell us that the diagram actually *commutes*. We need to prove that  $Gf \circ \eta_c = \eta_d \circ Ff$ .

The crux is to show that both of these are equal to  $H(f, 0 \rightarrow 1)$  by functoriality of  $H$ :

$$\begin{array}{ccc}
 Fc \simeq H(c, 0) & \xrightarrow{Ff \simeq H(f, id_0)} & H(d, 0) \simeq Fd \\
 \eta_c \simeq H(id_c, 0 \rightarrow 1) \downarrow & \searrow H(f, 0 \rightarrow 1) & \downarrow H(id_d, 0 \rightarrow 1) \simeq \eta_d \\
 Gc \simeq H(c, 1) & \xrightarrow{Gf \simeq H(f, id_1)} & H(d, 1) \simeq Gd
 \end{array}$$

Since in the original category we have  $f \circ id_c = f$  and  $id_1 \circ (0 \rightarrow 1) = id_1$ , we combine these equations to get  $(f, id_1) \circ (id_c, 0 \rightarrow 1) = (f, 0 \rightarrow 1)$ . Similarly, we show that  $(id_d, 0 \rightarrow 1) \circ (f, id_0) = (f, 0 \rightarrow 1)$ . Thus, the diagram does indeed commute, and what we have is a natural transformation.

**Question: Exercise 1.5.ii.** Define a category  $\Gamma$  whose objects are finite sets, and whose morphisms from  $S$  to  $T$  are maps  $\theta : S \rightarrow 2^T$  where  $\theta(\alpha)$  and  $\theta(\beta)$  are disjoint when  $\alpha \neq \beta$ . The composite map is given by  $\psi(\alpha) = \cup_{\beta \in \theta(\alpha)} \phi(\beta)$  [set/list monad]. Prove that  $\Gamma$  is equivalent to the opposite of the category  $Fin_*$  of finite pointed sets.

- I can see why it is the opposite of finite sets.
- The arrow  $\theta : S \rightarrow 2^T$  records the data of fibers of maps  $T \rightarrow S$ .
- Define  $f_\theta : (T, t_*) \rightarrow (S, s_*)$  given by  $f(t) = s$  when  $t \in \theta(s)$ . We are guaranteed such an  $s$  is unique since all sets  $\theta(s)$  is disjoint.
- At this stage, we also see why we need pointed sets. If there is no  $s$  such that  $t \in \theta(s)$ , then define  $f(t) = s_*$ , the basepoint of  $S$ . This is the “basepoint encoding” of partial functions.
- The above shows that the functor is full and faithful (each arrow in  $Fin_*$  has a corresponding unique arrow in  $\Gamma$ ), and surjective (not just essentially surjective), and thus the functor is an equivalence of categories.

**Question: Exercise 1.5.iii.**

Recall that the data of the isomorphism of objects  $a \simeq a'$  is given by morphisms  $\alpha : a \rightarrow a'$  and  $\alpha^{-1} : a' \rightarrow a$  such that  $\alpha^{-1} \circ \alpha : a \rightarrow a \simeq id_a$  and  $\alpha \circ \alpha^{-1} : a' \rightarrow a' \simeq id_{a'}$ . Similarly, posit a  $\beta$  to witness  $b \simeq b'$ . Now the square on the left gives us the equation  $\beta \circ f \circ \alpha^{-1} = f'$ . We compose with  $\beta^{-1}, \alpha$  to get the other squares:

$$\begin{array}{ccc}
 \alpha \circ \alpha^{-1} = id & a \xrightleftharpoons[\alpha^{-1}]{\alpha} a' & \begin{array}{ccc} a & \xleftarrow{\alpha^{-1}} & a' \\ \downarrow f & \beta \circ f \circ \alpha^{-1} = f' & \downarrow f' \\ f & \xrightarrow{\beta} & f' \end{array} \\
 \beta \circ \beta^{-1} = id & b \xrightleftharpoons[\beta^{-1}]{\beta} b' &
 \end{array}$$

- $\beta \circ f \circ \alpha^{-1} = f'$  implies  $f \circ \alpha^{-1} = \beta^{-1} \circ f'$ .
- $\beta \circ f \circ \alpha^{-1} = f'$  implies  $\beta \circ f = f' \circ \alpha$ .
- $\beta \circ f \circ \alpha^{-1} = f'$  implies  $f = \beta^{-1} \circ f' \circ \alpha$ .

**Question: 1.5.iv: Full faithful functor reflects and creates isos.**

**Proof (a) reflects isos**

- Let  $F : C \rightarrow D$  be a full and faithful functor. Let  $f : x \rightarrow y$  be an arrow in  $C$ . Let  $Ff : Fx \rightarrow Fy$  be an isomorphism. We must show that  $f$  is an isomorphism.
- Since  $Ff$  is an iso, let it have an inverse, say  $h$  such that  $(Ff) \circ h = id_{Fy}$  and  $h \circ (Ff) = id_{Fx}$ .
- Since  $F$  is full and faithful, there is a unique  $g$  such that  $Fg = h$ .
- This makes the iso condition  $Ff \circ Fg = id_{Fy}$ . By using functoriality (a)  $Ff \circ Fg = F(f \circ g)$  and (b)  $id_{Fy} = F(id_y)$ , we get  $F(f \circ g) = F(id_y)$ .
- Since  $F$  is faithful,  $F(f \circ g) = F(id_y) \implies f \circ g = id_y$ .
- Repeat proof for other sided inverse. We are done.

**Proof (b) creates isos**

- Let  $x, y \in C$  such that  $Fx \simeq Fy$ . Then we must show that  $x \simeq y$ .
- $Fx \simeq Fy$  means that we have an isomorphism arrow  $g : Fx \rightarrow Fy$  which has inverse  $g^{-1} : Fy \rightarrow Fx$ .
- Since the functor is full and faithful, there exists unique  $f_1 : x \rightarrow y, f_2 : y \rightarrow x$  such that  $Ff_1 = g$  and  $Ff_2 = g^{-1}$ .
- Repeat the previous proof to see that  $f_1, f_2$  witness an iso between  $x$  and  $y$ .

**Question: 1.5.v A faithful functor need not reflect isos.**

- High level idea: take a faithful functor  $F : C \rightarrow D$  adjoin arrows into  $D$  to make arrows in  $D$  isos, see that this does not reflect.
- consider a category  $C \equiv (a \xrightarrow{p} b)$ . Map into a category  $D$  with arrows  $x \xrightarrow{s} y$  and  $y \xrightarrow{s^{-1}} x$  where  $s, s^{-1}$  are inverses of each other.
- The functor  $F : C \equiv (a \xrightarrow{p} b) \rightarrow (x \xrightarrow{s} y)$  is faithful but does not reflect isos.

**Question: 1.5.vi (i) Composition of full is full.**

- Let  $F : C \rightarrow D, G : D \rightarrow E$  be full. We must show that  $G \circ F$  is full.
- Pick some element  $\alpha \in Hom(GFx, GFy)$ . Since  $G$  is full, there is an arrow  $\beta \in Hom(Fx, Fy)$  such that  $G\beta = \alpha$ .

- Since  $g$  is full, there is an arrow  $\gamma \in \text{Hom}(x, y)$  such that  $F\gamma = \beta$ .
- Combining, we see that  $F\gamma = \beta$  and  $G\beta = \alpha$ , or  $GF\gamma = \alpha$ .
- Thus  $GF$  is full since for any  $GFx \xrightarrow{\alpha} GFy$  we found a  $x \xrightarrow{\gamma} y$  such that  $GF\gamma = \alpha$ .

**Question: 1.5.vi (i) Composition of faithful is faithful.**

- Let  $F : C \rightarrow D, G : D \rightarrow E$  be faithful. We must show that  $G \circ F$  is faithful.
- Pick some element  $\alpha, \alpha' \in \text{Hom}(x, y)$  such that  $GF\alpha = GF\alpha'$ . We must show that  $\alpha = \alpha'$ .
- Since  $G$  is faithful, we get that  $F\alpha = F\alpha'$ . Since  $F$  is faithful, we get that  $\alpha = \alpha'$ .
- Thus  $GF$  is faithful.

**Question: 1.5.vi (i) Composition of eso is eso.**

- Let  $F : C \rightarrow D, G : D \rightarrow E$  be eso. We must show that  $GF$  is eso.
- Consider some element  $e \in E$ . We must show that there is some  $c \in C$  such that  $e \simeq GFc$ .
- Since  $G$  is eso, there must be some  $d \in D$  such that  $Gd \simeq e$ .
- Since  $F$  is eso, there must be some  $c \in C$  such that  $Fc \simeq d$ .
- Recall that since a functor preserves isos, we must have  $GFc \simeq Gd$  from  $Fc \simeq d$ .
- Combining  $GFc \simeq Gd$  with  $Gd \simeq e$  we get  $GFc \simeq e$ . Thus, we have found the  $c \in C$  such that  $GFc \simeq e$ .
- Thus,  $GF$  reflects isos. (Key lemma: image of iso is iso)  $\square$

**Question: 1.5.vii Construct inverse of inclusion of automorphism of some object of groupoid into groupoid.**

- TODO

**Question: 1.5.viii.**

**Question: 1.5.ix: Category equivalent to locally small is locally small.**

- Let  $F : C \rightleftarrows D : G$  be an equivalence of categories. Let  $D$  be locally small. We must show that  $C$  is locally small.
- Recall that we must have  $G : D \rightarrow C$  to be full, faithful, and essentially surjective as it witnesses an equivalence of categories. As  $D$  is locally small, all hom-sets  $\text{Hom}_D(X, Y)$  are small.
- Since  $G : D \rightarrow C$  is full, the image  $\text{Hom}_C(Gx, Gy)$  is surjective, and thus  $\text{Hom}_C(Gx, Gy)$  can have cardinality at most that of  $\text{Hom}_D(x, y)$  which is already small. Thus  $\text{Hom}_C(Gx, Gy)$  is also locally small. This settles the question for all Hom-sets in the image of  $G$ .

- Consider elements  $c, d \in C$  which are not in the image of  $G : D \rightarrow C$ . Since the functor  $G$  is essentially surjective, we must have elements  $Gx, Gy$  such that  $c \simeq Gx$  and  $d \simeq Gy$ . In particular, this implies that  $\text{Hom}_D(c, d) = \text{Hom}_D(Gx, Gy)$ . This reduces this case to the previous case, showing that these Hom-sets too are locally small.

**Question: 1.5.x: Categories equivalent to discrete categories.**

- TODO

1.6 1.6: THE ART OF THE DIAGRAM CHASE

1.6.1 *Musings*

1.6.2 *Exercises 1.6*

**1.6.i any map from terminal to initial is iso**

- Let  $f : t \rightarrow i$  be map from terminal to initial. We must show that  $f$  is iso.
- Consider the unique map  $g : i \rightarrow t$ . This map is unique both because it is (a) *from* the initial object and (b) *to* the terminal object.
- Consider  $f \circ g : i \rightarrow i$ . This is an arrow *from* the initial object, thus is unique. But there is already another arrow  $\text{id}_i : i \rightarrow i$ . This implies  $f \circ g = \text{id}_i$  by uniqueness.
- Consider  $g \circ f : t \rightarrow t$ . This an arrow *to* the terminal object, thus is unique. But there is already another arrow  $\text{id}_t : t \rightarrow t$ . From uniqueness, we get  $g \circ f = \text{id}_t$ .
- This implies  $f$  is iso, and furthermore  $f : t \rightarrow i$  is unique, since another such  $f'$  will also be an inverse to  $g$ , and thus we will have  $f = f'$ .

**1.6.ii: Any two terminal objects are connected by unique iso**

- Let  $t, t'$  be two terminal objects. This gives us two unique maps  $f : t \rightarrow t'$  and  $g : t' \rightarrow t$ , unique by the terminality of  $t, t'$ .
- Consider  $f \circ g : t' \rightarrow t'$ . There is another arrow with codomain  $t'$ ,  $\text{id}_{t'} : t' \rightarrow t'$ . By uniqueness of arrows into  $t'$ , we must have  $f \circ g = \text{id}_{t'}$ .
- Similarly,  $g \circ f = \text{id}_t$ . Thus,  $f, g$  are isomorphisms. Furthermore,  $f, g$  are unique. So,  $t, t'$  are isomorphic upto *unique* isomorphism.

**1.6.iii: Faithful functor reflects monos**

- Let  $F : C \rightarrow D$ , let  $Ff$  is mono in  $D$ . We must show that  $f : x \rightarrow y$  is mono in  $C$ .
- So, given arrows  $g, h : w \rightarrow x$ , given  $f \circ g = f \circ h$ , we must show that  $g = h$ .
- apply the functor, giving  $Ff \circ Fg = Ff \circ Fh$ .

- Since  $Ff$  is mono, it is left cancellable, giving  $Fg = Fh$ .
- Since  $F$  is faithful, it is injective on hom-sets, thus  $g = h$  (from  $Fg = Fh$ ).
- Hence, we've shown that  $f \circ g = f \circ h$  implies  $g = h$ , or that  $f$  is mono, and thus  $F$  reflects monos.

#### 1.6.iv, 1.6.v: Faithful functor need not preserve epis

- Consider  $F : \mathbf{Ring} \rightarrow \mathbf{Set}$ . This is faithful.
- Recall that the arrow  $f : \mathbb{Z} \rightarrow \mathbb{Q}$  was epi in  $\mathbf{Ring}$ . However, as a set valued function, this is not surjective. Thus, faithful functors need not *preserve* epis.
- Consider the functor  $G : \mathbf{Top} \rightarrow \mathbf{Set}$  which sends a space to its set of connected components. This is functorial, as given an arrow  $g$ , the arrow  $Gg$  tries to send connected components to connected components. This will always be the case, by virtue of continuity of  $g$ . Now see that the monomorphism  $g : \{0, 1\} \rightarrow [0, 1]$  where  $\{0, 1\} \subseteq \mathbb{R}$  is discrete and  $[0, 1]$  is connected, becomes  $Gg : \{0, 1\} \rightarrow \{*\}$  where  $\{*\}$  is the single connected component of  $[0, 1]$ .  $Gg$  is not mono,
- (Explanation: The property of being a mono or epi involves a quantification over all objects of a category. So if a functor is not essentially surjective on objects or not surjective on morphisms, such properties in the source category are usually not enough to guarantee the corresponding property in the target category. Note that this objection does not apply to isomorphisms, because they are defined by the explicit formulas for a two-sided inverse, not by a universal property.)

#### 1.6.vi: terminal coalgebras

- a coalgebra *for* an endofunctor  $T : C \rightarrow C$  is a tuple  $(c, \gamma : c \rightarrow Tc)$ . A morphism of coalgebras  $f : (c, \gamma) \rightarrow (c', \gamma')$  is a commuting square of the morphism  $f : c \rightarrow c'$ :

$$\begin{array}{ccc} c & \xrightarrow{f} & c' \\ \gamma \downarrow & & \downarrow \gamma' \\ Tc & \xrightarrow{Tf} & Tc' \end{array}$$

- We must show that if  $(c, \gamma : c \rightarrow Tc)$  is a terminal coalgebra (that is, it is terminal in the category of coalgebras), then  $\gamma$  is an isomorphism.
- Given any other coalgebra  $(d, \delta : d \rightarrow Td)$  we have a unique  $f : d \rightarrow c$  that makes the coalgebra diagram commute, since  $c$  is terminal.
- Consider the coalgebra  $(Tc, T\gamma : Tc \rightarrow TTc)$ . By terminality of  $(c, \gamma)$ , there is a morphism  $f : Tc \rightarrow c$  such that the diagram commutes:

$$\begin{array}{ccc} Tc & \xrightarrow{f} & c \\ T\gamma \downarrow & & \downarrow \gamma \\ TTc & \xrightarrow{TTf} & Tc \end{array}$$

- So we have the equation  $\gamma \circ f = Tf \circ T\gamma$ , or  $\gamma \circ f = T(f \circ \gamma)$ .
- Now consider the map of coalgebras  $(c, \gamma) \mapsto (Tc, T\gamma)$  given by  $\gamma : c \rightarrow Tc$ , with the following commutative diagram:

$$\begin{array}{ccc} c & \xrightarrow{\gamma} & Tc \\ \gamma \downarrow & & \downarrow T\gamma \\ Tc & \xrightarrow{T\gamma} & TTc \end{array}$$

- Composing the previous two diagrams, we get a map of coalgebras  $(c, \gamma) \mapsto (c, \gamma)$ :

$$\begin{array}{ccccc} c & \xrightarrow{\gamma} & Tc & \xrightarrow{f} & c \\ \gamma \downarrow & & \downarrow T\gamma & & \downarrow \gamma \\ Tc & \xrightarrow{T\gamma} & TTc & \xrightarrow{Tf} & Tc \end{array}$$

- From the terminality of  $(c, \gamma)$ , the arrow  $f \circ \gamma$  must be unique, and must be isomorphic to  $id_c$ :

$$\begin{array}{ccccc} c & \xrightarrow{\gamma} & Tc & \xrightarrow{f} & c \\ \gamma \downarrow & & \downarrow T\gamma & & \downarrow \gamma \\ Tc & \xrightarrow{T\gamma} & TTc & \xrightarrow{Tf} & Tc \end{array} \quad \begin{array}{ccc} c & \xrightarrow{id_c} & c \\ \gamma \downarrow & & \downarrow \gamma \\ Tc & \xrightarrow{id_{Tc}} & Tc \end{array}$$

- We've now proven  $f \circ \gamma = id_c$ . We need to show that  $\gamma \circ f = id_{Tc}$ .
- From the equation  $\gamma \circ f = T(f \circ \gamma)$ , and  $[f \circ \gamma = id_c]$  we derive  $\gamma \circ f = T(id_c) = id_{Tc}$ .
- thus,  $\gamma$  and  $f$  are inverses of each other, and we have the desired isomorphism.

## 1.7 THE 2-CATEGORY OF CATEGORIES

## 1.7.1 Musing

## Vertical Composition

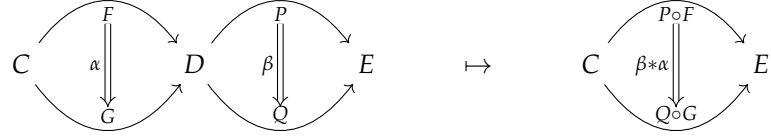
$$\begin{array}{c} x \xrightarrow{a} y \\ F \Rightarrow G \Rightarrow H \\ \downarrow \quad \downarrow \quad \downarrow \\ D \quad D \quad D \end{array} \quad \begin{array}{c} \textcircled{D} \quad F_x \xrightarrow{F_a} F_y \\ \alpha_x \downarrow \quad \downarrow \alpha_y \\ G_x \xrightarrow{G_a} G_y \\ G_a \circ \alpha_x = \alpha_y \circ F_a \end{array} \quad \begin{array}{c} \textcircled{D} \quad G_x \xrightarrow{G_a} G_y \\ \beta_x \downarrow \quad \downarrow \beta_y \\ H_x \xrightarrow{H_a} H_y \\ H_a \circ \beta_x = \beta_y \circ G_a \end{array}$$

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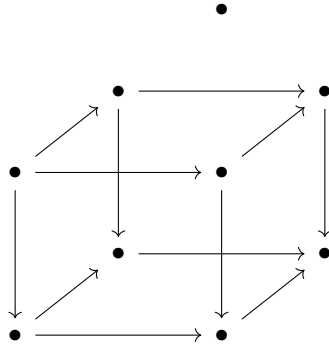
Claim: 
$$\begin{array}{c} F_x \xrightarrow{F_a} F_y \\ \alpha_x \downarrow \quad \downarrow \alpha_y \\ G_x \xrightarrow{G_a} G_y \\ \beta_x \downarrow \quad \downarrow \beta_y \\ H_x \xrightarrow{H_a} H_y \end{array} \quad \begin{array}{l} H_a \circ \beta_x \circ \alpha_x \xrightarrow{\quad} \quad \downarrow \\ = \beta_y \circ G_a \circ \alpha_x \quad \downarrow \\ = \beta_y \circ \alpha_y \circ F_a \quad \downarrow \end{array}$$

The idea is to rewrite the arrows in the down-then-right side of the square (in blue) given by  $H_\alpha \circ \beta_x \circ \alpha_x$  into the right-then-down side of the square (in pink) given by  $\beta_y \circ \alpha_y \circ F_a$ . To perform the rewrite, we apply the naturality of  $\alpha$  and  $\beta$ .

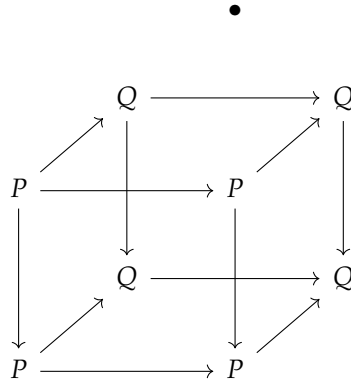
### 1.7.2 Horizontal Composition



We are trying to define the horizontal composition, given by  $\beta * \alpha : PF \Rightarrow GQ$ . First note that we have  $2 \times 2 \times 2$  parameters:  $\{P, Q\}$ ,  $\{F, G\}$ , and  $\{x, y\}$ . This is best arranged in a cube:

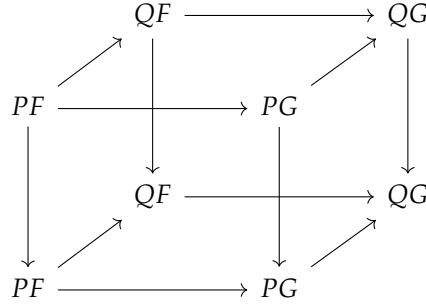


First fill up  $\{P, Q\}$ :

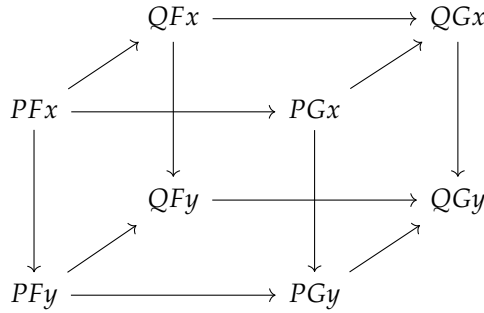




Next fill up  $\{F, G\}$ :



Finally, fill up  $\{x, y\}$ :



First, let's define  $(\beta * \alpha)(\bullet) : PF\bullet \rightarrow QG\bullet$  as the composition of the arrows:

$$PF\bullet \xrightarrow{P\alpha\bullet} PG\bullet \xrightarrow{\beta(G\bullet)} QG\bullet$$

That is,  $(\beta * \alpha)(\bullet) : PF\bullet \rightarrow QG\bullet \equiv \beta(G\bullet) \circ P(\alpha\bullet)$ .

### 1.7.3 Exercises

**Question 1.7.i** If  $C$  is small,  $D$  locally small, then  $D^C$  is locally small

**Answer** Recall that  $D^C$  has as objects as functors  $F, G : C \rightarrow D$ , and as arrows has natural transformations  $\eta : F \Rightarrow G \in \text{Hom}(F, G)$ . Recall that a natural transformation assigns to each object  $c \in C$  an arrow  $\eta_c : Fc \rightarrow Gc \in \text{Hom}_D(Fc, Gc)$ . So if we consider all natural transformations, the data is given by a choice function, which for every  $c \in C$  assigns an element in  $\text{Hom}_D(Fc, Gc)$ . Since  $C$  is small, the collection  $c \in C$  is a set. Since  $D$  is locally small, the set  $\text{Hom}_D(Fc, Gc)$  is a set. Thus, the data of all natural transformations is expressed by:

$$\text{Hom}(F, G) \equiv \prod_{c \in C} \text{Hom}_D(Fc, Gc)$$

This is not exactly a natural transformation, since this does not enforce the coherence conditions. So this is a super-collection of the collection of all natural transformations. We see that is a well defined set-theoretic

expression, since  $C$  is small, it is legal to range over it, and since  $D$  is locally small, it is legal to invoke  $\text{Hom}_D(Fc, Gc)$  as a set. Thus, the full  $\text{Hom}(F, G)$  is a set.

**Question 1.7.ii** Given  $C \xrightarrow{F} D \xrightarrow{H \Rightarrow K} E \xrightarrow{L} F$ , where  $\eta : H \Rightarrow E$ , define a natural transformation  $L\beta F : LHF \rightarrow LKF$  given by  $(L\beta F)(\bullet) \equiv L(\beta(F(\bullet)))$ . Prove that  $L\beta F$  is indeed natural (ie, that the appropriate diagram commutes)

**Answer** We start by considering an arrow  $x \xrightarrow{a} y \in C$ . By applying  $F$ , we get  $Fx \xrightarrow{Fa} Fy \in D$ . Next, to get access to  $\beta : H \Rightarrow K$ , we start by using  $H$  to get  $HFx \xrightarrow{HFa} HFy \in E$ . We use the naturality of  $\beta$  to transform to draw the commutative square with  $HF$  and  $KF$ , linked by  $\eta$ . This diagram lives in  $E$  and commutes by the naturality of  $\beta$ . Finally, we apply  $L$  to send a commutative diagram to another commutative diagram in  $F$ , with the natural transformation between  $LHF$  and  $LKF$ . Hence, naturality is proven.

$$\begin{array}{ll}
 x \xrightarrow{a} y & \text{arbitrary arrow in } C \\
 \\
 Fx \xrightarrow{Fa} Fy & \text{apply } F \text{ to land in } D \\
 \\
 HFx \xrightarrow{HFa} HFy & \text{apply } H \text{ to land in } E \\
 \\
 \begin{array}{ccc}
 H(Fx) & \xrightarrow{H(Fa)} & H(Fy) \\
 \beta(Fx) \downarrow & & \downarrow \beta(Fy) \\
 K(Fx) & \xrightarrow{K(Fa)} & K(Fy)
 \end{array} & \text{Naturality of } \beta \\
 \\
 \begin{array}{ccc}
 L(H(Fx)) & \xrightarrow{L(H(Fa))} & L(K(Fx)) \\
 L(\beta(Fx)) \downarrow & & \downarrow L(\beta(Fy)) \\
 L(K(Fx)) & \longrightarrow & L(K(Fy))
 \end{array} & \text{apply } L \text{ to land in } F
 \end{array}$$

**Question 1.7.iii** Redefine horizontal composition using vertical composition and whiskering. Given  $C \xrightarrow{F \Rightarrow G} D \xrightarrow{P \Rightarrow Q} E$ , where the natural transformations are  $\alpha : F \Rightarrow G$  and  $\beta : P \Rightarrow Q$ , we wish to define  $\beta * \alpha : PF \Rightarrow QG$ .

**Answer** TODO. I have no idea what the question wants us to do.

**Question 1.7.iv** Prove 1.7.7 (Middle four interchange), that states that  $(\beta \circ \alpha) * (\delta \circ \gamma)$  equals  $(\gamma * \alpha) \circ (\delta * \beta)$ .

**Answer** Recall that  $(\omega : C \xrightarrow{F \Rightarrow G} D * \phi : D \xrightarrow{P \Rightarrow Q} E) : D \xrightarrow{PF \Rightarrow QG} E$  is defined as  $(\omega * \phi) : PF \bullet \rightarrow QG \bullet$  given by:

$$\begin{array}{ccc}
 PF\bullet & \xrightarrow{P(\phi\bullet)} & PG\bullet \\
 \omega(F\bullet) \downarrow & \searrow \text{naturalness of } \omega & \downarrow \omega(G\bullet) \\
 QF\bullet & \xrightarrow{Q(\phi\bullet)} & QG\bullet
 \end{array}$$

$(\omega * \phi)(\bullet)$

$\omega : P\bullet \rightarrow Q\bullet$

$\phi : F\bullet \rightarrow G\bullet$

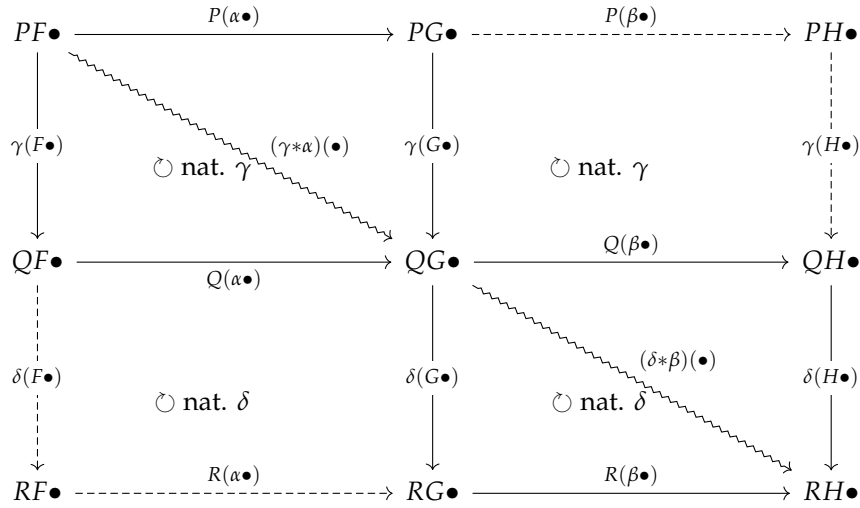
Consider the large commutative diagram:

$$\begin{array}{ccccccc}
 PF\bullet & \xrightarrow{P(\alpha\bullet)} & PG\bullet & \xrightarrow{P(\beta\bullet)} & PH\bullet \\
 \gamma(F\bullet) \downarrow & \text{naturalness of } \gamma & \downarrow \gamma(G\bullet) & \text{naturalness of } \gamma & \downarrow \gamma(H\bullet) \\
 QF\bullet & \xrightarrow{Q(\alpha\bullet)} & QG\bullet & \xrightarrow{Q(\beta\bullet)} & QH\bullet \\
 \delta(F\bullet) \downarrow & \text{naturalness of } \delta & \downarrow \delta(G\bullet) & \text{naturalness of } \delta & \downarrow \delta(H\bullet) \\
 RF\bullet & \xrightarrow{R(\alpha\bullet)} & RG\bullet & \xrightarrow{R(\beta\bullet)} & RH\bullet
 \end{array}$$

By composing the outer morphisms, we get:

$$\begin{array}{ccc}
 PF\bullet & \xrightarrow{P((\beta\circ\alpha)\bullet)} & PH\bullet \\
 (\delta\circ\gamma)(F\bullet) \downarrow & \searrow (\gamma\circ\delta)*(\beta\circ\alpha) & \downarrow (\delta\circ\gamma)(H\bullet) \\
 RF\bullet & \xrightarrow{R((\beta\circ\alpha)\bullet)} & RH\bullet
 \end{array}$$

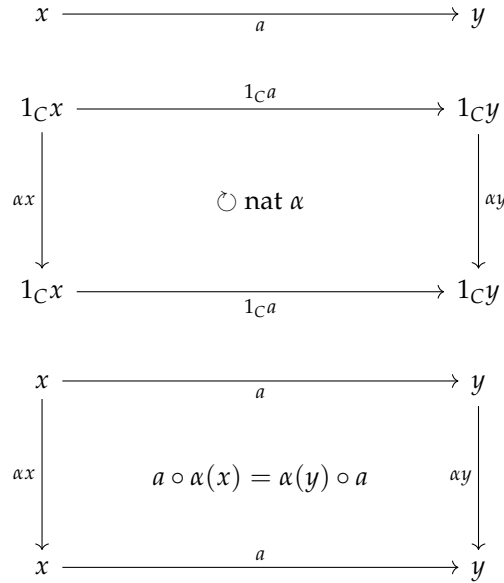
By composing the inner morphisms, we get  $(\gamma * \alpha) \circ (\delta * \beta)$



By the commutativity of the large square, these two are equal, and hence the four composition theorem holds.

**Question: 1.7.v.** Show that the collection of natural transformations of the form  $\{1_C \Rightarrow 1_C\}$  defines a commutative monoid (under vertical composition).

Consider such a natural transformation  $\alpha : 1_C \Rightarrow 1_C$ . From naturality, for all arrows  $x \xrightarrow{a} y$ ,  $\alpha$  must satisfy  $a \circ \alpha(x) = \alpha(y) \circ a$ :



- given two  $\alpha, \beta : 1_C \Rightarrow 1_C$ , we must have that  $\alpha(x) \circ \beta(x) = \beta(x) \circ \alpha(x)$  [since  $\alpha(x) \circ a = a \circ \alpha(y)$ ].
- Since this holds at all points, we get  $\alpha \circ \beta = \beta \circ \alpha$ , or that these are commutative.
- The identity natural transformation  $e$  given by  $e(1_C x) = e(x) \equiv x = 1_C x$  is the identity for the monoid of endo-natural transformations of the functor  $1_C$ . Verification is formal, and left to be jotted down to future Siddharth.

**Question: 1.7.vi.** TODO

**Question: 1.7.vii.** Show that a bifunction  $F : C \times D \rightarrow E$  is equivalent to the data:

- A functor  $F(c, -) : D \rightarrow E$  for each  $c \in C$
- A natural transformation  $F(f, -) : F(x, -) \Rightarrow F(y, -)$  for each  $x \xrightarrow{f} y \in C$ , defined functorially in  $C$
- To be “defined functorially” is to say that we have a functor  $G : C \rightarrow D^E$ , which is in bijection with  $F : C \times D \rightarrow E$ .

**Answer (  $\Rightarrow$  ): Bifunctor implies partial application**

- Given a bifunctor  $F$ , define for each  $c \in C$  a functor  $\partial F(c, -) : D \rightarrow E$
- On objects, we define  $\partial F(c, -)(d) \equiv F(c, d)$
- On arrows, we define  $\partial F(c, -)(x \xrightarrow{g} y) \equiv F(1_c, g)$ .
- See that the definition on objects and arrows is consistent:

$$\begin{aligned} x \in D &\xrightarrow{g} y \in D \\ \partial F(c, -)(x) \in E &\xrightarrow{\partial F(c, -)(g)} \partial F(c, -)(y) \in E \\ F(c, x) &\xrightarrow{F(\text{id}_c, g)} F(c, y) \end{aligned}$$

- See that  $\partial F(c, -)$  preserves identity:

$$\begin{aligned} \partial F(c, -)(\text{id}_d) &= F(\text{id}_c, \text{id}_d) \quad (\text{Defn of } \partial F(c, -)) = \text{id}_{F(c, d)} \quad (\text{Functoriality of } F) \end{aligned}$$

- See that  $\partial F(c, -)$  distributes over  $\circ$ :

$$\begin{aligned} \partial F(c, -)(x \xrightarrow{f} y \xrightarrow{g} z) &= F(\text{id}_c, g \circ_D f) \quad (\text{Defn of } \partial F(c, -)) \\ &= F(\text{id}_c \circ_C \text{id}_c, g \circ_D f) \quad (h \circ \text{id}_c = \text{id}_c) \\ &= F((\text{id}_c, g) \circ_{C \times D} (\text{id}_c, f)) \quad (\text{Defn. of composition in } C \times D) \\ &= F((\text{id}_c, g)) \circ_E F((\text{id}_c, f)) \quad (\text{Functoriality of } F) \\ &= \partial F(c, -)(g) \circ_E \partial F(c, -)(f) \quad (\text{Defn of } \partial F(c, -)) \end{aligned}$$

- This completes our verification that  $\partial F(c, -)$  is a functor.
- We move to constructing the natural transformations  $\partial F(f, -) : \partial F(c, -) \Rightarrow \partial F(c', -)$  for each  $f : c \rightarrow c'$ .

- The natural transformation assigns components for each  $d \in D$ . It must produce arrows  $\partial F(c, -)(d) \rightarrow \partial F(c', -)(d)$  which live in  $E$ . We choose to produce the arrow  $F(f, id_d)$ . That is,  $\partial F(f, -)(d) \equiv F(f, id_d)$ . This assembles into a square whose commutativity is to be established:

$$\begin{array}{ccc}
 d & \xrightarrow{a} & d' \\
 \\
 \partial F(c, -)(d) & \xrightarrow{\partial F(c, -)(a)} & \partial F(c, -)(d') \\
 \downarrow \partial F(f, -)(d) & \circlearrowleft ? & \downarrow \partial F(f, -)(d') \\
 \partial F(c', -)(d) & \xrightarrow{\partial F(c', -)(a)} & \partial F(c', -)(d')
 \end{array}$$

Which upon substituting definitions becomes:

$$\begin{array}{ccc}
 F(c, d) & \xrightarrow{F(id_c, a)} & F(c, d') \\
 \downarrow F(f, id_d) & & \downarrow F(f, id_{d'}) \\
 F(c', d) & \xrightarrow{F(id_{c'}, a)} & F(c', d')
 \end{array}$$

Which commutes since  $F$  preserves commuting diagrams as it is a functor, and the following diagram commutes (by direct verification):

$$\begin{array}{ccc}
 (c, d) & \xrightarrow{(id_c, a)} & (c, d') \\
 \downarrow (f, id_d) & & \downarrow (f, id_{d'}) \\
 (c', d) & \xrightarrow{(id_{c'}, a)} & (c', d')
 \end{array}$$

- To prove functoriality of this assignment, we must show that given  $d_1 \xrightarrow{a} d_2 \xrightarrow{b} d_3$ , the equation  $\partial F(f, -)(b \circ_D a) = \partial F(f, -)(b) \circ_E \partial F(f, -)a$ . This follows by computation:

$$\begin{aligned}
 & \partial F(f, -)(b \circ_D a) \\
 & =
 \end{aligned}$$

## UNIVERSAL PROPERTIES, REPRESENTABILITY, THE YONEDA LEMMA

### 2.1 REPRESENTABLE FUNCTORS

#### 2.1.1 *Musing*

Let  $F : \mathbf{Set} \rightarrow \mathbf{Grp}$  and  $U : \mathbf{Grp} \rightarrow \mathbf{Set}$  be adjoints, where  $F$  is free and  $U$  is forgetful. So we can translate arrows of the form  $Fx \rightarrow y$  into arrows  $x \rightarrow Gy$ . Let  $1 \equiv \{*\}$  be the final object in  $\mathbf{Set}$ . **Claim:**  $F(1) : \mathbf{Grp}$  is the representing object for the forgetful functor  $U : \mathbf{Grp} \rightarrow \mathbf{Set}$ .

For  $F(1)$  to be a representing object, there must be a natural isomorphism between the functor  $U : \mathbf{Grp} \rightarrow \mathbf{Set}$  and the functor  $\text{Hom}(F(1), -) : \mathbf{Grp} \rightarrow \mathbf{Set}$ . So we must establish a natural bijection between  $U\bullet$  and  $\text{Hom}(F(1), \bullet)$  for any group  $\bullet$ .

See that any morphism  $[F(1) \rightarrow \bullet]$  is in bijection with  $[1 \rightarrow U(\bullet)]$ . Morphisms of the form  $[1 \rightarrow U(\bullet)]$  is isomorphic to  $\bullet$ , since a map of the form  $f : 1 \rightarrow U\bullet$  picks out elements of  $U\bullet$  ( $\text{im}(f) = f(*) \in \bullet$ ).

In a single line, we have:

$$\text{Hom}_{\mathbf{Grp}}(F(1), G) \simeq \text{Hom}_{\mathbf{Set}}(1, UG) \simeq UG$$

*Proof that functors upto equivalence form a groupoid, with all rewrites witnessed by natural transformations.*

#### 2.1.2 *Exercises*

**Question: 2.1.i.** Describe natural transformations between (a) the functors  $0 : \mathbb{1} \rightarrow \mathbf{mathbb{b}b2}$ ,  $1 : \mathbb{1} \rightarrow \mathbf{}$ , and  $! : \mathbf{ } \rightarrow \mathbb{1}$  and (b) the covariant functors  $\mathbf{Cat} \rightarrow \mathbf{Set}$  represented by the categories  $\mathbb{1}$  and  $\mathbf{ }$ ,

TODO: what should we prove? I don't think I understand the question.

**Question: 2.1.ii.** Prove that if  $F : \mathbf{C} \rightarrow \mathbf{Set}$  is representable then it preserves monomorphisms. Let  $F$  be represented by some  $r \in \mathbf{C}$ . So we have a natural isomorphism  $\eta : F \rightarrow \text{Hom}_{\mathbf{C}}(r, -)$ . Suppose we have a monomorphism  $y \xrightarrow{m} z$ . So given any other arrows  $f, g : x \rightarrow y$ , we have that  $m \circ f = m \circ g$  implies  $f = g$ .

- Consider the image under  $\text{Hom}(r, -)$ .
- We wish to show that if  $\text{Hom}(r, -)(m) \circ \text{Hom}(r, -)(f) = \text{Hom}(r, -)(m) \circ \text{Hom}(r, -)(g)$  then  $\text{Hom}(r, -)(f) = \text{Hom}(r, -)(g)$ .
- Simplifying using the definition of the Hom functor, this asks us to show that if  $m \circ f \circ - = m \circ g \circ -$  then  $f \circ - = g \circ -$ .
- We prove this by applying the desired equality pointwise.
- Suppose that  $m \circ f \circ \alpha = m \circ g \circ \alpha$ . This can be written as  $m \circ (f \circ \alpha) = m \circ (g \circ \alpha)$ .

- This implies  $f \circ \alpha = g \circ \alpha$  ( $m$  is a monomorphism, is left cancellable). So we have that  $f \circ \alpha = g \circ \alpha$  for all  $\alpha$ , or  $f \circ - = g \circ -$ .
- Since this works for Hom functors, it works for representables since a representable is naturally isomorphic to Hom, and thus witnesses the same categorical properties, including being a monomorphism.

**Question: 2.1.iii.** Let  $F : C \rightarrow \text{Set}$  be equivalent to  $G : C \rightarrow \text{Set}$ . So there is an equivalence of categories  $H : C \rightarrow D$  such that  $GH$  is naturally isomorphic to  $F$ . We must check what the representability of  $F$  ( $G$ ) implies about the representability of  $G$  ( $F$ ).

**answer:  $F$  representable, is  $G$ ?** Recall that an equivalence of categories implies that we have functors  $H : C \rightarrow D$  and  $H^{-1} : D \rightarrow C$  such that  $H \circ H^{-1} \simeq \text{id}_D$  and  $H^{-1} \circ H \simeq \text{id}_C$ . We have that  $GH \simeq F$  and  $F$  is represented by an object  $c \in C$  so  $F \simeq \text{Hom}_C(c, -)$ . We need to show that  $G$  is is representable, that is, there exists an object  $d \in D$  such that  $G \simeq \text{Hom}_D(d, -)$ . A derivation proceeds as follows:

$$\begin{aligned}
G \circ H &\simeq F \quad (\text{given}) \\
G &\simeq F \circ H^{-1} \quad (H \text{ is equivalence, has an inverse}) \\
G &\simeq \text{Hom}_C(c, -) \circ H^{-1} \quad (F \text{ is represented by } c) \\
G &\simeq \text{Hom}_C(c, H^{-1}(-)) \quad (\text{Computation: Compose the functors}) \\
G &\simeq \text{Hom}_C(H(c), H(H^{-1}(-))) \quad (\text{Equivalence preserves hom-sets}) \\
G &\simeq \text{Hom}_C(H(c), -) \quad (H \circ H^{-1} \simeq \text{id})
\end{aligned}$$

So from the above, we find that  $G$  is represented by  $H(c)$  where  $c$  is the representing object for  $F$ .  $\square$

**Answer:  $G$  representable, is  $F$ ?** As per the question,  $F$  and  $G$  are symmetric, so we repeat the same argument swapping  $F$  for  $G$  and  $H$  for  $H^{-1}$  throughout.  $\square$

**Question: 2.1.iv.** Characterize the subsets that assemble into a subfunctor of the functor  $\text{Hom}_C(c, -)$  for a given  $c \in C$ .

**Answer**  $F$  is a subfunctor of  $G$  iff there is a natural transformation  $\alpha : F \Rightarrow G$  whose components are mono (that is, each of the arrows  $\alpha_\bullet : F_\bullet \rightarrow G_\bullet$  is a monomorphism). Let  $G : C^{\text{op}} \rightarrow \text{Set}$  be a functor, and let  $F : C^{\text{op}} \rightarrow \text{Set}$  be a subfunctor of  $G$ . A natural transformation  $\alpha : F \rightarrow G$  will have as components monic arrows  $F_\bullet \rightarrow G_\bullet \in \text{Set}$ . So we get a subsets  $F_\bullet$  of  $G_\bullet$ .

Let  $F$  be a subfunctor of  $\text{Hom}_C(r, -)$  ( $r$  for representable). So, we have a natural transformation  $\eta : F \Rightarrow \text{Hom}_C(r, -)$  such that each of the components  $Fx \rightarrow \text{Hom}_C(r, x)$  is a monomorphism / set embedding. So TODO: Follow what topos told me, and think of this as a sieve.



## 2.2 THE YONEDA LEMMA

## 2.2.1 Exercises

**Question: 2.2.i.** Characterize natural transformations  $C(c, -) \Rightarrow F$  for contravariant  $F : C^{\text{op}} \rightarrow \text{Set}$ .

**Answer**

- Following Yoneda, we suspect that such natural transformations  $\eta : C(-, c) \Rightarrow F$  are in bijection with elements of the set  $F(c)$ .
- To prove this, consider a natural transformation  $\eta : C(-, c) \Rightarrow F$ .
- Consider the component  $\eta_c : C(c, c) \rightarrow Fc$ .
- Since  $1_c \in C(c, c)$ , we have  $\eta_c(1_c \in C(c, c)) \in Fc$ .
- We claim that the free choice of the image of  $\eta_c(1_c)$  (in  $Fc$ ) determines the action of  $\eta$  everywhere. So given the functor  $F$  and the value of  $\eta_c(1_c)$ , we can define  $\eta_o$  for all objects  $o \in C$  (including  $o = c$  at other values than  $1_c$ )
- Consider some object  $o \in C$ . We wish to determine the action  $\eta_o : C(o, c) \rightarrow Fo$ .
- Let  $o2c \in C(o, c)$ . Let's determine the value of  $\eta_o(o2c) \in Fo$ . If we do this for arbitrary  $o2c$ , then we have determined  $\eta_o$ .
- This is both an element of the set  $C(o, c)$ , and a morphism  $C(o, c) \xrightarrow{C(-,c)(o2c) \equiv \lambda c2c.c2c \circ o2c} C(o, c)$ .
- We draw a commutative square and deduce the value of  $\eta_o(o2c)$  for arbitrary  $o \in C$ , arbitrary  $o2c \in C(o, c)$ .

$$\begin{array}{ccc}
 o & \xrightarrow{\quad o2c \in C(o, c) \quad} & c \\
 \\ 
 C(o, c) & \xrightarrow{\quad \eta_o \equiv ? \quad} & Fo \\
 \\ 
 o2c \in C(o, c) & \xrightarrow{\quad \eta_o \equiv ? \quad} & Fo \\
 \\ 
 1_c \in C(c, c) & \xrightarrow{C(-,c)(o2c) \equiv \lambda c2c.c2c \circ o2c} & (o2c(1_c) = 1_c \circ o2c = o2c) \in C(o, c) \\
 \downarrow \eta_c & & \downarrow \eta_o \\
 (\eta_c(1_c) \equiv \text{free}) \in Fc & \xrightarrow{F(o2c) \equiv \text{given}} & Fo
 \end{array}$$

$F(o2c)(\eta_c(1_c)) = \eta_o(o2c)$   
 Use as defn of  $\eta_o(o2c)$   
 $\eta_o(o2c) \equiv F(o2c)(\eta_c(1_c))$

- See that this deduced value is in terms of  $\eta_c(1_c)$  [which is freely chosen] and  $F(o2c)$  which is given.
- Thus, the value of  $\eta$  is determined everywhere else.

**Question: 2.2.ii Explain why Yoneda does not dualize to classify natural transformations from an arbitrary set valued functor  $F : C \rightarrow cSet$  to a represented functor  $Hom(c, -)$ .**

- Suppose such a thing were possible. Then we would have a natural isomorphism between natural transformations  $\eta : F \Rightarrow Hom(c, -)$  and elements of the set  $Fc$ .
- However, see that in the equation  $Fc$ ,  $F$  and  $c$  are covariant, while in the equation  $\eta_x : Fx \rightarrow Hom(c, x)$ ,  $F$  and  $c$  are contravariant.
- Hence, the variances do not align.

**Question: 2.2.iii Describe the yoneda embedding  $y : \omega \rightarrow Set^{\omega^{op}}$  as a family of  $\omega^{op}$  indexed functors and natural transformations. Prove directly without using yoneda that  $y$  is full and faithful.**

- foo

**Question: 2.2.vi Do there exist families of continuous maps  $\{X \rightarrow X : X \in Top\}$  where not all maps are identities, and are natural in all maps in  $Top$ ?**

- I claim that such a family of maps don't exist.
- Suppose they do for contradiction.
- See that such a family of maps is a natural transformation from the identity functor to itself. So we have a non-trivial  $\eta : id_{Top} \Rightarrow id_{Top}$ .
- Forget the topological structure to land in  $Set$ . This leaves us with a  $\eta : id_{Set} \Rightarrow id_{Set}$  whose components  $\eta_x$  are not all identity arrows (in  $Set$ ).
- Recall that the identity functor  $id_{Set}$  is representable, and is represented by the single element set. So  $id_{Set} \simeq Hom(\{*\}, -)$ .
- Substituting we have that  $\eta \equiv id_{Set} \simeq Hom(\{*\}, -) \Rightarrow id_{Set}$ .
- By yoneda, we have that  $Hom(\{*\}, -) \Rightarrow id_{Set} \simeq id_{Set}(\{*\}) \equiv \{*\}$
- We already have one choice of  $\eta$ , the identity natural transformation. This must be the only one possible, since we have a set of cardinality 1 ( $\{*\}$ ) which classifies  $\eta$ s.
- Thus, we have a contradiction, which is the existence of another non-trivial  $\eta$ .  $\square$ .

**Question: 2.2.vii Use Yoneda to connect homeomorphisms of the standard unit interval to automorphisms of the path functor  $P : Top \rightarrow Set$ .**

- Path functor is represented by the unit interval  $[0, 1]$ .

- Natural transformations from  $P$  to itself (ie, natural automorphisms of  $P$ ) is the same as natural transformations from  $\text{Hom}([0, 1], -)$  to  $P$ .
- Yoneda:  $\text{Hom}([0, 1], -) \Rightarrow P$  is in bijection with  $P([0, 1]) \simeq \text{Hom}([0, 1], [0, 1])$ .
- The RHS is continuous maps from  $[0, 1]$  to itself. If we want invertibility (as we do on the LHS for automorphisms), we get homeomorphisms on the RHS.
- To make this precise: isos preserve isos. The natural isomorphism given by Yoneda must preserve isos on both sides of the equation.
- This establishes a mapping between natural automorphisms of the path functor and homeomorphisms of the unit interval to itself.  $\square$