Notto

tkunn

August 2020

Solutions for problems on the second edition of *Category for the Working Mathematician* by S. Mac Lane.

1

1.1

1.2

1.3

1.3.1

1.3.2

1.3.3

1.3.4

1.3.5

1.4

1.4.1

1.4.2

1.4.3

1.4.4

1.4.5

1.4.6

1.5

1.5.1

1.5.2

1.5.3

1.5.4

1.5.5

1.5.6

1.5.7

1.5.8

1.5.9

1.6

Let U be a set that satisfies following conditions:

(i) $x \in u \in U \Rightarrow x \in U$

(ii) $(u \in U \wedge v \in U) \Rightarrow (\{u, v\}, \langle u, v \rangle, u \times v \in U)$

(iii) (1) $x \in U \Rightarrow \mathcal{P}x \in U$

(2) $x \in U \Rightarrow \bigcup x \in U$

(iv) $\omega \in U$, where $\omega = \{0, 1, 2, \dots\}$ is a set of all finite ordinal numbers.

(v) If there exists a surjection $f : a \to b$ and $a \in U$ and $b \subset U$, then $b \in U$.

1.6.1

$$(\cdot \underset{\frown}{\tau} \cdot)$$

For all $q \in \prod_i f_i$, we can construct a bijection $r : I \to q$. $q \subset U$ because $\forall w \in q,\ \exists j \in I,\ w \in f_j \in U$. Since $I \in U$ and $q \subset U$, we can say $q \in U$. Therefore $\prod_i f_i \subset U$.

Let $|f_k| \geq |f_i|$ for all i. Then, we can construct a surjection $g : f_k^I \to \prod_i f_i$. Also, we can construct a surjection $h : X \to f_k^I$, with X is either $\mathcal{P} f_k$ or $\mathcal{P} I$. As $X \in U$, $g \circ h : X \to \prod_i f_i$ and $\prod_i f_i \subset U$, we can say $\prod_i f_i \in U$.

1.6.2

$$\begin{tikzcd}
 & * \arrow[dl] \arrow[dr, "h"] & & & * \arrow[dl, "i"'] \arrow[dr] & \\
* & & * & * & & *
\end{tikzcd}$$

$$\phi \longrightarrow \theta$$

(a) We can construct a bijection $g : I \to \{f_i \mid i \in I\}$, $g(i) = f_i$. As $I \in U$ and $f_i \in U$ for all i, $\{f_i \mid i \in I\} \in U$. Therefore $\bigcup_i f_i = \bigcup\{f_i \mid i \in I\} \in U$.

(b) Because $x \in U$, we have $y \in U$ for all $y \in x$. Therefore we can apply $f : x \to x, f(i) = i$ to (a) to get $\bigcup x \in U$.

Because $a \in U$ and $b \subset U$, we can apply f to (a) to get $\bigcup_i f_i \in U$. f is surjective, therefore $b = \bigcup_i f_i$. Hence $b \in U$.

1.7

1.8

2

2.1

2.2

2.3

2.3.1

$$\begin{tikzcd} & * \arrow[dl] \arrow[dr, "h"] & & & * \arrow[dl, "i"'] \arrow[dr] & \\ * & & * & * & & * \end{tikzcd}$$

$$\begin{tikzcd} \phi \arrow[rr, bend right] & & \theta \end{tikzcd}$$

In this section, $\times_S$ is a product operation for sets, $\times_C$ is for categories, $\times_G$ is for groups and $\times_M$ is for monoids.

Monoids. Let M, N be a monoid with object m, n respectively. The only object in $M \times_C N$ is $\langle m, n \rangle$. ... (TODO)

Groups. Let G, H be a group with object a, b respectively. $G \times_C H$ ... (TODO)

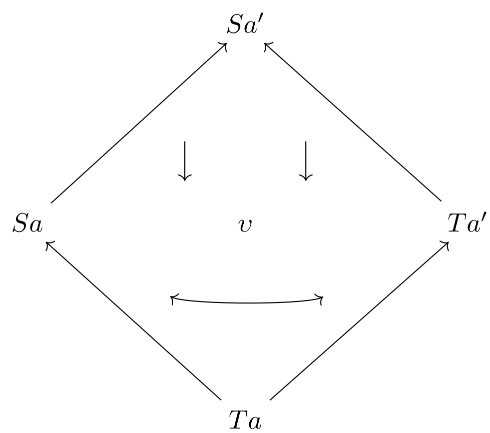
Sets. Let A, B be discrete categories. The set of all objects in $A \times_C B$ is $X = A \times_S B$. The set of all arrows in $A \times_C B$ is $\{\langle f, g \rangle \mid a \in A,\ b \in B,\ f \in A(a,a)\ \wedge\ g \in B(b,b)\} = \{\langle \mathrm{id}_A(c_0), \mathrm{id}_B(c_1) \rangle \mid c \in X\}$. Therefore $A \times_C B$ is a discrete category of $X = A \times_S B$.

2.3.2

$$(\,\hat{}\,{}_{\sigma}\,\hat{}\,)$$

Let P, Q be preorders. $\forall a \forall b\ |\hom(a,b)| \leq 1$ for both P and Q. Therefore, for all $p_1 \in P,\ p_2 \in P,\ q_1 \in Q,\ q_2 \in Q,\ |\hom_{P \times Q}(\langle p_1, q_1 \rangle, \langle p_2, q_2 \rangle)| = |\hom_P(p_1, p_2) \times \hom_Q(q_1, q_2)| \leq 1$. Hence $P \times Q$ is preorder.

2.3.3



Let $\mathrm{id}_X(a) : a \to a$ be an identity in the category X.

Let the set of all object in C be the product set $\prod_i C_i$ and $C(a,b) = \prod_i C_i(a_i, b_i)$. Let $\mathrm{id}_C(c)_i = \mathrm{id}_{C_i}(c_i)$ for all $c \in C$. Now, we prove C has a universal property:

1. For every i there is a functor $P_i : C \to C_i$.

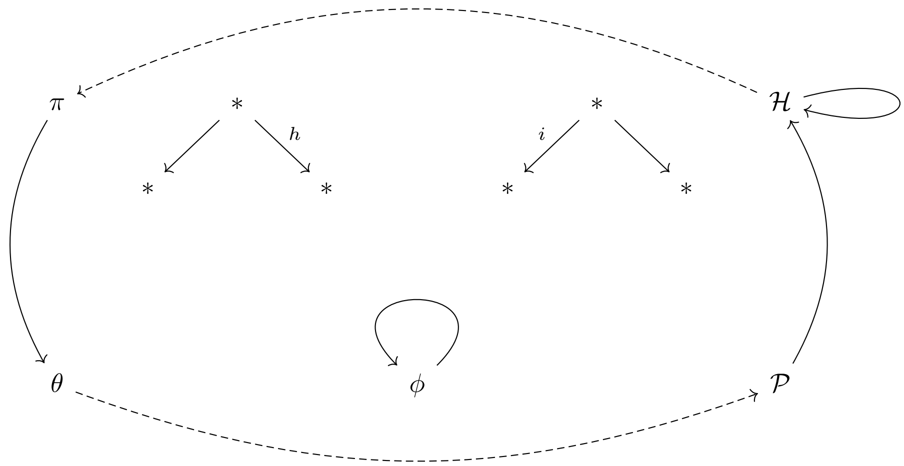
2. For every category B such that a functor $G_i : B \to C_i$ presents for every C_i, there is a functor $F : B \to C$, which makes the following diagram commute.

$$\begin{tikzcd} B \arrow[d, dashed, "F"'] \arrow[dr, "G_i"] & \\ C \arrow[r, "P_i"] & C_i \end{tikzcd}$$

First, we prove $P_i : C \to C_i$ exists. Let the object function be $P_i(x) = x_i$. Let the arrow function be $P_i(f) = f_i$. For all object $c \in C$, $P_i(\mathrm{id}_C(c)) = \mathrm{id}_C(c)_i = \mathrm{id}_{C_i}(c_i) = \mathrm{id}_{C_i}(P_i(c))$. For all arrow f, g in C, $P_i(g \circ f) = (g \circ f)_i = g_i \circ f_i = P_i(g) \circ P_i(f)$. Therefore P_i is a functor.

Second, we prove $F : B \to C$ exists. Let the object function be $F(x)_i = G_i(x)$. Let the arrow function be $F(f)_i = G_i(f)$. For all object $b \in B$, $F(\mathrm{id}_B(b))_i = G_i(\mathrm{id}_B(b)) = \mathrm{id}_{C_i}(G_i(b)) = \mathrm{id}_{C_i}(F(b)_i)$. Thus $F(\mathrm{id}_B(b)) = \mathrm{id}_C(F(b))$. For all arrow f, g in B, $F(f \circ g)_i = G_i(f \circ g) = G_i(f) \circ G_i(g)$. Thus $F(f \circ g) = F(f) \circ F(g)$. Therefore F is a functor.

2.3.4



In $\mathbf{Matr}_K$, the object set is all positive integers $\{1, 2, 3, ...\} = \omega \setminus \{0\}$. $\mathbf{Matr}_K(n, m)$ is all rectangular matrix on K of shape $m \times n$. Therefore $\mathbf{Matr}_K^{\mathrm{op}}$ has the same objects $\omega \setminus \{0\}$ and $\mathbf{Matr}_K^{\mathrm{op}}(n, m)$ is all rectangular matrix on K of shape $n \times m$.

2.3.5

$$\langle Q \perp Q \rangle$$

Let $R_T \subseteq (T \to \mathbb{R})$ be a ring whose elements are continuous functions from a topological space T to real number. We construct R_T as follows:

1. Additive identity. $0_{R_T} : x \mapsto 0$.
2. Multiplicative identity. $1_{R_T} : x \mapsto 1$.
3. Addition. $f + g : x \mapsto f(x) + g(x)$.
4. Multiplication. $f \times g : x \mapsto f(x) \times g(x)$.

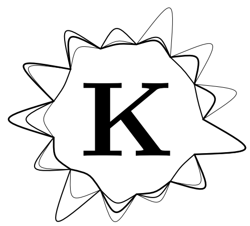
Let X and Y be any topological spaces. If we have a continuous function $f : Y \to X$, we can construct a ring homomorphism $H(f) = h : R_X \to R_Y$. We define $h(r) = r \circ f$. Then $h(0_{R_X}) = 0_{R_Y}$, $h(1_{R_X}) = 1_{R_Y}$, $(h(s+t))(x) = (s+t)(f(x)) = s(f(x))+t(f(x))$, $(h(s\times t))(x) = (s\times t)(f(x)) = s(f(x))\times t(f(x))$. Therefore $H(f)$ is a ring homomorphism.

Now we construct a functor $F : \mathbf{Top}^{\mathrm{op}} \to \mathbf{Rng}$. Let the object function be $F(A) = R_A$ and the arrow function be $F(g) = H(g^{\mathrm{op}})$. For all arrow a, b in $\mathbf{Top}^{\mathrm{op}}$, $F(b \circ a) = H((b \circ a)^{\mathrm{op}}) = H(a^{\mathrm{op}} \circ b^{\mathrm{op}}) = H(b^{\mathrm{op}}) \circ H(a^{\mathrm{op}}) = F(b) \circ F(a)$. For all topological space $T \in \mathbf{Top}^{\mathrm{op}}$, $F(\mathrm{id}(T)) = H(\mathrm{id}(T)) = \mathrm{id}(R_T)$. Therefore F is a functor and $\overline{F}$ is a contravariant functor on $\mathbf{Top}$ to $\mathbf{Rng}$.

2.4

2.4.1

2.4.2



For any functor $T : X \to B$, if its object function is $T(a) = b$, its arrow function maps $\mathrm{id}(a)$ to $\mathrm{id}(b)$. Such a functor T is an object of B^X.

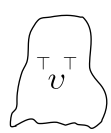
Let $R, S : X \to B$ be functors and τ be a map on an object of X to an arrow in B. $(\tau : R \dot{\to} S) \Leftrightarrow (\forall x \in X,\ \tau_x(R(x)) = S(x))$. Therefore $\hom(R, S) = \{\tau \mid \forall x \in X,\ \tau_x(R(x)) = S(x)\}$. Therefore an arrow on R to S exists iff $(\forall x, y \in X,\ e_R(x, y) \to e_S(x, y)) \ \wedge\ (\forall x \in X,\ \hom(R(x), S(x)) \neq \emptyset)$, where $e_T(x, y) \Leftrightarrow (\exists a \in B, \{x, y\} \subseteq \{w \mid a = T(w)\})$.

2.4.3

$(\cdot\underset{\smile}{\tau}\cdot)$

An object of $\mathbf{Ab}^{\mathbf{N}}$ is a map on $\mathbb{N}$ to $\mathbf{Ab}$. Same as above, $\hom(R, S) = \{\tau \mid \forall n \in N,\ \tau_n(R(n)) = S(n)\}$. In other words, a map $\tau : \mathbb{N} \to (\mathbf{Ab} \to \mathbf{Ab})$ is an arrow iff, for every $n \in \mathbb{N}$, there is a corresponding group homomorphism τ_n on $R(n)$ to $S(n)$, and, for every $m \in \mathbb{N}$ such that $R(n) = R(m)$, $S(n) = S(m)$.

2.4.4



Let $R, S : P \to Q$. Then R and S are objects of Q^P. Let τ be a natural transform $\tau : R \dot{\to} S$. τ is an arrow on R to S in Q^P. Since τ is natural and P is preorder, the following diagram commutes for every pair of objects $p, p' \in P$. $a = f(p, p')$, where $f(p, p')$ is the only arrow on p to p'. Since Q is preorder, $\tau p = g(Rp, Sp)$, where $g(Rp, Sp)$ is the only arrow on Rp to Sp.

$$\begin{tikzcd} Rp \arrow[r, "\tau p"] \arrow[d, "Ra"'] & Sp \arrow[d, "Sa"] \\ Rp' \arrow[r, "\tau p'"] & Sp' \end{tikzcd}$$

From the two downward arrows in the diagram, we can say that $\mathrm{Im}(R)$ and $\mathrm{Im}(S)$ contain the preorder structure of P. There are two functors $P \to \mathrm{Im}(R)$ and $P \to \mathrm{Im}(S)$, where $\mathrm{Im}(T)$ is a category from the image of the object function of T and all arrows between any two pairs in the image.

As explained above, $\sigma p = g(Rp, Sp)$ for all $\sigma : R \dot{\to} S$. Thus $|\hom(R, S)| \leq |\{\sigma \mid \forall p \in P,\ \sigma p = g(Rp, Sp)\}| = 1$. Therefore Q^P is preorder.

2.4.5

$$\langle \wedge \_ \wedge \rangle$$

Let **Fin** be a category of all finite sets. The object is every finite set and the arrow is every mapping between every pair of finite sets.

Let G be a finite group. G is a category of only one object. Every arrow a in G has its inverse a^{-1} such that $a \circ a^{-1} = a^{-1} \circ a = \mathrm{id}$.

$\mathbf{Fin}^G$ is a category that have any functor on G to **Fin** as objects and any natural transform between two objects as arrows. The group G has only one object $x \in G$, thus any functor $T \in \mathbf{Fin}^G$ map x to a finite set $T(x) \in \mathbf{Fin}$, and endomorphisms of x to endomorphisms of $T(x)$. For any arrow a, b in G, $T(b \circ a) = T(b) \circ T(a)$. Also, $\mathrm{id} = T(\mathrm{id}) = T(a \circ a^{-1}) = T(a) \circ T(a^{-1})$. Thus any element in the image of the arrow function of T is invertible. Therefore T is a permutation representation of G.

Now, let $\tau : R \dot{\to} S$ be an arrow in $\mathbf{Fin}^G$. Then, the following diagram commutes for any arrow a in G:

$$\begin{array}{ccc} Rx & \xrightarrow{\tau x} & Sx \\ {\scriptstyle Ra}\downarrow & & \downarrow{\scriptstyle Sa} \\ Rx & \xrightarrow{\tau x} & Sx \end{array}$$

From the diagram, $\hom(R, S) = \{\tau \mid \forall a,\ \tau x \circ Ra = Sa \circ \tau x\}$... what does it mean???? TODO

2.4.6

2.4.7

2.4.8

2.5

2.5.1

$$\begin{tikzcd}
 & * \arrow[dl] \arrow[dr, "h"] & & & * \arrow[dl, "i"'] \arrow[dr] & \\
* & & * & * & & *
\end{tikzcd}$$

$$\begin{tikzcd}
\phi \arrow[r, bend right] & \theta
\end{tikzcd}$$

symbols: A B C F S T

We prove there is a bijection $F : \mathbf{Cat}(A \times B, C) \to \mathbf{Cat}(A, C^B)$.

Let $FT = S$, where $T : A \times B \to C$ and $S : A \to C^B$. First, we make the object function of S. Given $a \in A$, we make a subcategory $A_a \subseteq A$, a category of an object a and an arrow $\mathrm{id}(a)$. There is a functor $f_a : B \to A_a \times B$ such that $f_a(b) = \langle a, b \rangle$ for objects, $f_a(b) = \langle \mathrm{id}(a), b \rangle$ for arrows. Since $A_a \times B \subseteq A \times B$, now we define $Sa : B \to C$ by $Sa = T \circ f_a$. Second, we make the arrow function of S. Let $Sa = \tau$, where $a : a_0 \to a_1$ is an arrow in A, $\tau : Sa_0 \dot{\to} Sa_1$, $\tau b = T\langle a, \mathrm{id}(b) \rangle$. Let $g : b_0 \to b_1$ be an arrow in B. Then $Sa_1 g(\tau b_0(Sa_0 b_0)) = Sa_1 b_1 = \tau b_1(Sa_0 g(Sa_0 b_0))$. Thus τ is natural.

Next, we prove that for all $S : A \to C^B$, there exists $T : A \times B \to C$, such that $FT = S$. First, we prove it for the object function of T. Let $a \in A$, $b \in B$, $T\langle a, b \rangle = Sab$. $FTab = T\langle a, b \rangle$, thus $FT = S$. Second, we prove it for the arrow function. Let there be two arrows a in A and b in B, and $T\langle a, b \rangle = Sa(\mathrm{dom}(b))$. Then $FTab = Sab$, thus $FT = S$.

Finally, we prove that for all $T_0,\ T_1 : A \times B \to C$, if $FT_0 = FT_1$, then $T_0 = T_1$. Let $FT_0 = FT_1$ and $n \in \{0,\ 1\}$. We write $T_=\langle x, y \rangle$ when $T_0\langle x, y \rangle = T_1\langle x, y \rangle$. First, for all $a \in A$, $b \in B$, $FT_n ab = T_n\langle a, b \rangle$. Thus $T_=\langle a, b \rangle$ (object equality). Second, for every object $a \in A$, arrow b in B, $FT_n ab = T_n\langle \mathrm{id}(a), b \rangle$, and, for every arrow a in A, object $b \in B$, $FT_n ab = T_n\langle a, \mathrm{id}(b) \rangle$. Now, let $a : a_0 \to a_1$ be any arrow in A and $b : b_0 \to b_1$ be any arrow in B. $T_=\langle \mathrm{id}(a_0), b \rangle$ and $T_=\langle a, \mathrm{id}(b_1) \rangle$, thus $T_=(\langle \mathrm{id}(a_0), b \rangle \circ \langle a, \mathrm{id}(b_1) \rangle)$. Hence $T_=\langle a, b \rangle$ (arrow equality).

2.5.2

$$\langle Q \smile Q \rangle$$

For any $x \in (A \times B)^C$, there are two functions $G(c) = x(c)_0$ and $H(c) = x(c)_1$. Let the object function be $F(x) = \langle G, H \rangle$, where $F : (A \times B)^C \to A^C \times B^C$.

For any natural transform $\tau : (A \times B) \dot{\to} C$, there are two natural transforms $\tau_0 : A \dot{\to} C$ and $\tau_1 : B \dot{\to} C$. Let $\tau_0(x) =$ and $\tau_1(x) =$.

Thus we can construct the arrow function $F(\tau) = \langle \tau_0, \tau_1 \rangle$.

TODO

2.5.3

2.5.4

2.5.5

2.5.6

2.5.7

2.5.8

2.6

2.6.1

$$(\hat{\ }_{\upsilon}\hat{\ })$$

(seems to be trivial...)

In **CRng**, $f : K \to L$ is a ring homomorphism on K to L. Thus $K \downarrow \mathbf{CRng}$ is the category of all small commutative K-algebra.

2.6.2

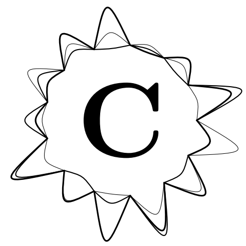
$$\begin{tikzcd} & * \arrow[dl] \arrow[dr, "h"] & \\ * & & * \end{tikzcd} \qquad \begin{tikzcd} & * \arrow[dl, "i"'] \arrow[dr] & \\ * & & * \end{tikzcd}$$

$$\begin{tikzcd} \phi \arrow[loop above] \end{tikzcd}$$

(seems to be trivial...)

We make a functor $F : C \to (C \downarrow t)$. Since t is a terminal object in C, for all object $c \in C$, there is a unique arrow $a_c : c \to t$. We use the arrow-making function a_c as the object function of F. For any objects $c_0, c_1 \in C$, $C(c_0, c_1) = (C \downarrow t)(a_{c_0}, a_{c_1})$. We use the identity as the arrow function. It is trivial that F is a functor. Likewise, a functor $G : (C \downarrow t) \to C$ is established with the inverse of a_c (object function) and the identity (arrow function). Therefore, C is isomorphic to $(C \downarrow t)$.

2.6.3



An alternative diagram for objects:

$$\begin{tikzcd}
 & & t \arrow[dll, mapsto, "t_0"'] \arrow[d, mapsto, "t_2"] \arrow[drr, mapsto, "t_1"] & & \\
e \arrow[r, mapsto, "Te"'] & Te & f \arrow[l, mapsto, "\operatorname{dom} f"] \arrow[r, mapsto, "\operatorname{cod} f"'] & Sd & d \arrow[l, mapsto, "Sd"]
\end{tikzcd}$$

A diagram for arrows:

$$\begin{tikzcd}
 & & \langle k, h\rangle \arrow[dll, mapsto] \arrow[d, mapsto] \arrow[drr, mapsto] & & \\
k \arrow[r, mapsto] & Tk & \langle Tk, Sh\rangle \arrow[l, mapsto] \arrow[r, mapsto] & Sh & h \arrow[l, mapsto]
\end{tikzcd}$$

An alternative diagram for arrows:

$$\begin{tikzcd}
 & & t \arrow[dll, mapsto, "t_0"'] \arrow[d, mapsto, "\langle Tt_0, St_1\rangle"] \arrow[drr, mapsto, "t_1"] & & \\
k \arrow[r, mapsto, "Tk"'] & Tk & t' \arrow[l, mapsto, "t'_0"] \arrow[r, mapsto, "t'_1"'] & Sh & h \arrow[l, mapsto, "Sh"]
\end{tikzcd}$$

2.6.4

$$\begin{tikzcd}
 & * \arrow[dl] \arrow[dr, "h"] & & & * \arrow[dl, "i"'] \arrow[dr] & \\
* & & * & * & & *
\end{tikzcd}$$

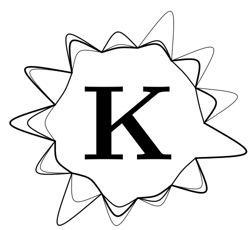
$$\begin{tikzcd}
\phi \arrow[r, bend right] & \theta
\end{tikzcd}$$

Let $T, S : D \to C$ be two functors, $\tau : T \dot{\to} S$ be a natural transform, $\tau' : D \to (T \downarrow S)$ be a functor such that $(\tau_d)_0 = (\tau_d)_1 = d$. Thus the object function maps an object $d \in D$ to $\langle d, d, Td \to Sd \rangle$. Then, for any arrow $g : d \to d'$ in D, $f : Td \to Sd$ and $f' : Td' \to Sd'$ in C, the following diagram commutes:

$$\begin{tikzcd}
Td \arrow[r, "f"] \arrow[d, "Tg"] & Sd \arrow[d, "Sg"] \\
Td' \arrow[r, "f'"] & Sd'
\end{tikzcd}$$

This means that τ' is a natural transform on T to S.

2.6.5



Let E, C, D, X be categories, P, Q, R, P', Q', R', T, S be functors. We prove that if the following diagram commutes, there is a unique functor $L : X \to (T \downarrow S)$ that keeps it commute.

$$\begin{tikzcd}
 & & X \arrow[dll, "P'"'] \arrow[d, "Q'"] \arrow[drr, "R'"] \arrow[dd, dashed, bend right, "L"'] & & \\
E \arrow[r, "T"] & C & C^2 \arrow[l, "C^{d_0}"'] \arrow[r, "C^{d_1}"] & C & D \arrow[l, "S"'] \\
 & & (T \downarrow S) \arrow[ull, "P"] \arrow[u, "Q"'] \arrow[urr, "R"'] & &
\end{tikzcd}$$

For any object $x \in X$, let $e' = P'x$, $d' = R'x$, $f' = Q'x$. Since $TP' = C^{d_0}Q'$ and $SR' = C^{d_1}Q'$, $f' : Te' \to Sd'$. Thus $\langle P'x, R'x, Q'x \rangle \in (T \downarrow S)$.

For any arrow $x : x_0 \to x_1$ in X, $Q'x_1 \circ TP'x = SR'x \circ Q'x_0$. Thus $\langle P'x, R'x \rangle$ is an arrow in $(T \downarrow S)$. (TODO)

Therefore we define the object function by $Lx = \langle P'x, R'x, Q'x \rangle$ and the arrow function by $Lx = \langle P'x, R'x \rangle$. L is a functor, because $L(x) \circ L(y) = \langle P'x, R'x \rangle \circ \langle P'y, R'y \rangle = \langle P'x \circ P'y, R'x \circ R'y \rangle = \langle P'(x \circ y), R'(x \circ y) \rangle = L(x \circ y)$, and $L\ \mathrm{id} = \langle P'\ \mathrm{id}, R'\ \mathrm{id} \rangle = \langle \mathrm{id}, \mathrm{id} \rangle = \mathrm{id}$.

Let $L_0, L_1 : X \to (T \downarrow S)$ be two functors which make the diagram commute. Then $L_0 = L_1$. Indeed, (TODO)

2.6.6

$$\begin{tikzcd} & * \arrow[dl] \arrow[dr, "h"] & \\ * & & * \end{tikzcd} \qquad \begin{tikzcd} & * \arrow[dl, "i"'] \arrow[dr] & \\ * & & * \end{tikzcd}$$

$$\begin{tikzcd} \phi \arrow[loop above] \end{tikzcd}$$

(a) We make a functor $F : (C^E)^{\text{op}} \times (C^D) \to \mathbf{Cat}$ with the object function $\langle T, S\rangle \mapsto (T \downarrow S)$. The arrow function of F takes $\tau : T_1 \dot{\to} T_0$ and $\sigma : S_0 \dot{\to} S_1$ as arguments, where $T_0, T_1 \in C^E$ and $S_0, S_1 \in C^D$. F returns a functor $G : (T_0 \downarrow S_0) \to (T_1 \downarrow S_1)$. We define G by the object function $G\langle e, d, f\rangle = \langle e, d, \sigma d \circ f \circ \tau e\rangle$ and the arrow function $G\langle k, h\rangle = \langle k, h\rangle$.

Then for any pair of arrows $\upsilon_0 = \langle \tau_0 : T_1 \to T_0,\ \sigma_0 : S_0 \to S_1\rangle$ and $\upsilon_1 = \langle \tau_1 : T_2 \to T_1,\ \sigma_1 : S_1 \to S_2\rangle$ in $(C^E)^{\text{op}} \times (C^D)$, the object function $(F(\upsilon_1) \circ F(\upsilon_0))\langle e, d, f\rangle = \langle e, d, \sigma_1 d \circ \sigma_0 d \circ f \circ \tau_0 e \circ \tau_1 e\rangle = \langle e, d, (\sigma_1 \circ \sigma_0) d \circ f \circ (\tau_0 \circ \tau_1) e\rangle = (F(\upsilon_1 \circ \upsilon_0))\langle e, d, f\rangle$. In picture,

$$\begin{tikzcd} T_0 e \arrow[r, "f"] & S_0 d \arrow[d, "\sigma_0 d"] \\ T_1 e \arrow[u, "\tau_0 e"] & S_1 e \arrow[d, "\sigma_1 d"] \\ T_2 e \arrow[u, "\tau_1 e"] & S_2 e \end{tikzcd}$$

And the arrow function $F(\upsilon_1) \circ F(\upsilon_0) = F(\upsilon_1 \circ \upsilon_0)$ is trivial. Thus there is a functor F with the object function $\langle T, S\rangle \mapsto (T \downarrow S)$.

(b) TODO come back later ...

2.7

2.7.1

$$\langle \wedge \_ \wedge \rangle$$

Opposites. Let G, G^{op} be a graph of the set of objects O, O and the set of arrows A, A^{op}, respectively. Make the opposite G^{op} as follows. Map a object $o \in O$ to $o^{\text{op}} = o$ and an arrow f in G to $f^{\text{op}} : \text{cod} f \to \text{dom} f$ in one-to-one correspondence.

Then, $U(C^{\text{op}}) \cong (UC)^{\text{op}}$ for any category C. Indeed, for any objects $a, b \in C$, $|C_{a,b}| = |(C^{\text{op}})_{a,b}|$, $(C^{\text{op}})_{a,b} = (U(C^{\text{op}}))_{a,b}$, $C_{a,b} = (UC)_{a,b}$, $|(UC)_{a,b}| =$

$|((UC)^{\mathrm{op}})_{a,b}|$, where $X_{a,b}$ denotes the set of all arrows on a to b in X. Thus $|(U(C^{\mathrm{op}}))_{a,b}| = |((UC)^{\mathrm{op}})_{a,b}|$. Since the object mappings of op and U are both identities, $U(C^{\mathrm{op}}) \cong (UC)^{\mathrm{op}}$. In picture,

$$\begin{tikzcd}
C_{a,b} \arrow[r, "\mathrm{op}", "\cong"'] \arrow[dr, "U", "="'] & (C^{\mathrm{op}})_{a,b} \arrow[r, "U", "="'] & (U(C^{\mathrm{op}}))_{a,b} \\
& (UC)_{a,b} \arrow[r, "\mathrm{op}", "\cong"'] & ((UC)^{\mathrm{op}})_{a,b}
\end{tikzcd}$$

where $\cong$ denotes that the cardinality of two sets are equal (i.e. there is a bijection between them).

Products. TODO

2.7.2

$$\langle Q \perp Q \rangle$$

(seems to be trivial...)

For a finite ordinal number n, let G_n be a graph with the objects n, the arrows $a_k : k \to k+1$ for each $k < n-1$ (no arrow when $n = 0, 1$). Let C be the free category generated by G. Let $\mathbf{n}$ be a preorder category of the number n, which consists of the objects n and the arrows $b_k : k \to k+1$ for each $k < n-1$ and all of their composite arrows. Since C has the arrows of G, all its composable arrows, and the same objects as C, we can say $C \cong \mathbf{n}$.

2.7.3

$$\begin{tikzcd}
& * \arrow[dl] \arrow[dr, "h"] & & & * \arrow[dl, "i"'] \arrow[dr] & \\
* & & * & * & & *
\end{tikzcd}$$

$$\phi \longrightarrow \theta$$

We make a free groupoid F from a graph G as follows. Map every object $o \in G$ to $o \in F$. For each arrow $a : a_0 \to a_1$ in G, map a to the two arrows in F, a and $a^{-1} : a_1 \to a_0$ such that $a \circ a^{-1} = \mathrm{id}$, $a^{-1} \circ a = \mathrm{id}$. Then add all composable arrows (i.e. paths) in F to F. We call the mapping $P' : \mathbf{Grph} \to \mathbf{Grpd}$, where $\mathbf{Grpd}$ is the set of all groupoids.

$P = U \circ P'$ satisfies the following universal property: given any groupoid E and graph morphism D, there is a unique functor D' that makes the diagram commute.

$$
\begin{tikzcd}
F \arrow[d, dashed, "D'"] \\
E
\end{tikzcd}
\qquad
\begin{tikzcd}
G \arrow[r, "P"] \arrow[dr, "D"'] & UF \arrow[d, dashed, "UD'"] \\
& UE
\end{tikzcd}
$$

Indeed,

2.8

3

4

5

6

7

8

9

10

11

12