Constructions With Relations

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00NE This chapter contains some material about constructions with relations. Notably, we discuss and explore:

029U 1. The existence or non-existence of Kan extensions and Kan lifts in the 2-category **Rel** (??).

029V 2. The various kinds of constructions involving relations, such as graphs, domains, ranges, unions, intersections, products, converse relations, composition of relations, and collages (Section 9.2).

This chapter is under revision. TODO:

1. Rename range to image

2. Co/limits in **Rel**.

Contents

00NF 9.1 Co/Limits in the Category of Relations

This section is currently just a stub, and will be properly developed later on.

00NZ 9.2 More Constructions With Relations

00PM 9.2.1 The Domain and Range of a Relation

Let A and B be sets.

00PN **Definition 9.2.1.1.1.** Let $R\colon A \nrightarrow B$ be a relation.[1,2]

02AV 1. The **domain of** R is the subset $\mathrm{dom}(R)$ of A defined by

$$\mathrm{dom}(R) \stackrel{\text{def}}{=} \left\{ a \in A \,\middle|\, \begin{array}{l} \text{there exists some } b \in B \\ \text{such that } a \sim_R b \end{array} \right\}.$$

[1]Following ??, ??, we may compute the (characteristic functions associated to the) domain and range of a relation using the following colimit formulas:

$$\begin{aligned} \chi_{\mathrm{dom}(R)}(a) &\cong \operatorname*{colim}_{b \in B}\left(R^b_a\right) \qquad (a \in A) \\ &\cong \bigvee_{b \in B} R^b_a, \\ \chi_{\mathrm{range}(R)}(b) &\cong \operatorname*{colim}_{a \in A}\left(R^b_a\right) \qquad (b \in B) \\ &\cong \bigvee_{a \in A} R^b_a, \end{aligned}$$

where the join $\bigvee$ is taken in the poset $(\{\mathsf{true}, \mathsf{false}\}, \preceq)$ of Constructions With Sets, Definition 3.2.2.1.3.

[2]Viewing R as a function $R\colon A \to \mathcal{P}(B)$, we have

$$\begin{aligned} \mathrm{dom}(R) &\cong \operatorname*{colim}_{y \in Y}(R(y)) \\ &\cong \bigcup_{y \in Y} R(y), \\ \mathrm{range}(R) &\cong \operatorname*{colim}_{x \in X}(R(x)) \\ &\cong \bigcup_{x \in X} R(x), \end{aligned}$$

02AW 2. The **range of** R is the subset $\mathrm{range}(R)$ of B defined by

$$\mathrm{range}(R) \stackrel{\mathrm{def}}{=} \left\{ b \in B \;\middle|\; \begin{array}{l} \text{there exists some } a \in A \\ \text{such that } a \sim_R b \end{array} \right\}.$$

00PP 9.2.2 Binary Unions of Relations

Let A and B be sets and let R and S be relations from A to B.

00PQ **Definition 9.2.2.1.1.** The **union of** R **and** S[3] is the relation $R \cup S$ from A to B defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define[4]

  $$R \cup S \stackrel{\mathrm{def}}{=} \{(a, b) \in B \times A \mid \text{we have } a \sim_R b \text{ or } a \sim_S b\}.$$

- Viewing relations from A to B as functions $A \to \mathcal{P}(B)$, we define

  $$[R \cup S](a) \stackrel{\mathrm{def}}{=} R(a) \cup S(a)$$

  for each $a \in A$.

00PR **Proposition 9.2.2.1.2.** Let R, S, R_1, and R_2 be relations from A to B, and let S_1 and S_2 be relations from B to C.

00PS 1. *Interaction With Converses.* We have

$$(R \cup S)^{\dagger} = R^{\dagger} \cup S^{\dagger}.$$

00PT 2. *Interaction With Composition.* We have

$$(S_1 \diamond R_1) \cup (S_2 \diamond R_2) \stackrel{\text{poss.}}{\neq} (S_1 \cup S_2) \diamond (R_1 \cup R_2).$$

Proof. *Item 1, Interaction With Converses*: Clear.
Item 2, Interaction With Composition: Unwinding the definitions, we see that:

- The condition for $(S_1 \diamond R_1) \cup (S_2 \diamond R_2)$ is:
  - There exists some $b \in B$ such that:

[3] *Further Terminology:* Also called the **binary union of** R **and** S, for emphasis.
[4] This is the same as the union of R and S as subsets of $A \times B$.

* $a \sim_{R_1} b$ and $b \sim_{S_1} c$;

or

* $a \sim_{R_2} b$ and $b \sim_{S_2} c$;

- The condition for $(S_1 \cup S_2) \diamond (R_1 \cup R_2)$ is:
  - There exists some $b \in B$ such that:
    * $a \sim_{R_1} b$ or $a \sim_{R_2} b$;

    and

    * $b \sim_{S_1} c$ or $b \sim_{S_2} c$.

These two conditions may fail to agree (counterexample omitted), and thus the two resulting relations on $A \times C$ may differ. □

00PU 9.2.3 Unions of Families of Relations

Let A and B be sets and let $\{R_i\}_{i \in I}$ be a family of relations from A to B.

00PV **Definition 9.2.3.1.1.** The **union of the family** $\{R_i\}_{i \in I}$ is the relation $\bigcup_{i \in I} R_i$ from A to B defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define[5]

$$\bigcup_{i \in I} R_i \stackrel{\text{def}}{=} \left\{ (a, b) \in (A \times B)^{\times I} \;\middle|\; \begin{array}{l} \text{there exists some } i \in I \\ \text{such that } a \sim_{R_i} b \end{array} \right\}.$$

- Viewing relations from A to B as functions $A \to \mathcal{P}(B)$, we define

$$\left[\bigcup_{i \in I} R_i \right](a) \stackrel{\text{def}}{=} \bigcup_{i \in I} R_i(a)$$

  for each $a \in A$.

00PW **Proposition 9.2.3.1.2.** Let A and B be sets and let $\{R_i\}_{i \in I}$ be a family of relations from A to B.

00PX 1. *Interaction With Converses.* We have

$$\left(\bigcup_{i \in I} R_i \right)^{\dagger} = \bigcup_{i \in I} R_i^{\dagger}.$$

Proof. *Item 1, Interaction With Converses*: Clear. □

[5] This is the same as the union of $\{R_i\}_{i \in I}$ as a collection of subsets of $A \times B$.

00PY 9.2.4 Binary Intersections of Relations

Let A and B be sets and let R and S be relations from A to B.

00PZ **Definition 9.2.4.1.1.** The **intersection of** R **and** S[6] is the relation $R \cap S$ from A to B defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define[7]

$$R \cap S \stackrel{\text{def}}{=} \{(a, b) \in B \times A \mid \text{we have } a \sim_R b \text{ and } a \sim_S b\}.$$

- Viewing relations from A to B as functions $A \to \mathcal{P}(B)$, we define

$$[R \cap S](a) \stackrel{\text{def}}{=} R(a) \cap S(a)$$

  for each $a \in A$.

00Q0 **Proposition 9.2.4.1.2.** Let R, S, R_1, and R_2 be relations from A to B, and let S_1 and S_2 be relations from B to C.

00Q1 1. *Interaction With Converses.* We have

$$(R \cap S)^{\dagger} = R^{\dagger} \cap S^{\dagger}.$$

00Q2 2. *Interaction With Composition.* We have

$$(S_1 \diamond R_1) \cap (S_2 \diamond R_2) = (S_1 \cap S_2) \diamond (R_1 \cap R_2).$$

Proof. *Item 1, Interaction With Converses*: Clear.
Item 2, Interaction With Composition: Unwinding the definitions, we see that:

- The condition for $(S_1 \diamond R_1) \cap (S_2 \diamond R_2)$ is:
  - There exists some $b \in B$ such that:
    - $a \sim_{R_1} b$ and $b \sim_{S_1} c$;

    and

    - $a \sim_{R_2} b$ and $b \sim_{S_2} c$;

[6] *Further Terminology:* Also called the **binary intersection of** R **and** S, for emphasis.
[7] This is the same as the intersection of R and S as subsets of $A \times B$.

- The condition for $(S_1 \cap S_2) \diamond (R_1 \cap R_2)$ is:
  - There exists some $b \in B$ such that:
    - $a \sim_{R_1} b$ and $a \sim_{R_2} b$;

    and
    - $b \sim_{S_1} c$ and $b \sim_{S_2} c$.

These two conditions agree, and thus so do the two resulting relations on $A \times C$. □

00Q3 9.2.5 Intersections of Families of Relations

Let A and B be sets and let $\{R_i\}_{i\in I}$ be a family of relations from A to B.

00Q4 **Definition 9.2.5.1.1.** The **intersection of the family** $\{R_i\}_{i\in I}$ is the relation $\bigcup_{i\in I} R_i$ defined as follows:

- Viewing relations from A to B as subsets of $A \times B$, we define[8]

$$\bigcup_{i\in I} R_i \overset{\mathrm{def}}{=} \left\{ (a,b) \in (A \times B)^{\times I} \;\middle|\; \begin{array}{l} \text{for each } i \in I, \\ \text{we have } a \sim_{R_i} b \end{array} \right\}.$$

- Viewing relations from A to B as functions $A \to \mathcal{P}(B)$, we define

$$\left[\bigcap_{i\in I} R_i\right](a) \overset{\mathrm{def}}{=} \bigcap_{i\in I} R_i(a)$$

  for each $a \in A$.

00Q5 **Proposition 9.2.5.1.2.** Let A and B be sets and let $\{R_i\}_{i\in I}$ be a family of relations from A to B.

00Q6 1. *Interaction With Converses.* We have

$$\left(\bigcap_{i\in I} R_i\right)^{\dagger} = \bigcap_{i\in I} R_i^{\dagger}.$$

Proof. *Item 1, Interaction With Converses*: Clear. □

[8] This is the same as the intersection of $\{R_i\}_{i\in I}$ as a collection of subsets of $A \times B$.

00Q7 9.2.6 Binary Products of Relations

Let A, B, X, and Y be sets, let $R\colon A \nrightarrow B$ be a relation from A to B, and let $S\colon X \nrightarrow Y$ be a relation from X to Y.

00Q8 **Definition 9.2.6.1.1.** The **product of** R **and** S[9] is the relation $R \times S$ from $A \times X$ to $B \times Y$ defined as follows:

- Viewing relations from $A \times X$ to $B \times Y$ as subsets of $(A \times X) \times (B \times Y)$, we define $R \times S$ as the Cartesian product of R and S as subsets of $A \times X$ and $B \times Y$.[10]
- Viewing relations from $A \times X$ to $B \times Y$ as functions $A \times X \to \mathcal{P}(B \times Y)$, we define $R \times S$ as the composition

  $$A \times X \xrightarrow{R \times S} \mathcal{P}(B) \times \mathcal{P}(Y) \overset{\mathcal{P}^{\otimes}_{B,Y}}{\hookrightarrow} \mathcal{P}(B \times Y)$$

  in Sets, i.e. by

  $$[R \times S](a, x) \overset{\text{def}}{=} R(a) \times S(x)$$

  for each $(a, x) \in A \times X$.

00Q9 **Proposition 9.2.6.1.2.** Let A, B, X, and Y be sets.

00QA 1. *Interaction With Converses.* Let

$$\begin{aligned} R&\colon A \nrightarrow A,\\ S&\colon X \nrightarrow X \end{aligned}$$

We have

$$(R \times S)^{\dagger} = R^{\dagger} \times S^{\dagger}.$$

00QB 2. *Interaction With Composition.* Let

$$\begin{aligned} R_1&\colon A \nrightarrow B,\\ S_1&\colon B \nrightarrow C,\\ R_2&\colon X \nrightarrow Y,\\ S_2&\colon Y \nrightarrow Z \end{aligned}$$

be relations. We have

$$(S_1 \diamond R_1) \times (S_2 \diamond R_2) = (S_1 \times S_2) \diamond (R_1 \times R_2).$$

[9] *Further Terminology:* Also called the **binary product of** R **and** S, for emphasis.

[10] That is, $R \times S$ is the relation given by declaring $(a, x) \sim_{R \times S} (b, y)$ iff $a \sim_R b$ and

Proof. *Item 1, Interaction With Converses*: Unwinding the definitions, we see that:

- We have $(a,x) \sim_{(R\times S)^{\dagger}} (b,y)$ iff:
  - We have $(b,y) \sim_{R\times S} (a,x)$, i.e. iff:
    - We have $b \sim_R a$;
    - We have $y \sim_S x$;
- We have $(a,x) \sim_{R^{\dagger}\times S^{\dagger}} (b,y)$ iff:
  - We have $a \sim_{R^{\dagger}} b$ and $x \sim_{S^{\dagger}} y$, i.e. iff:
    - We have $b \sim_R a$;
    - We have $y \sim_S x$.

These two conditions agree, and thus the two resulting relations on $A \times X$ are equal.
Item 2, Interaction With Composition: Unwinding the definitions, we see that:

- We have $(a,x) \sim_{(S_1\diamond R_1)\times(S_2\diamond R_2)} (c,z)$ iff:
  - We have $a \sim_{S_1\diamond R_1} c$ and $x \sim_{S_2\diamond R_2} z$, i.e. iff:
    - There exists some $b \in B$ such that $a \sim_{R_1} b$ and $b \sim_{S_1} c$;
    - There exists some $y \in Y$ such that $x \sim_{R_2} y$ and $y \sim_{S_2} z$;
- We have $(a,x) \sim_{(S_1\times S_2)\diamond(R_1\times R_2)} (c,z)$ iff:
  - There exists some $(b,y) \in B \times Y$ such that $(a,x) \sim_{R_1\times R_2} (b,y)$ and $(b,y) \sim_{S_1\times S_2} (c,z)$, i.e. such that:
    - We have $a \sim_{R_1} b$ and $x \sim_{R_2} y$;
    - We have $b \sim_{S_1} c$ and $y \sim_{S_2} z$.

These two conditions agree, and thus the two resulting relations from $A \times X$ to $C \times Z$ are equal. □

$x \sim_S y$.

00QC 9.2.7 Products of Families of Relations

Let $\{A_i\}_{i\in I}$ and $\{B_i\}_{i\in I}$ be families of sets, and let $\{R_i\colon A_i \nrightarrow B_i\}_{i\in I}$ be a family of relations.

00QD **Definition 9.2.7.1.1.** The **product of the family** $\{R_i\}_{i\in I}$ is the relation $\prod_{i\in I} R_i$ from $\prod_{i\in I} A_i$ to $\prod_{i\in I} B_i$ defined as follows:

- Viewing relations as subsets, we define $\prod_{i\in I} R_i$ as its product as a family of sets, i.e. we have

$$\prod_{i\in I} R_i \overset{\text{def}}{=} \left\{ (a_i, b_i)_{i\in I} \in \prod_{i\in I}(A_i \times B_i) \;\middle|\; \begin{array}{l}\text{for each } i \in I,\\ \text{we have } a_i \sim_{R_i} b_i\end{array} \right\}.$$

- Viewing relations as functions to powersets, we define

$$\left[\prod_{i\in I} R_i\right]\left((a_i)_{i\in I}\right) \overset{\text{def}}{=} \prod_{i\in I} R_i(a_i)$$

  for each $(a_i)_{i\in I} \in \prod_{i\in I} R_i$.

00R2 9.2.8 The Collage of a Relation

Let A and B be sets and let $R\colon A \nrightarrow B$ be a relation from A to B.

00R3 **Definition 9.2.8.1.1.** The **collage of** R[11] is the poset $\mathbf{Coll}(R) \overset{\text{def}}{=} \left(\mathrm{Coll}(R), \preceq_{\mathbf{Coll}(R)}\right)$ consisting of:

- *The Underlying Set.* The set $\mathrm{Coll}(R)$ defined by

$$\mathrm{Coll}(R) \overset{\text{def}}{=} A \coprod B.$$

- *The Partial Order.* The partial order

$$\preceq_{\mathbf{Coll}(R)}\colon \mathrm{Coll}(R) \times \mathrm{Coll}(R) \to \{\mathsf{true}, \mathsf{false}\}$$

  on $\mathrm{Coll}(R)$ defined by

$$\preceq(a, b) \overset{\text{def}}{=} \begin{cases} \mathsf{true} & \text{if } a = b \text{ or } a \sim_R b,\\ \mathsf{false} & \text{otherwise.}\end{cases}$$

[11] *Further Terminology:* Also called the **cograph of** R.

02AZ **Notation 9.2.8.1.2.** We write $\mathsf{Pos}_{/\Delta^1}(A,B)$ for the category defined as the pullback

$$\mathsf{Pos}_{/\Delta^1}(A,B) \stackrel{\text{def}}{=} \mathsf{pt} \underset{[A],\mathsf{Pos},\mathrm{ev}_0}{\times} \mathsf{Pos}_{/\Delta^1} \underset{\mathrm{ev}_1,\mathsf{Pos},[B]}{\times} \mathsf{pt},$$

as in the diagram

$$\begin{tikzcd}
 & & \mathbf{Pos}_{/\Delta^1}(A,B) \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner"{rotate=-45}, very near start] & & \\
 & \mathbf{Pos}_{/\Delta^1} \underset{\mathbf{Pos}}{\times} \mathsf{pt} \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner"{rotate=-45}, very near start] & & \mathsf{pt} \underset{\mathbf{Pos}}{\times} \mathbf{Pos}_{/\Delta^1} \arrow[dl] \arrow[dr] \arrow[dd, phantom, "\lrcorner"{rotate=-45}, very near start] & \\
\mathsf{pt} \arrow[dr, "{[A]}"'] & & \mathbf{Pos}_{/\Delta^1} \arrow[dl, "\mathrm{ev}_{[0]}"] \arrow[dr, "\mathrm{ev}_{[1]}"'] & & \mathsf{pt}. \arrow[dl, "{[B]}"] \\
 & \mathbf{Pos} & & \mathbf{Pos} &
\end{tikzcd}$$

02B0 **Remark 9.2.8.1.3.** In detail, $\mathsf{Pos}_{/\Delta^1}(A,B)$ is the category where:

- *Objects.* An object of $\mathsf{Pos}_{/\Delta^1}(A,B)$ is a pair (X,ϕ_X) consisting of
  - A poset X;
  - A morphism $\phi_X \colon X \to \Delta^1$;

  such that we have

  $$\begin{aligned}\phi_X^{-1}(0) &= A,\\ \phi_X^{-1}(1) &= B.\end{aligned}$$

- *Morphisms.* A morphism of $\mathsf{Pos}_{/\Delta^1}(A,B)$ from (X,ϕ_X) to (Y,ϕ_Y) is a morphism of posets $f \colon X \to Y$ making the diagram

  $$\begin{tikzcd}
  X \arrow[rr, "f"] \arrow[dr, "\phi_X"'] & & Y \arrow[dl, "\phi_Y"] \\
  & \Delta^1 &
  \end{tikzcd}$$

  commute.

00R4 **Proposition 9.2.8.1.4.** Let A and B be sets and let $R \colon A \nrightarrow B$ be a relation from A to B.

00R5 1. *Functoriality.* The assignment $R \mapsto \mathbf{Coll}(R)$ defines a functor

$$\mathbf{Coll}\colon \mathbf{Rel}(A,B) \to \mathsf{Pos}_{/\Delta^1}(A,B),$$

where

- *Action on Objects.* For each $R \in \mathrm{Obj}(\mathbf{Rel}(A,B))$, we have

  $$[\mathbf{Coll}](R) \overset{\text{def}}{=} (\mathbf{Coll}(R), \phi_R)$$

  for each $R \in \mathbf{Rel}(A,B)$, where
  - The poset $\mathbf{Coll}(R)$ is the collage of R of Definition 9.2.8.1.1.
  - The morphism $\phi_R\colon \mathbf{Coll}(R) \to \Delta^1$ is given by

    $$\phi_R(x) \overset{\text{def}}{=} \begin{cases} 0 & \text{if } x \in A, \\ 1 & \text{if } x \in B \end{cases}$$

    for each $x \in \mathbf{Coll}(R)$.
- *Action on Morphisms.* For each $R, S \in \mathrm{Obj}(\mathbf{Rel}(A,B))$, the action on Hom-sets

  $$\mathbf{Coll}_{R,S}\colon \mathrm{Hom}_{\mathbf{Rel}(A,B)}(R,S) \to \mathsf{Pos}(\mathbf{Coll}(R), \mathbf{Coll}(S))$$

  of $\mathbf{Coll}$ at (R,S) is given by sending an inclusion

  $$\iota\colon R \subset S$$

  to the morphism

  $$\mathbf{Coll}(\iota)\colon \mathbf{Coll}(R) \to \mathbf{Coll}(S)$$

  of posets over Δ^1 defined by

  $$[\mathbf{Coll}(\iota)](x) \overset{\text{def}}{=} x$$

  for each $x \in \mathbf{Coll}(R)$.[12]

00R6 2. *Equivalence.* The functor of Item 1 is an equivalence of categories.

Proof. *Item 1, Functoriality*: Clear.
Item 2, Equivalence: Omitted. □

Appendices

[12]Note that this is indeed a morphism of posets: if $x \preceq_{\mathbf{Coll}(R)} y$, then $x = y$ or $x \sim_R y$,

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so we have either $x = y$ or $x \sim_S y$ (as $R \subset S$), and thus $x \preceq_{\mathbf{Coll}(S)} y$.