Conditions on Relations

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00TJ This chapter contains some material about reflexive, symmetric, transitive, equivalence, and apartness relations.

Contents

00TK 1 Reflexive Relations

00TL 1.1 Foundations

Let A be a set.

00TM **Definition 1.1.1 ► Reflexive Relations**

A **reflexive relation** is equivalently:[1]

- An $\mathbb{E}_0$-monoid in $\left(\mathrm{N}_\bullet(\mathbf{Rel}(A,A)),\chi_A\right)$.
- A pointed object in $\left(\mathbf{Rel}(A,A),\chi_A\right)$.

[1]Note that since $\mathbf{Rel}(A,A)$ is posetal, reflexivity is a property of a relation, rather than extra structure.

00TN **Remark 1.1.2 ► Unwinding Definition 1.1.1**

In detail, a relation R on A is **reflexive** if we have an inclusion

$$\eta_R\colon \chi_A \subset R$$

of relations in $\mathbf{Rel}(A,A)$, i.e. if, for each $a\in A$, we have $a\sim_R a$.

00TP **Definition 1.1.3 ► The Po/Set of Reflexive Relations on a Set**

Let A be a set.

00TQ 1. The **set of reflexive relations on** A is the subset $\mathrm{Rel}^{\mathsf{refl}}(A,A)$ of $\mathrm{Rel}(A,A)$ spanned by the reflexive relations.

00TR 2. The **poset of relations on** A is is the subposet $\mathbf{Rel}^{\mathsf{refl}}(A,A)$ of $\mathbf{Rel}(A,A)$ spanned by the reflexive relations.

00TS **Proposition 1.1.4 ► Properties of Reflexive Relations**

Let R and S be relations on A.

00TT 1. *Interaction With Inverses.* If R is reflexive, then so is $R^\dagger$.

00TU 2. *Interaction With Composition.* If R and S are reflexive, then so is $S \diamond R$.

Proof 1.1.5 ▶ Proof of Proposition 1.1.4

Item 1: Interaction With Inverses

Clear.

Item 2: Interaction With Composition

Clear. □./../../pictures/trans-

00TV 1.2 The Reflexive Closure of a Relation

Let R be a relation on A.

00TW **Definition 1.2.1 ▶ The Reflexive Closure of a Relation**

The **reflexive closure** of $\sim_R$ is the relation $\sim_R^{\mathrm{refl}}$[1] satisfying the following universal property:[2]

(★) Given another reflexive relation $\sim_S$ on A such that $R \subset S$, there exists an inclusion $\sim_R^{\mathrm{refl}} \subset \sim_S$.

[1] *Further Notation:* Also written R^{refl}.

[2] *Slogan:* The reflexive closure of R is the smallest reflexive relation containing R.

00TX **Construction 1.2.2 ▶ The Reflexive Closure of a Relation**

Concretely, $\sim_R^{\mathrm{refl}}$ is the free pointed object on R in $(\mathbf{Rel}(A, A), \chi_A)$[1], being given by

$$\begin{aligned} R^{\mathrm{refl}} &\stackrel{\mathrm{def}}{=} R \coprod^{\mathbf{Rel}(A,A)} \Delta_A \\ &= R \cup \Delta_A \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } a = b\}. \end{aligned}$$

[1] Or, equivalently, the free $\mathbb{E}_0$-monoid on R in $(\mathsf{N}_\bullet(\mathbf{Rel}(A, A)), \chi_A)$.

Proof 1.2.3 ▶ Proof of Construction 1.2.2

Clear. □./../../pictures/trans-

00TY **Proposition 1.2.4 ▶ Properties of the Reflexive Closure of a Relation**

Let R be a relation on A.

00TZ 1. *Adjointness.* We have an adjunction

$$\left((-)^{\mathrm{refl}} \dashv 忘\right)\colon\quad \begin{tikzcd} \mathbf{Rel}(A,A) \arrow[r, bend left, "(-)^{\mathrm{refl}}"] \arrow[r, phantom, "\perp"] & \mathbf{Rel}^{\mathrm{refl}}(A,A), \arrow[l, bend left, "忘"] \end{tikzcd}$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\mathrm{refl}}\left(R^{\mathrm{refl}}, S\right) \cong \mathbf{Rel}(R,S),$$

natural in $R \in \mathrm{Obj}\left(\mathbf{Rel}^{\mathrm{refl}}(A,A)\right)$ and $S \in \mathrm{Obj}(\mathbf{Rel}(A,A))$.

00U0 2. *The Reflexive Closure of a Reflexive Relation.* If R is reflexive, then $R^{\mathrm{refl}} = R$.

00U1 3. *Idempotency.* We have

$$\left(R^{\mathrm{refl}}\right)^{\mathrm{refl}} = R^{\mathrm{refl}}.$$

00U2 4. *Interaction With Inverses.* We have

$$\left(R^{\dagger}\right)^{\mathrm{refl}} = \left(R^{\mathrm{refl}}\right)^{\dagger}, \qquad \begin{tikzcd} \mathrm{Rel}(A,A) \arrow[r, "(-)^{\mathrm{refl}}"] \arrow[d, "(-)^{\dagger}"'] & \mathrm{Rel}(A,A) \arrow[d, "(-)^{\dagger}"] \\ \mathrm{Rel}(A,A) \arrow[r, "(-)^{\mathrm{refl}}"'] & \mathrm{Rel}(A,A). \end{tikzcd}$$

00U3 5. *Interaction With Composition.* We have

$$(S \diamond R)^{\mathrm{refl}} = S^{\mathrm{refl}} \diamond R^{\mathrm{refl}}, \qquad \begin{tikzcd} \mathrm{Rel}(A,A) \times \mathrm{Rel}(A,A) \arrow[r, "\diamond"] \arrow[d, "(-)^{\mathrm{refl}} \times (-)^{\mathrm{refl}}"'] & \mathrm{Rel}(A,A) \arrow[d, "(-)^{\mathrm{refl}}"] \\ \mathrm{Rel}(A,A) \times \mathrm{Rel}(A,A) \arrow[r, "\diamond"'] & \mathrm{Rel}(A,A). \end{tikzcd}$$

Proof 1.2.5 ▶ Proof of Proposition 1.2.4

Item 1: Adjointness

This is a rephrasing of the universal property of the reflexive closure of a relation, stated in Definition 1.2.1.

Item 2: The Reflexive Closure of a Reflexive Relation

Clear.

Item 3: Idempotency

This follows from Item 2.

Item 4: Interaction With Inverses

Clear.

Item 5: Interaction With Composition

This follows from Item 2 of Proposition 1.1.4. □./../../pictures/trans-

00U4 2 Symmetric Relations

00U5 2.1 Foundations

Let A be a set.

00U6 **Definition 2.1.1 ▶ Symmetric Relations**

A relation R on A is **symmetric** if we have $R^{\dagger} = R$.

00U7 **Remark 2.1.2 ▶ Unwinding Definition 2.1.1**

In detail, a relation R is symmetric if it satisfies the following condition:

($\star$) For each $a, b \in A$, if $a \sim_R b$, then $b \sim_R a$.

00U8 **Definition 2.1.3 ▶ The Po/Set of Symmetric Relations on a Set**

Let A be a set.

00U9 1. The **set of symmetric relations on** A is the subset $\mathrm{Rel}^{\mathsf{symm}}(A, A)$ of $\mathrm{Rel}(A, A)$ spanned by the symmetric relations.

00UA 2. The **poset of relations on** A is is the subposet $\mathbf{Rel}^{\mathsf{symm}}(A, A)$ of $\mathbf{Rel}(A, A)$ spanned by the symmetric relations.

00UB **Proposition 2.1.4 ▶ Properties of Symmetric Relations**

Let R and S be relations on A.

00UC 1. *Interaction With Inverses.* If R is symmetric, then so is $R^{\dagger}$.

00UD 2. *Interaction With Composition.* If R and S are symmetric, then so is $S \diamond R$.

Proof 2.1.5 ▶ Proof of Proposition 2.1.4

Item 1: Interaction With Inverses

Clear.

Item 2: Interaction With Composition

Clear. □ ./../../pictures/trans-

00UE 2.2 The Symmetric Closure of a Relation

Let R be a relation on A.

00UF **Definition 2.2.1 ► The Symmetric Closure of a Relation**

The **symmetric closure** of $\sim_R$ is the relation $\sim_R^{\mathrm{symm}}$[1] satisfying the following universal property:[2]

(★) Given another symmetric relation $\sim_S$ on A such that $R \subset S$, there exists an inclusion $\sim_R^{\mathrm{symm}} \subset \sim_S$.

[1] *Further Notation:* Also written R^{symm}.

[2] *Slogan:* The symmetric closure of R is the smallest symmetric relation containing R.

00UG **Construction 2.2.2 ► The Symmetric Closure of a Relation**

Concretely, $\sim_R^{\mathrm{symm}}$ is the symmetric relation on A defined by

$$\begin{aligned} R^{\mathrm{symm}} &\overset{\mathrm{def}}{=} R \cup R^{\dagger} \\ &= \{(a, b) \in A \times A \mid \text{we have } a \sim_R b \text{ or } b \sim_R a\}. \end{aligned}$$

Proof 2.2.3 ► Proof of Construction 2.2.2

Clear. □./../../pictures/trans-

00UH **Proposition 2.2.4 ► Properties of the Symmetric Closure of a Relation**

Let R be a relation on A.

00UJ 1. *Adjointness.* We have an adjunction

$$\left((-)^{\mathrm{symm}} \dashv 忘\right)\colon\quad \begin{tikzcd} \mathbf{Rel}(A, A) \arrow[r, bend left, "(-)^{\mathrm{symm}}"] \arrow[r, phantom, "\perp"] & \mathbf{Rel}^{\mathrm{symm}}(A, A), \arrow[l, bend left, "忘"] \end{tikzcd}$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\mathrm{symm}}(R^{\mathrm{symm}}, S) \cong \mathbf{Rel}(R, S),$$

natural in $R \in \mathrm{Obj}(\mathbf{Rel}^{\mathrm{symm}}(A, A))$ and $S \in \mathrm{Obj}(\mathbf{Rel}(A, A))$.

00UK 2. *The Symmetric Closure of a Symmetric Relation.* If R is symmetric, then $R^{\mathrm{symm}} = R$.

00UL 3. *Idempotency.* We have

$$(R^{\mathrm{symm}})^{\mathrm{symm}} = R^{\mathrm{symm}}.$$

00UM 4. *Interaction With Inverses.* We have

$$\left(R^{\dagger}\right)^{\mathrm{symm}} = \left(R^{\mathrm{symm}}\right)^{\dagger}, \qquad \begin{tikzcd} \mathrm{Rel}(A,A) \arrow[r, "(-)^{\mathrm{symm}}"] \arrow[d, "(-)^{\dagger}"'] & \mathrm{Rel}(A,A) \arrow[d, "(-)^{\dagger}"] \\ \mathrm{Rel}(A,A) \arrow[r, "(-)^{\mathrm{symm}}"'] & \mathrm{Rel}(A,A). \end{tikzcd}$$

00UN 5. *Interaction With Composition.* We have

$$(S \diamond R)^{\mathrm{symm}} = S^{\mathrm{symm}} \diamond R^{\mathrm{symm}}, \qquad \begin{tikzcd} \mathrm{Rel}(A,A) \times \mathrm{Rel}(A,A) \arrow[r, "\diamond"] \arrow[d, "(-)^{\mathrm{symm}} \times (-)^{\mathrm{symm}}"'] & \mathrm{Rel}(A,A) \arrow[d, "(-)^{\mathrm{symm}}"] \\ \mathrm{Rel}(A,A) \times \mathrm{Rel}(A,A) \arrow[r, "\diamond"'] & \mathrm{Rel}(A,A). \end{tikzcd}$$

PROOF 2.2.5 ► PROOF OF PROPOSITION 2.2.4

Item 1: Adjointness

This is a rephrasing of the universal property of the symmetric closure of a relation, stated in Definition 2.2.1.

Item 2: The Symmetric Closure of a Symmetric Relation

Clear.

Item 3: Idempotency

This follows from Item 2.

Item 4: Interaction With Inverses

Clear.

Item 5: Interaction With Composition

This follows from Item 2 of Proposition 2.1.4. □ ../../pictures/trans-

00UP # 3 Transitive Relations

00UQ ## 3.1 Foundations

Let A be a set.

00UR **Definition 3.1.1 ▶ Transitive Relations**

A **transitive relation** is equivalently:[1]

- A non-unital $\mathbb{E}_1$-monoid in $(\mathbf{N}_\bullet(\mathbf{Rel}(A, A)), \diamond)$.
- A non-unital monoid in $(\mathbf{Rel}(A, A), \diamond)$.

[1] Note that since $\mathbf{Rel}(A, A)$ is posetal, transitivity is a property of a relation, rather than extra structure.

00US **Remark 3.1.2 ▶ Unwinding Definition 3.1.1**

In detail, a relation R on A is **transitive** if we have an inclusion

$$\mu_R : R \diamond R \subset R$$

of relations in $\mathbf{Rel}(A, A)$, i.e. if, for each $a, c \in A$, the following condition is satisfied:

($\star$) If there exists some $b \in A$ such that $a \sim_R b$ and $b \sim_R c$, then $a \sim_R c$.

00UT **Definition 3.1.3 ▶ The Po/Set of Transitive Relations on a Set**

Let A be a set.

00UU 1. The **set of transitive relations from A to B** is the subset $\mathrm{Rel}^{\mathrm{trans}}(A)$ of $\mathrm{Rel}(A, A)$ spanned by the transitive relations.

00UV 2. The **poset of relations from A to B** is is the subposet $\mathbf{Rel}^{\mathrm{trans}}(A)$ of $\mathbf{Rel}(A, A)$ spanned by the transitive relations.

00UW **PROPOSITION 3.1.4 ► PROPERTIES OF TRANSITIVE RELATIONS**

Let R and S be relations on A.

00UX 1. *Interaction With Inverses.* If R is transitive, then so is $R^{\dagger}$.

00UY 2. *Interaction With Composition.* If R and S are transitive, then $S \diamond R$ ***may fail to be transitive***.

PROOF 3.1.5 ► PROOF OF PROPOSITION 3.1.4

Item 1: Interaction With Inverses

Clear.

Item 2: Interaction With Composition

See [**MSE2096272**].[1] □./../../pictures/trans-

[1] *Intuition:* Transitivity for R and S fails to imply that of $S \diamond R$ because the composition operation for relations intertwines R and S in an incompatible way:

- If $a \sim_{S\diamond R} c$ and $c \sim_{S\diamond r} e$, then:
  - There is some $b \in A$ such that:
    - $a \sim_R b$;
    - $b \sim_S c$;
  - There is some $d \in A$ such that:
    - $c \sim_R d$;
    - $d \sim_S e$.

00UZ 3.2 The Transitive Closure of a Relation

Let R be a relation on A.

00V0 **DEFINITION 3.2.1 ► THE TRANSITIVE CLOSURE OF A RELATION**

The **transitive closure** of $\sim_R$ is the relation $\sim_R^{\text{trans}}$[1] satisfying the following universal property:[2]

(★) Given another transitive relation $\sim_S$ on A such that $R \subset S$, there exists an inclusion $\sim_R^{\text{trans}} \subset \sim_S$.

[1] *Further Notation:* Also written R^{trans}.

[2] *Slogan:* The transitive closure of R is the smallest transitive relation containing R.

00V1 **Construction 3.2.2 ► The Transitive Closure of a Relation**

Concretely, $\sim_R^{\mathrm{trans}}$ is the free non-unital monoid on R in $(\mathbf{Rel}(A,A),\diamond)$[1], being given by

$$
\begin{aligned}
R^{\mathrm{trans}} &\overset{\mathrm{def}}{=} \coprod_{n=1}^{\infty} R^{\diamond n}\\
&\overset{\mathrm{def}}{=} \bigcup_{n=1}^{\infty} R^{\diamond n}\\
&\overset{\mathrm{def}}{=} \left\{(a,b)\in A\times B \;\middle|\; \begin{array}{l}\text{there exists some } (x_1,\ldots,x_n)\in R^{\times n}\\ \text{such that } a\sim_R x_1\sim_R\cdots\sim_R x_n\sim_R b\end{array}\right\}.
\end{aligned}
$$

[1] Or, equivalently, the free non-unital $\mathbb{E}_1$-monoid on R in $(\mathrm{N}_\bullet(\mathbf{Rel}(A,A)),\diamond)$.

Proof 3.2.3 ► Proof of Construction 3.2.2

Clear. □ ./../../pictures/trans-

00V2 **Proposition 3.2.4 ► Properties of the Transitive Closure of a Relation**

Let R be a relation on A.

00V3 1. *Adjointness.* We have an adjunction

$$
\left((-)^{\mathrm{trans}} \dashv 忘\right)\colon\quad \begin{tikzcd} \mathbf{Rel}(A,A) \arrow[r, bend left, "(-)^{\mathrm{trans}}"] \arrow[r, phantom, "\perp"] & \mathbf{Rel}^{\mathrm{trans}}(A,A) \arrow[l, bend left, "忘"] \end{tikzcd},
$$

witnessed by a bijection of sets

$$
\mathbf{Rel}^{\mathrm{trans}}\left(R^{\mathrm{trans}},S\right)\cong\mathbf{Rel}(R,S),
$$

natural in $R\in\mathrm{Obj}\left(\mathbf{Rel}^{\mathrm{trans}}(A,A)\right)$ and $S\in\mathrm{Obj}\left(\mathbf{Rel}(A,B)\right)$.

00V4 2. *The Transitive Closure of a Transitive Relation.* If R is transitive, then $R^{\mathrm{trans}}=R$.

00V5 3. *Idempotency.* We have

$$
\left(R^{\mathrm{trans}}\right)^{\mathrm{trans}}=R^{\mathrm{trans}}.
$$

00V6 4. *Interaction With Inverses.* We have

$$\left(R^{\dagger}\right)^{\mathrm{trans}} = \left(R^{\mathrm{trans}}\right)^{\dagger}, \qquad \begin{tikzcd} \mathrm{Rel}(A,A) \arrow[r, "(-)^{\mathrm{trans}}"] \arrow[d, "(-)^{\dagger}"'] & \mathrm{Rel}(A,A) \arrow[d, "(-)^{\dagger}"] \\ \mathrm{Rel}(A,A) \arrow[r, "(-)^{\mathrm{trans}}"'] & \mathrm{Rel}(A,A). \end{tikzcd}$$

00V7 5. *Interaction With Composition.* We have

$$(S \diamond R)^{\mathrm{trans}} \overset{\text{poss.}}{\neq} S^{\mathrm{trans}} \diamond R^{\mathrm{trans}}, \qquad \begin{tikzcd} \mathrm{Rel}(A,A) \times \mathrm{Rel}(A,A) \arrow[r, "\diamond"] \arrow[d, "(-)^{\mathrm{trans}} \times (-)^{\mathrm{trans}}"'] \arrow[dr, phantom, "\times"] & \mathrm{Rel}(A,A) \arrow[d, "(-)^{\mathrm{trans}}"] \\ \mathrm{Rel}(A,A) \times \mathrm{Rel}(A,A) \arrow[r, "\diamond"'] & \mathrm{Rel}(A,A). \end{tikzcd}$$

Proof 3.2.5 ▶ Proof of Proposition 3.2.4

Item 1: Adjointness

This is a rephrasing of the universal property of the transitive closure of a relation, stated in Definition 3.2.1.

Item 2: The Transitive Closure of a Transitive Relation

Clear.

Item 3: Idempotency

This follows from Item 2.

Item 4: Interaction With Inverses

We have

$$\left(R^{\dagger}\right)^{\mathrm{trans}} = \bigcup_{n=1}^{\infty} \left(R^{\dagger}\right)^{\diamond n}$$

$$
\begin{aligned}
&= \bigcup_{n=1}^{\infty} \left(R^{\diamond n}\right)^{\dagger} \\
&= \left(\bigcup_{n=1}^{\infty} R^{\diamond n}\right)^{\dagger} \\
&= \left(R^{\mathrm{trans}}\right)^{\dagger},
\end{aligned}
$$

where we have used, respectively:

- Construction 3.2.2.
- Constructions With Relations, ?? of ??.
- Constructions With Relations, ?? of ??.
- Construction 3.2.2.

This finishes the proof.

Item 5: Interaction With Composition

This follows from Item 2 of Proposition 3.1.4. □./../../pictures/trans-

00V8 4 Equivalence Relations

00V9 4.1 Foundations

Let A be a set.

00VA **Definition 4.1.1 ► Equivalence Relations**

A relation R is an **equivalence relation** if it is reflexive, symmetric, and transitive.[1]

[1] *Further Terminology:* If instead R is just symmetric and transitive, then it is called a **partial equivalence relation**.

00VB **Example 4.1.2 ▶ The Kernel of a Function**

The **kernel of a function** $f\colon A \to B$ is the equivalence relation $\sim_{\mathrm{Ker}(f)}$ on A obtained by declaring $a \sim_{\mathrm{Ker}(f)} b$ iff $f(a) = f(b)$.[1]

[1]The kernel $\mathrm{Ker}(f)\colon A \nrightarrow A$ of f is the underlying functor of the monad induced by the adjunction $\mathrm{Gr}(f) \dashv f^{-1}\colon A \rightleftarrows B$ in **Rel** of Constructions With Relations, **??** of **??**.

00VC **Definition 4.1.3 ▶ The Po/Set of Equivalence Relations on a Set**

Let A and B be sets.

00VD 1. The **set of equivalence relations from** A **to** B is the subset $\mathrm{Rel}^{\mathrm{eq}}(A, B)$ of $\mathrm{Rel}(A, B)$ spanned by the equivalence relations.

00VE 2. The **poset of relations from** A **to** B is is the subposet $\mathbf{Rel}^{\mathrm{eq}}(A, B)$ of $\mathbf{Rel}(A, B)$ spanned by the equivalence relations.

00VF 4.2 The Equivalence Closure of a Relation

Let R be a relation on A.

00VG **Definition 4.2.1 ▶ The Equivalence Closure of a Relation**

The **equivalence closure**[1] of $\sim_R$ is the relation $\sim_R^{\mathrm{eq}}$[2] satisfying the following universal property:[3]

(★) Given another equivalence relation $\sim_S$ on A such that $R \subset S$, there exists an inclusion $\sim_R^{\mathrm{eq}} \subset \sim_S$.

[1]*Further Terminology:* Also called the **equivalence relation associated to** $\sim_R$.
[2]*Further Notation:* Also written R^{eq}.
[3]*Slogan:* The equivalence closure of R is the smallest equivalence relation containing R.

00VH **Construction 4.2.2 ▶ The Equivalence Closure of a Relation**

Concretely, $\sim_R^{\mathrm{eq}}$ is the equivalence relation on A defined by

$$R^{\mathrm{eq}} \overset{\mathrm{def}}{=} \left(\left(R^{\mathrm{refl}}\right)^{\mathrm{symm}}\right)^{\mathrm{trans}}$$

$$= \left(\left(R^{\mathrm{symm}}\right)^{\mathrm{trans}}\right)^{\mathrm{refl}}$$

$$= \left\{ (a, b) \in A \times B \;\middle|\; \begin{array}{l} \text{there exists } (x_1, \ldots, x_n) \in R^{\times n} \text{ satisfying at} \\ \text{least one of the following conditions:} \\ \quad 1. \text{ The following conditions are satisfied:} \\ \qquad \text{(a) We have } a \sim_R x_1 \text{ or } x_1 \sim_R a; \\ \qquad \text{(b) We have } x_i \sim_R x_{i+1} \text{ or } x_{i+1} \sim_R x_i \\ \qquad\quad \text{for each } 1 \leq i \leq n-1; \\ \qquad \text{(c) We have } b \sim_R x_n \text{ or } x_n \sim_R b; \\ \quad 2. \text{ We have } a = b. \end{array} \right\}.$$

Proof 4.2.3 ► Proof of Construction 4.2.2

From the universal properties of the reflexive, symmetric, and transitive closures of a relation (Definitions 1.2.1, 2.2.1 and 3.2.1), we see that it suffices to prove that:

00VJ 1. The symmetric closure of a reflexive relation is still reflexive.

00VK 2. The transitive closure of a symmetric relation is still symmetric.

which are both clear. □./../../pictures/trans-

00VL **Proposition 4.2.4 ► Properties of Equivalence Relations**

Let R be a relation on A.

00VM 1. *Adjointness.* We have an adjunction

$$\left((-)^{\mathrm{eq}} \dashv 忘\right)\colon \quad \mathbf{Rel}(A, B) \underset{忘}{\overset{(-)^{\mathrm{eq}}}{\underset{\perp}{\rightleftarrows}}} \mathbf{Rel}^{\mathrm{eq}}(A, B),$$

witnessed by a bijection of sets

$$\mathbf{Rel}^{\mathrm{eq}}(R^{\mathrm{eq}}, S) \cong \mathbf{Rel}(R, S),$$

natural in $R \in \mathrm{Obj}(\mathbf{Rel}^{\mathrm{eq}}(A, B))$ and $S \in \mathrm{Obj}(\mathbf{Rel}(A, B))$.

00VN 2. *The Equivalence Closure of an Equivalence Relation.* If R is an equivalence relation, then $R^{\mathrm{eq}} = R$.

00VP 3. *Idempotency.* We have

$$(R^{\mathrm{eq}})^{\mathrm{eq}} = R^{\mathrm{eq}}.$$

Proof 4.2.5 ▶ Proof of Proposition 4.2.4

Item 1: Adjointness

This is a rephrasing of the universal property of the equivalence closure of a relation, stated in Definition 4.2.1.

Item 2: The Equivalence Closure of an Equivalence Relation

Clear.

Item 3: Idempotency

This follows from Item 2. □ ./../../pictures/trans-

00VQ # 5 Quotients by Equivalence Relations

00VR ## 5.1 Equivalence Classes

Let A be a set, let R be a relation on A, and let $a \in A$.

02B1 **Definition 5.1.1 ▶ Equivalence Classes**

The **equivalence class associated to** a is the set $[a]$ defined by

$$\begin{aligned} [a] &\overset{\mathrm{def}}{=} \{x \in X \mid x \sim_R a\} \\ &= \{x \in X \mid a \sim_R x\}. && \text{(since } R \text{ is symmetric)} \end{aligned}$$

02B2 ## 5.2 Quotients of Sets by Equivalence Relations

Let A be a set and let R be a relation on A.

Definition 5.2.1 ▶ Quotients of Sets by Equivalence Relations

02B3

The **quotient of X by R** is the set $X/{\sim_R}$ defined by

$$X/{\sim_R} \overset{\text{def}}{=} \{[a] \in \mathcal{P}(X) \mid a \in X\}.$$

00VV **Remark 5.2.2 ▶ Why Use "Equivalence" Relations for Quotient Sets**

The reason we define quotient sets for equivalence relations only is that each of the properties of being an equivalence relation—reflexivity, symmetry, and transitivity—ensures that the equivalences classes $[a]$ of X under R are well-behaved:

- *Reflexivity.* If R is reflexive, then, for each $a \in X$, we have $a \in [a]$.
- *Symmetry.* The equivalence class $[a]$ of an element a of X is defined by
$$[a] \overset{\text{def}}{=} \{x \in X \mid x \sim_R a\},$$
but we could equally well define
$$[a]' \overset{\text{def}}{=} \{x \in X \mid a \sim_R x\}$$
instead. This is not a problem when R is symmetric, as we then have $[a] = [a]'$.[1]
- *Transitivity.* If R is transitive, then $[a]$ and $[b]$ are disjoint iff $a \nsim_R b$, and equal otherwise.

[1] When categorifying equivalence relations, one finds that $[a]$ and $[a]'$ correspond to presheaves and copresheaves; see Constructions With Categories, ??.

00VW **Proposition 5.2.3 ▶ Properties of Quotient Sets**

Let $f\colon X \to Y$ be a function and let R be a relation on X.

02B4 1. *As a Coequaliser.* We have an isomorphism of sets
$$X/{\sim^{\mathrm{eq}}_R} \cong \mathrm{CoEq}\left(R \to X \times X \overset{\mathrm{pr}_1}{\underset{\mathrm{pr}_2}{\rightrightarrows}} X\right),$$
where $\sim^{\mathrm{eq}}_R$ is the equivalence relation generated by $\sim_R$.

02B5 2. *As a Pushout.* We have an isomorphism of sets[1]

$$X/{\sim_R^{\mathrm{eq}}} \cong X \textstyle\coprod_{\mathrm{Eq}(\mathrm{pr}_1,\mathrm{pr}_2)} X, \qquad \begin{tikzcd} X/{\sim_R^{\mathrm{eq}}} \arrow[dr, phantom, "\ulcorner", very near start] & X \arrow[l] \\ X \arrow[u] & \mathrm{Eq}(\mathrm{pr}_1, \mathrm{pr}_2). \arrow[l] \arrow[u] \end{tikzcd}$$

where $\sim_R^{\mathrm{eq}}$ is the equivalence relation generated by $\sim_R$.

02B6 3. *The First Isomorphism Theorem for Sets.* We have an isomorphism of sets[2,3]

$$X/{\sim_{\mathrm{Ker}(f)}} \cong \mathrm{Im}(f).$$

00W0 4. *Descending Functions to Quotient Sets, I.* Let R be an equivalence relation on X. The following conditions are equivalent:

02B7 (a) There exists a map

$$\overline{f}\colon X/{\sim_R} \to Y$$

making the diagram

$$\begin{tikzcd} X \arrow[r, "f"] \arrow[d, "q"'] & Y \\ X/{\sim_R} \arrow[ur, dotted, "\exists", "\overline{f}"'] & \end{tikzcd}$$

commute.

02B8 (b) We have $R \subset \mathrm{Ker}(f)$.

02B9 (c) For each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$.

00W1 5. *Descending Functions to Quotient Sets, II.* Let R be an equivalence relation on X. If the conditions of Item 4 hold, then $\overline{f}$ is the *unique* map making the diagram

$$\begin{tikzcd} X \arrow[r, "f"] \arrow[d, "q"'] & Y \\ X/\sim_R \arrow[ur, dashed, "\exists!", "\overline{f}"'] & \end{tikzcd}$$

commute.

00W2 6. *Descending Functions to Quotient Sets, III.* Let R be an equivalence relation on X. We have a bijection

$$\mathrm{Hom}_{\mathsf{Sets}}(X/\sim_R, Y) \cong \mathrm{Hom}^R_{\mathsf{Sets}}(X, Y),$$

natural in $X, Y \in \mathrm{Obj}(\mathsf{Sets})$, given by the assignment $f \mapsto \overline{f}$ of Items 4 and 5, where $\mathrm{Hom}^R_{\mathsf{Sets}}(X, Y)$ is the set defined by

$$\mathrm{Hom}^R_{\mathsf{Sets}}(X, Y) \overset{\text{def}}{=} \left\{ f \in \mathrm{Hom}_{\mathsf{Sets}}(X, Y) \;\middle|\; \begin{array}{l} \text{for each } x, y \in X, \\ \text{if } x \sim_R y, \text{ then} \\ f(x) = f(y) \end{array} \right\}.$$

02BA 7. *Descending Functions to Quotient Sets, IV.* Let R be an equivalence relation on X. If the conditions of Item 4 hold, then the following conditions are equivalent:

02BB (a) The map $\overline{f}$ is an injection.

02BC (b) We have $R = \mathrm{Ker}(f)$.

02BD (c) For each $x, y \in X$, we have $x \sim_R y$ iff $f(x) = f(y)$.

02BE 8. *Descending Functions to Quotient Sets, V.* Let R be an equivalence relation on X. If the conditions of Item 4 hold, then the following conditions are equivalent:

02BF (a) The map $f \colon X \to Y$ is surjective.

02BG (b) The map $\overline{f} \colon X/\sim_R \to Y$ is surjective.

02BH 9. *Descending Functions to Quotient Sets, VI.* Let R be a relation on X and let $\sim_R^{\mathrm{eq}}$ be the equivalence relation associated to R. The following conditions are equivalent:

02BJ (a) The map f satisfies the equivalent conditions of Item 4:

- There exists a map

$$\bar{f}\colon X/{\sim_R^{\mathrm{eq}}} \to Y$$

making the diagram

$$\begin{tikzcd} X \arrow[r, "f"] \arrow[d, "q"'] & Y \\ X/{\sim_R^{\mathrm{eq}}} \arrow[ur, dotted, "\exists"', "\bar{f}"] & \end{tikzcd}$$

commute.

- For each $x, y \in X$, if $x \sim_R^{\mathrm{eq}} y$, then $f(x) = f(y)$.

02BK (b) For each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$.

---

[1]Dually, we also have an isomorphism of sets

$$\mathrm{Eq}(\mathrm{pr}_1, \mathrm{pr}_2) \cong X \times_{X/\sim_R^{\mathrm{eq}}} X, \qquad \begin{tikzcd} \mathrm{Eq}(\mathrm{pr}_1, \mathrm{pr}_2) \arrow[r] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & X \arrow[d] \\ X \arrow[r] & X/{\sim_R^{\mathrm{eq}}}. \end{tikzcd}$$

[2]*Further Terminology:* The set $X/{\sim_{\mathrm{Ker}(f)}}$ is often called the **coimage of** f, and denoted by $\mathrm{CoIm}(f)$.

[3]In a sense this is a result relating the monad in **Rel** induced by f with the comonad in **Rel** induced by f, as the kernel and image

$$\begin{aligned} \mathrm{Ker}(f)&\colon X \nrightarrow X, \\ \mathrm{Im}(f)&\subset Y \end{aligned}$$

of f are the underlying functors of (respectively) the induced monad and comonad of the adjunction

$$(\mathrm{Gr}(f) \dashv f^{-1})\colon \quad \begin{tikzcd} A \arrow[r, bend left, "\mathrm{Gr}(f)"] \arrow[r, phantom, "\perp"] & B \arrow[l, bend left, "f^{-1}"] \end{tikzcd}$$

of Constructions With Relations, ?? of ??.

Proof 5.2.4 ▶ Proof of Proposition 5.2.3

Item 1: As a Coequaliser

Omitted.

Item 2: As a Pushout

Omitted.

Item 3: The First Isomorphism Theorem for Sets

Clear.

Item 4: Descending Functions to Quotient Sets, I

See [**proof-wiki:condition-for-mapping-from-quotient-set-to-be-well-defined**].

Item 5: Descending Functions to Quotient Sets, II

See [**proof-wiki:mapping-from-quotient-set-when-defined-is-unique**].

Item 6: Descending Functions to Quotient Sets, III

This follows from Items 5 and 6.

Item 7: Descending Functions to Quotient Sets, IV

See [**proof-wiki:condition-for-mapping-from-quotient-set-to-be-an-injection**].

Item 8: Descending Functions to Quotient Sets, V

See [**proof-wiki:condition-for-mapping-from-quotient-set-to-be-a-surjection**].

Item 9: Descending Functions to Quotient Sets, VI

The implication Item 8a $\implies$ Item 8b is clear.
Conversely, suppose that, for each $x, y \in X$, if $x \sim_R y$, then $f(x) = f(y)$. Spelling out the definition of the equivalence closure of R, we see that the condition $x \sim_R^{\mathrm{eq}} y$ unwinds to the following:

($\star$) There exist $(x_1, \ldots, x_n) \in R^{\times n}$ satisfying at least one of the following conditions:

- The following conditions are satisfied:
  * We have $x \sim_R x_1$ or $x_1 \sim_R x$;
  * We have $x_i \sim_R x_{i+1}$ or $x_{i+1} \sim_R x_i$ for each $1 \leq i \leq n-1$;
  * We have $y \sim_R x_n$ or $x_n \sim_R y$;
- We have $x = y$.

Now, if $x = y$, then $f(x) = f(y)$ trivially; otherwise, we have

$$\begin{aligned} f(x) &= f(x_1), \\ f(x_1) &= f(x_2), \\ &\vdots \\ f(x_{n-1}) &= f(x_n), \\ f(x_n) &= f(y), \end{aligned}$$

and $f(x) = f(y)$, as we wanted to show. □../../pictures/trans-

Appendices

A Other Chapters