

Automated Theorem Proving

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based on exercises by Dr. Uwe Waldmann

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Exercises 1: Motivation and Preliminaries

More difficult exercises are identified with an asterisk (*). These are included because they can be fun and instructive, but they are not typical exam questions.

Exercise 1.1: Solve the sudoku puzzle presented in the lecture.

Proposed solution.

	1	2	3	4	5	6	7	8	9
1	6	9	3	7	8	4	5	1	2
2	4	8	7	5	1	2	9	3	6
3	1	2	5	9	6	3	8	7	4
4	9	3	2	6	5	1	4	8	7
5	5	6	8	2	4	7	3	9	1
6	7	4	1	3	9	8	6	2	5
7	3	1	9	4	7	5	2	6	8
8	8	5	6	1	2	9	7	4	3
9	2	7	4	8	3	6	1	5	9

Exercise 1.2: Find an abstract reduction system $(A, \rightarrow)$ such that the relations $\rightarrow$, $\leftrightarrow$, and $\leftrightarrow^*$ are all different.

Proposed solution. We take $A := \mathbb{N} = \{0, 1, 2, \dots\}$ and

$$\rightarrow := \{(n + 1, n + 2) \mid n \in \mathbb{N}\}.$$

Then

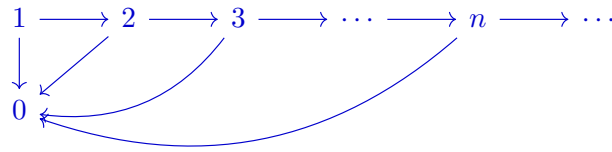
$$\begin{aligned}\leftrightarrow &:= \{(n + 1, n + 2) \mid n \in \mathbb{N}\} \cup \{(n + 2, n + 1) \mid n \in \mathbb{N}\} \\ \leftrightarrow^+ &:= \{(m + 1, n + 1) \mid m, n \in \mathbb{N}\}, \\ \leftrightarrow^* &:= \{(m + 1, n + 1) \mid m, n \in \mathbb{N}\} \cup \{(0, 0)\}.\end{aligned}$$

Exercise 1.3: Find an abstract reduction system $(A, \rightarrow)$ such that $\rightarrow^+$ is irreflexive and $\rightarrow$ is normalizing but not terminating.

Proposed solution. We take $A := \mathbb{N}$ and

$$\rightarrow := \{(n + 1, n + 2) \mid n \in \mathbb{N}\} \cup \{(n + 1, 0) \mid n \in \mathbb{N}\}.$$

The relation is clearly irreflexive (e.g., $1 \rightarrow 2$ but $2 \not\rightarrow 1$). It is also normalizing, with $n \downarrow = 0$ as the unique normal form of any number $n \in \mathbb{N}$. But it is not terminating, because it allows the infinite chain $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow \dots$. Graphically:



Exercise 1.4: Let $(\mathbb{N} \setminus \{0, 1\}, <_d)$ be the set of natural numbers larger than 1 ordered by the divisibility ordering $<_d$ that is defined by $a <_d b$ if a divides b and $a \neq b$. Are there minimal elements? Is there a smallest element? What do they look like?

Proposed solution. There are minimal elements; namely, the prime numbers $(2, 3, 5, 7, 11, \dots)$ are the minimal elements.

There is, however, no smallest element. A plausible candidate might be 2, but since $2 \not<_d 3$, it does not satisfy the criterion of being smallest.

Exercise 1.5: Let $(\mathbb{Q}, <)$ be the set of rational numbers with the usual ordering $<$. Construct infinite subsets M_1, M_2, M_3 , and M_4 of $\mathbb{Q}$ with the following properties:

- (1) M_1 is well-founded and has a minimal element.
- (2) M_2 is not well-founded and has a minimal element.
- (3) M_3 is well-founded and does not have a maximal element.
- (4) M_4 is not well-founded and has a maximal element.

Proposed solution. (1) We take $M_1 := \{0, 1, 2, \dots\}$. It is clearly well-founded, and the minimal element is 0.

(2) We take $M_2 := \{q \in \mathbb{Q} \mid 0 \leq q\}$. It admits infinite chains $1 > \frac{1}{2} > \frac{1}{3} > \frac{1}{4} > \dots$, and the minimal element is 0.

(3) We take $M_3 := \{0, 1, 2, \dots\}$. Clearly it has no maximal element.

(4) We take $M_4 := \{q \in \mathbb{Q} \mid 0 \leq q \leq 1\}$. It admits infinite chains $1 > \frac{1}{2} > \frac{1}{3} > \frac{1}{4} > \dots$, and the maximal element is 1.

Exercise 1.6 (*): You are asked to review a scientific article that has been submitted to a conference on automated reasoning. On page 3 of the article, the authors write the following:

Theorem 2. Let $\rightarrow_1$ and $\rightarrow_2$ be two binary relations over a nonempty set M . If $\rightarrow_1$ and $\rightarrow_2$ are terminating, then $\rightarrow_1 \cup \rightarrow_2$ is also terminating.

Proof. Since $\rightarrow_1$ is terminating, $\rightarrow_1^+$ is a well-founded ordering. Assume that there exists an infinite descending $(\rightarrow_1 \cup \rightarrow_2)$ -chain. Since $\rightarrow_1^+$ is well-founded, there exists a minimal element b with respect to $\rightarrow_1^+$ such that there exists an infinite descending $(\rightarrow_1 \cup \rightarrow_2)$ -chain starting with b .

Case 1: The $(\rightarrow_1 \cup \rightarrow_2)$ -chain starts with a $\rightarrow_1$ -step $b \rightarrow_1 b'$. The rest of the chain, starting with b' , is still infinite. However, b' is smaller than b with respect to $\rightarrow_1^+$. This contradicts the minimality of b .

Case 2: The $(\rightarrow_1 \cup \rightarrow_2)$ -chain starts with a $\rightarrow_2$ -step $b \rightarrow_2 b'$. Since $\rightarrow_2$ is terminating, the chain cannot consist only of $\rightarrow_2$ -steps. Therefore there must be some $\rightarrow_1$ -step in the chain, say $b'' \rightarrow_1 b'''$. Hence there exists an infinite $(\rightarrow_1 \cup \rightarrow_2)$ -chain starting with this step. But as we have seen in Case 1, an infinite $(\rightarrow_1 \cup \rightarrow_2)$ -chain cannot start with a $\rightarrow_1$ -step. So there is again a contradiction.

Consequently, every descending $(\rightarrow_1 \cup \rightarrow_2)$ -chain must be finite, which means that $\rightarrow_1 \cup \rightarrow_2$ is terminating.

- (1) Is the “proof” correct?
- (2) If the “proof” is not correct:

- (a) Which step is incorrect?
- (b) Does the “theorem” hold? If yes, give a correct proof; otherwise, give a counterexample.

Proposed solution. No, the “proof” is not correct.

The step “But as we have seen in Case 1, an infinite $(\rightarrow_1 \cup \rightarrow_2)$ -chain cannot start with a $\rightarrow_1$ -step” is incorrect. What we have seen in Case 1 is that an infinite $(\rightarrow_1 \cup \rightarrow_2)$ -chain cannot start with a $\rightarrow_1$ -step of the form $b \rightarrow_1 b'$, where b is the minimal element w.r.t. $\rightarrow_1^+$. Nothing prevents the step from having the form $b'' \rightarrow_1 b'''$, where $b'' \neq b$.

In fact, the “theorem” does not hold. A counterexample is $M := \mathbb{N}$ and

$$\begin{aligned}\rightarrow_1 &:= \{(2n+1, 2n) \mid n \in \mathbb{N}\}, \\ \rightarrow_2 &:= \{(2n, 2n+1) \mid n \in \mathbb{N}\}.\end{aligned}$$

Each relation $\rightarrow_i$ admits only chains of length at most 1 (e.g., $5 \rightarrow_1 4$ or $4 \rightarrow_2 5$), but the two relations in combination admit infinite chains $5 \rightarrow_1 4 \rightarrow_2 5 \rightarrow_1 4 \rightarrow_2 5 \rightarrow_1 \dots$. Methodologically, a good way to locate the flaw in the “proof” is to analyze where the proof goes wrong for this counterexample.

Exercise 1.7 (*): (1) Prove: If $>$ is a well-founded strict partial ordering on a set M and if b is the only element of M that is minimal in M , then b is the smallest element of M .

(2) Give an example of a strict partial ordering $>$ on a set M and an element $b \in M$ such that b is the only element of M that is minimal in M but not the smallest element of M .

Proposed solution. (1) Assume that $>$ is well-founded and that b is the only element of M that is minimal in M , but that b is not the smallest element of M . Let $X = \{x \in M \mid b \leq x\}$, and let $Y = M \setminus X$. Since b is not the smallest element of M , we know that $Y \neq \emptyset$. Since $>$ is well-founded, this implies that there exists some $c \in Y$ that is minimal in Y . By assumption, b is the only element of M that is minimal in M , so c is not minimal in M . Therefore, there exists some $d \in M$ such that $d < c$. Since c is minimal in Y , d cannot be contained in Y . But then $d \in X$, which implies $b \leq d < c$ and thus $c \in X$, contradicting the fact that $c \in Y$.

(2) Let $M = \{x \in \mathbb{Z} \mid x \leq 0\} \cup \{b\}$, where $>$ is the usual ordering on integer numbers and b is incomparable with all integer numbers. Then b is minimal in M (since no element of M is smaller), and it is the only minimal element of M (since for every other $x \in M$ there exists a smaller element $x - 1 \in M$, but b is not the smallest element of M , since the other elements of M are not larger than b).

Exercise 1.8 (*): Let $(A, \rightarrow)$ be an abstract reduction system such that every element of A has exactly one normal form w.r.t. $\rightarrow$. For every $b \in A$, define $L(b)$ as the minimal $n \in \mathbb{N}$ such that $b \rightarrow^n b'$ and b' is in normal form w.r.t. $\rightarrow$. Define the binary relation $\Rightarrow$ over A by $b \Rightarrow c$ if and only if $b \rightarrow c$ and $L(b) > L(c)$.

- (1) Give an example that shows that $\rightarrow \neq \Rightarrow$.
- (2) Show that for every $b \in A$ we have $b \Rightarrow^* b'$, where b' is the normal form of b w.r.t. $\rightarrow$.
- (3) Use part (2) to show that $\leftrightarrow^* = \Leftrightarrow^*$.

Proposed solution. (1) Let $A = \{a, b\}$ with $\rightarrow = \{(a, a), (a, b)\}$. Every element of A has exactly one normal form, namely b . We get $L(a) = 1$ and $L(b) = 0$, so $a \rightarrow a$ but not $a \Rightarrow a$. Graphically:



(2) We use induction over $L(b)$. If $L(b) = 0$, then the normal form of b with respect to $\rightarrow$ is b itself. Obviously, $b \Rightarrow^0 b$ and therefore $b \Rightarrow^* b$.

If $L(b) = n+1$, then there exists a derivation with $n+1$ steps $b \rightarrow b'' \rightarrow^n b'$, where b' is the normal form of both b and b'' . Clearly, there cannot exist any shorter derivation $b'' \rightarrow^m b'$ with $m < n$, since otherwise there would be a derivation $b \rightarrow^{m+1} b'$, contradicting the minimality assumption. So $L(b'') = n$, and therefore $b \Rightarrow b''$. By induction, $b'' \Rightarrow^* b'$, so $b \Rightarrow^* b'$.

(3) Since $\rightarrow \supseteq \Rightarrow$, we get $\leftrightarrow^* \supseteq \Leftrightarrow^*$. To prove the reverse inclusion, we first show that $\rightarrow \subseteq \Leftrightarrow^*$. Assume that $a \rightarrow b$. Let c be the normal form of b . Clearly, c is also the normal form of a . By part (2), $a \Rightarrow^* c \Leftarrow^* b$, so $a \Leftrightarrow^* b$ as required. Since $\Leftrightarrow^*$ is reflexive, symmetric, and transitive, $\rightarrow \subseteq \Leftrightarrow^*$ implies $\leftrightarrow^* \subseteq \Leftrightarrow^*$.