

und.1 Verifying the Representation

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In order to verify that our representation works, we have to prove two things. First, we have to show that if M halts on input w , then $\tau(M, w) \rightarrow \alpha(M, w)$ is valid. Then, we have to show the converse, i.e., that if $\tau(M, w) \rightarrow \alpha(M, w)$ is valid, then M does in fact eventually halt when run on input w .

explanation

The strategy for proving these is very different. For the first result, we have to show that a **sentence** of first-order logic (namely, $\tau(M, w) \rightarrow \alpha(M, w)$) is valid. The easiest way to do this is to give a **derivation**. Our proof is supposed to work for all M and w , though, so there isn't really a single **sentence** for which we have to give a derivation, but infinitely many. So the best we can do is to prove by induction that, whatever M and w look like, and however many steps it takes M to halt on input w , there will be a **derivation** of $\tau(M, w) \rightarrow \alpha(M, w)$.

Naturally, our induction will proceed on the number of steps M takes before it reaches a halting configuration. In our inductive proof, we'll establish that for each step n of the run of M on input w , $\tau(M, w) \models \chi(M, w, n)$, where $\chi(M, w, n)$ correctly describes the configuration of M run on w after n steps. Now if M halts on input w after, say, n steps, $\chi(M, w, n)$ will describe a halting configuration. We'll also show that $\chi(M, w, n) \models \alpha(M, w)$, whenever $\chi(M, w, n)$ describes a halting configuration. So, if M halts on input w , then for some n , M will be in a halting configuration after n steps. Hence, $\tau(M, w) \models \chi(M, w, n)$ where $\chi(M, w, n)$ describes a halting configuration, and since in that case $\chi(M, w, n) \models \alpha(M, w)$, we get that $\tau(M, w) \models \alpha(M, w)$, i.e., that $\models \tau(M, w) \rightarrow \alpha(M, w)$.

The strategy for the converse is very different. Here we assume that $\models \tau(M, w) \rightarrow \alpha(M, w)$ and have to prove that M halts on input w . From the hypothesis we get that $\tau(M, w) \models \alpha(M, w)$, i.e., $\alpha(M, w)$ is true in every **structure** in which $\tau(M, w)$ is true. So we'll describe a **structure** \mathfrak{M} in which $\tau(M, w)$ is true: its domain will be \mathbb{N} , and the interpretation of all the Q_q and S_σ will be given by the configurations of M during a run on input w . So, e.g., $\mathfrak{M} \models Q_q(\bar{m}, \bar{n})$ iff T , when run on input w for n steps, is in state q and scanning square m . Now since $\tau(M, w) \models \alpha(M, w)$ by hypothesis, and since $\mathfrak{M} \models \tau(M, w)$ by construction, $\mathfrak{M} \models \alpha(M, w)$. But $\mathfrak{M} \models \alpha(M, w)$ iff there is some $n \in |\mathfrak{M}| = \mathbb{N}$ so that M , run on input w , is in a halting configuration after n steps.

Definition und.1. Let $\chi(M, w, n)$ be the **sentence**

$$Q_q(\bar{m}, \bar{n}) \wedge S_{\sigma_0}(\bar{0}, \bar{n}) \wedge \cdots \wedge S_{\sigma_k}(\bar{k}, \bar{n}) \wedge \forall x (\bar{k} < x \rightarrow S_0(x, \bar{n}))$$

where q is the state of M at time n , M is scanning square m at time n , square i contains symbol σ_i at time n for $0 \leq i \leq k$ and k is the right-most non-blank square of the tape at time 0, or the right-most square the tape head has visited after n steps, whichever is greater.

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Lemma und.2. *If M run on input w is in a halting configuration after n steps, then $\chi(M, w, n) \models \alpha(M, w)$.*

Proof. Suppose that M halts for input w after n steps. There is some state q , square m , and symbol σ such that:

1. After n steps, M is in state q scanning square m on which σ appears.
2. The transition function $\delta(q, \sigma)$ is undefined.

$\chi(M, w, n)$ is the description of this configuration and will include the clauses $Q_q(\bar{m}, \bar{n})$ and $S_\sigma(\bar{m}, \bar{n})$. These clauses together imply $\alpha(M, w)$:

$$\exists x \exists y \left(\bigvee_{\langle q, \sigma \rangle \in X} (Q_q(x, y) \wedge S_\sigma(x, y)) \right)$$

since $Q_{q'}(\bar{m}, \bar{n}) \wedge S_{\sigma'}(\bar{m}, \bar{n}) \models \bigvee_{\langle q, \sigma \rangle \in X} (Q_q(\bar{m}, \bar{n}) \wedge S_\sigma(\bar{m}, \bar{n}))$, as $\langle q', \sigma' \rangle \in X$. □

explanation

So if M halts for input w , then there is some n such that $\chi(M, w, n) \models \alpha(M, w)$. We will now show that for any time n , $\tau(M, w) \models \chi(M, w, n)$.

Lemma und.3. *For each n , if M has not halted after n steps, $\tau(M, w) \models \chi(M, w, n)$.* tms:und:ver:
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Proof. Induction basis: If $n = 0$, then the conjuncts of $\chi(M, w, 0)$ are also conjuncts of $\tau(M, w)$, so entailed by it.

Inductive hypothesis: If M has not halted before the n th step, then $\tau(M, w) \models \chi(M, w, n)$. We have to show that (unless $\chi(M, w, n)$ describes a halting configuration), $\tau(M, w) \models \chi(M, w, n + 1)$.

Suppose $n > 0$ and after n steps, M started on w is in state q scanning square m . Since M does not halt after n steps, there must be an instruction of one of the following three forms in the program of M :

1. $\delta(q, \sigma) = \langle q', \sigma', R \rangle$
2. $\delta(q, \sigma) = \langle q', \sigma', L \rangle$
3. $\delta(q, \sigma) = \langle q', \sigma', N \rangle$

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We will consider each of these three cases in turn.

1. Suppose there is an instruction of the form (1). By ??, ??, this means that

$$\forall x \forall y ((Q_q(x, y) \wedge S_\sigma(x, y)) \rightarrow (Q_{q'}(x', y') \wedge S_{\sigma'}(x, y') \wedge \varphi(x, y)))$$

is a conjunct of $\tau(M, w)$. This entails the following **sentence** (universal instantiation, \bar{m} for x and \bar{n} for y):

$$(Q_q(\bar{m}, \bar{n}) \wedge S_\sigma(\bar{m}, \bar{n})) \rightarrow (Q_{q'}(\bar{m}', \bar{n}') \wedge S_{\sigma'}(\bar{m}, \bar{n}') \wedge \varphi(\bar{m}, \bar{n})).$$

By induction hypothesis, $\tau(M, w) \models \chi(M, w, n)$, i.e.,

$$Q_q(\bar{m}, \bar{n}) \wedge S_{\sigma_0}(\bar{0}, \bar{n}) \wedge \cdots \wedge S_{\sigma_k}(\bar{k}, \bar{n}) \wedge \forall x (\bar{k} < x \rightarrow S_0(x, \bar{n}))$$

Since after n steps, tape square m contains σ , the corresponding conjunct is $S_\sigma(\bar{m}, \bar{n})$, so this entails:

$$Q_q(\bar{m}, \bar{n}) \wedge S_\sigma(\bar{m}, \bar{n})$$

We now get

$$\begin{aligned} & Q_{q'}(\bar{m}', \bar{n}') \wedge S_{\sigma'}(\bar{m}, \bar{n}') \wedge \\ & S_{\sigma_0}(\bar{0}, \bar{n}') \wedge \cdots \wedge S_{\sigma_k}(\bar{k}, \bar{n}') \wedge \\ & \forall x (\bar{k} < x \rightarrow S_0(x, \bar{n}')) \end{aligned}$$

as follows: The first line comes directly from the consequent of the preceding conditional, by modus ponens. Each conjunct in the middle line—which excludes $S_{\sigma_m}(\bar{m}, \bar{n}')$ —follows from the corresponding conjunct in $\chi(M, w, n)$ together with $\varphi(\bar{m}, \bar{n})$.

If $m < k$, $\tau(M, w) \vdash \bar{m} < \bar{k}$ (??) and by transitivity of $<$, we have $\forall x (\bar{k} < x \rightarrow \bar{m} < x)$. If $m = k$, then $\forall x (\bar{k} < x \rightarrow \bar{m} < x)$ by logic alone. The last line then follows from the corresponding conjunct in $\chi(M, w, n)$, $\forall x (\bar{k} < x \rightarrow \bar{m} < x)$, and $\varphi(\bar{m}, \bar{n})$. If $m < k$, this already is $\chi(M, w, n+1)$.

Now suppose $m = k$. In that case, after $n + 1$ steps, the tape head has also visited square $k + 1$, which now is the right-most square visited. So $\chi(M, w, n + 1)$ has a new conjunct, $S_0(\bar{k}', \bar{n}')$, and the last conjunct is $\forall x (\bar{k}' < x \rightarrow S_0(x, \bar{n}'))$. We have to verify that these two **sentences** are also implied.

We already have $\forall x (\bar{k} < x \rightarrow S_0(x, \bar{n}'))$. In particular, this gives us $\bar{k} < \bar{k}' \rightarrow S_0(\bar{k}', \bar{n}')$. From the axiom $\forall x x < x'$ we get $\bar{k} < \bar{k}'$. By modus ponens, $S_0(\bar{k}', \bar{n}')$ follows.

Also, since $\tau(M, w) \vdash \bar{k} < \bar{k}'$, the axiom for transitivity of $<$ gives us $\forall x (\bar{k}' < x \rightarrow S_0(x, \bar{n}'))$. (We leave the verification of this as an exercise.)

2. Suppose there is an instruction of the form (2). Then, by ??, ??,

$$\begin{aligned} & \forall x \forall y ((Q_q(x', y) \wedge S_\sigma(x', y)) \rightarrow \\ & (Q_{q'}(x, y') \wedge S_{\sigma'}(x', y') \wedge \varphi(x, y))) \wedge \\ & \forall y ((Q_{q_i}(0, y) \wedge S_\sigma(0, y)) \rightarrow \\ & (Q_{q_j}(0, y') \wedge S_{\sigma'}(0, y') \wedge \varphi(0, y))) \end{aligned}$$

is a conjunct of $\tau(M, w)$. If $m > 0$, then let $l = m - 1$ (i.e., $m = l + 1$). The first conjunct of the above [sentence](#) entails the following:

$$(Q_q(\bar{l}', \bar{n}) \wedge S_\sigma(\bar{l}', \bar{n})) \rightarrow \\ (Q_{q'}(\bar{l}, \bar{n}') \wedge S_{\sigma'}(\bar{l}', \bar{n}') \wedge \varphi(\bar{l}, \bar{n}))$$

Otherwise, let $l = m = 0$ and consider the following [sentence](#) entailed by the second conjunct:

$$((Q_{q_i}(o, \bar{n}) \wedge S_\sigma(o, \bar{n})) \rightarrow \\ (Q_{q_j}(o, \bar{n}') \wedge S_{\sigma'}(o, \bar{n}') \wedge \varphi(o, \bar{n})))$$

Either sentence implies

$$Q_{q'}(\bar{l}, \bar{n}') \wedge S_{\sigma'}(\bar{m}, \bar{n}') \wedge \\ S_{\sigma_0}(\bar{0}, \bar{n}') \wedge \cdots \wedge S_{\sigma_k}(\bar{k}, \bar{n}') \wedge \\ \forall x (\bar{k} < x \rightarrow S_0(x, \bar{n}'))$$

as before. (Note that in the first case, $\bar{l}' = \bar{m}$ and in the second case $\bar{l} = o$.) But this just is $\chi(M, w, n + 1)$.

3. Case (3) is left as an exercise.

We have shown that for any n , $\tau(M, w) \models \chi(M, w, n)$. □

Problem und.1. Complete case (3) of the proof of [Lemma und.3](#).

Problem und.2. Give a [derivation](#) of $S_{\sigma_i}(\bar{i}, \bar{n}')$ from $S_{\sigma_i}(\bar{i}, \bar{n})$ and $\varphi(m, n)$ (assuming $i \neq m$, i.e., either $i < m$ or $m < i$).

Problem und.3. Give a [derivation](#) of $\forall x (\bar{k}' < x \rightarrow S_0(x, \bar{n}'))$ from $\forall x (\bar{k} < x \rightarrow S_0(x, \bar{n}'))$, $\forall x x < x'$, and $\forall x \forall y \forall z ((x < y \wedge y < z) \rightarrow x < z)$.

Lemma und.4. *If M halts on input w , then $\tau(M, w) \rightarrow \alpha(M, w)$ is valid.*

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Proof. By [Lemma und.3](#), we know that, for any time n , the description $\chi(M, w, n)$ of the configuration of M at time n is entailed by $\tau(M, w)$. Suppose M halts after k steps. It will be scanning square m , say. Then $\chi(M, w, k)$ describes a halting configuration of M , i.e., it contains as conjuncts both $Q_q(\bar{m}, \bar{k})$ and $S_\sigma(\bar{m}, \bar{k})$ with $\delta(q, \sigma)$ undefined. By [Lemma und.2](#) Thus, $\chi(M, w, k) \models \alpha(M, w)$. But since $(M, w) \models \chi(M, w, k)$, we have $\tau(M, w) \models \alpha(M, w)$ and therefore $\tau(M, w) \rightarrow \alpha(M, w)$ is valid. □

[explanation](#)

To complete the verification of our claim, we also have to establish the reverse direction: if $\tau(M, w) \rightarrow \alpha(M, w)$ is valid, then M does in fact halt when started on input m .

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lem:halt-if-valid

Lemma und.5. *If $\models \tau(M, w) \rightarrow \alpha(M, w)$, then M halts on input w .*

Proof. Consider the \mathcal{L}_M -**structure** \mathfrak{M} with domain \mathbb{N} which interprets 0 as 0, ' as the successor function, and $<$ as the less-than relation, and the predicates Q_q and S_σ as follows:

$$Q_q^{\mathfrak{M}} = \{ \langle m, n \rangle : \begin{array}{l} \text{started on } w, \text{ after } n \text{ steps,} \\ M \text{ is in state } q \text{ scanning square } m \end{array} \}$$
$$S_\sigma^{\mathfrak{M}} = \{ \langle m, n \rangle : \begin{array}{l} \text{started on } w, \text{ after } n \text{ steps,} \\ \text{square } m \text{ of } M \text{ contains symbol } \sigma \end{array} \}$$

In other words, we construct the **structure** \mathfrak{M} so that it describes what M started on input w actually does, step by step. Clearly, $\mathfrak{M} \models \tau(M, w)$. If $\models \tau(M, w) \rightarrow \alpha(M, w)$, then also $\mathfrak{M} \models \alpha(M, w)$, i.e.,

$$\mathfrak{M} \models \exists x \exists y \left(\bigvee_{\langle q, \sigma \rangle \in X} (Q_q(x, y) \wedge S_\sigma(x, y)) \right).$$

As $|\mathfrak{M}| = \mathbb{N}$, there must be $m, n \in \mathbb{N}$ so that $\mathfrak{M} \models Q_q(\bar{m}, \bar{n}) \wedge S_\sigma(\bar{m}, \bar{n})$ for some q and σ such that $\delta(q, \sigma)$ is undefined. By the definition of \mathfrak{M} , this means that M started on input w after n steps is in state q and reading symbol σ , and the transition function is undefined, i.e., M has halted. \square

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Bibliography