A Verified Translation of Multitape Turing Machines into Singletape Turing Machines

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Abstract

We define single- and multitape Turing machines (TMs) and verify a translation from multitape TMs to singletape TMs. In particular, the following results have been formalized: the accepted languages coincide, and whenever the multitape TM runs in $\mathcal{O}(f(n))$ time, then the singletape TM has a worst-time complexity of $\mathcal{O}(f(n)^2 + n)$. The translation is applicable both on deterministic and non-deterministic TMs.

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1 Introduction

In 1965 Hartmanis and Stearns proved that multitape Turing machines (TMs) can be simulated by singletape Turing machines [1]. Since then, alternative approaches for translating multitape TMs to singletape TMs have been formulated [2, 3]. In this AFP entry we define a translation which has the usual quadratic overhead in running time.

For the design of the translation we had to choose between the approach how to encode the k tapes of a multitape TM onto a single tape.

In the textbooks [2, 3] the k tapes $t_1, \ldots, t_n$ are stored sequentially onto a single tape $t_1 \# \ldots \# t_n$ via a separator $\#$. The technical problem with this definition is that once a tape t_i needs to be enlarged to the right, the later tape content $\#t_{i+1} \# \ldots \# t_n$ needs to be shifted correspondingly.

To avoid this problem, we followed the idea in the original work of Hartmanis et al. where the k-tapes are stored on top of each other, i.e., basically for the tape alphabet Γ of the multitape TM we switch to Γ^k in the singletape TM. As a consequence, the formal translation could be kept simple, in particular no tape shifts need to be performed.

2 Preparations

theory *TM-Common*
  imports
    HOL−Library.FuncSet
begin

A direction of a TM: go right, go left, or neutral (stay)

datatype *dir* = *R* | *L* | *N*

fun *go-dir* :: *dir* ⇒ *nat* ⇒ *nat* **where**
  go-dir R n = *Suc n*
| *go-dir L n* = *n* − *1*
| *go-dir N n* = *n*

lemma *finite-UNIV-dir*[*simp*, *intro*]: *finite* (*UNIV* :: *dir set*)
proof −
  have *id*: *UNIV* = {*L*,*R*,*N*}
    using *dir.exhaust* **by** *auto*
  show *?thesis* **unfolding** *id* **by** *auto*
qed

hide-const (**open**) *L R N*

lemma *fin-funcsetI*[*intro*]: *finite A* ⟹ *finite* ((*UNIV* :: *'a* :: *finite set*) → *A*)
  by (*metis PiE-UNIV-domain finite-PiE finite-code*)

lemma *finite-UNIV-fun-dir*[*simp*,*intro*]: *finite* (*UNIV* :: (*'k* :: *finite* ⇒ *dir*) *set*)
using *fin-funcsetI*[*OF finite-UNIV-dir*] **by** *auto*

lemma *relpow-transI*: (*x*,*y*) ∈ *R*^^*n* ⟹ (*y*,*z*) ∈ *R*^^*m* ⟹ (*x*,*z*) ∈ *R*^^(*n*+*m*)
by (*simp add*: *relcomp.intros relpow-add*)

lemma *relpow-mono*: **fixes** *R* :: *'a rel* **shows** *R* ⊆ *S* ⟹ *R*^^*n* ⊆ *S*^^*n*
by (*induct n*, *auto*)

lemma *finite-infinite-inj-on*: **assumes** *A*: *finite* (*A* :: *'a set*) **and** *inf*: *infinite* (*UNIV* :: *'b set*)
shows ∃ *f* :: *'a* ⇒ *'b*. *inj-on f A*
proof −
from *inf* **obtain** *B* :: *'b set* **where** *B*: *finite B card B* = *card A*
by (*meson infinite-arbitrarily-large*)
from *A B* **obtain** *f* :: *'a* ⇒ *'b* **where** *bij-betw f A B*
by (*metis bij-betw-iff-card*)
thus *?thesis* **by** (*intro exI*[*of - f*], *auto simp*: *bij-betw-def*)
qed

lemma *gauss-sum-nat2*: (∑ *i*< (*n* :: *nat*). *i*) = (*n* − *1*) ∗ *n div 2*
proof (*cases n*)
case (*Suc m*)
hence *id*: {..<*n*} = {*0*..*m*} **by** *auto*
show *?thesis* **unfolding** *id* **unfolding** *gauss-sum-nat* **unfolding** *Suc* **by** *auto*
qed *auto*

lemma *aux-sum-formula*: (∑ *i*<*n*. *10* + *5* ∗ *i*) ≤ *3* ∗ *n*^*2* + *7* ∗ (*n* :: *nat*)
proof −
have (∑ *i*<*n*. *10* + *5* ∗ *i*) = *10* ∗ *n* + *5* ∗ (∑ *i*<*n*. *i*)
by (*subst sum.distrib*, *auto simp*: *sum-distrib-left*)
also have ... ≤ *10* ∗ *n* + *3* ∗ ((*n* − *1*) ∗ *n*)
by (*unfold gauss-sum-nat2*, *rule add-left-mono*, *cases n*, *auto*)
also have ... = *3* ∗ *n*^*2* + *7* ∗ *n*
unfolding *power2-eq-square* **by** (*cases n*, *auto*)
finally show *?thesis* **.**
qed

end

3 Multitape Turing Machines

theory *Multitape-TM*
imports
TM-Common
begin

Turing machines can be either defined via a datatype or via a locale. We use TMs with left endmarker and dedicated accepting and rejecting state

from which no further transitions are allowed. Deterministic TMs can be partial.

Having multiple tapes, tape positions, directions, etc. is modelled via functions of type $'k \Rightarrow 'whatever$ for some finite index type $'k$.

The input will always be provided on the first tape, indexed by *0*.

datatype $('q,'a,'k)mttm = MTTM$
$(Q\text{-}tm\text{: } 'q\ set)$
$'a\ set$
$(\Gamma\text{-}tm\text{: } 'a\ set)$
$'a$
$'a$
$('q \times ('k \Rightarrow 'a) \times 'q \times ('k \Rightarrow 'a) \times ('k \Rightarrow dir))\ set$
$'q$
$'q$
$'q$

datatype $('a,'q,'k)\ mt\text{-}config = Config_M$
$(mt\text{-}state\text{: } 'q)$
$'k \Rightarrow nat \Rightarrow 'a$
$(mt\text{-}pos\text{: } 'k \Rightarrow nat)$

locale *multitape-tm* =
fixes
$Q :: 'q\ set$ **and**
$\Sigma :: 'a\ set$ **and**
$\Gamma :: 'a\ set$ **and**
$blank :: 'a$ **and**
$LE :: 'a$ **and**
$\delta :: ('q \times ('k \Rightarrow 'a) \times 'q \times ('k \Rightarrow 'a) \times ('k :: \{finite,zero\} \Rightarrow dir))\ set$ **and**
$s :: 'q$ **and**
$t :: 'q$ **and**
$r :: 'q$
assumes
$fin\text{-}Q$: $finite\ Q$ **and**
$fin\text{-}\Gamma$: $finite\ \Gamma$ **and**
$\Sigma\text{-}sub\text{-}\Gamma$: $\Sigma \subseteq \Gamma$ **and**
sQ: $s \in Q$ **and**
tQ: $t \in Q$ **and**
rQ: $r \in Q$ **and**
$blank$: $blank \in \Gamma\ blank \notin \Sigma$ **and**
LE: $LE \in \Gamma\ LE \notin \Sigma$ **and**
tr: $t \neq r$ **and**
$\delta\text{-}set$: $\delta \subseteq (Q - \{t,r\}) \times (UNIV \to \Gamma) \times Q \times (UNIV \to \Gamma) \times (UNIV \to UNIV)$ **and**
δLE: $(q,\ a,\ q',\ a',\ d) \in \delta \Longrightarrow a\ k = LE \Longrightarrow a'\ k = LE \wedge d\ k \in \{dir.N,dir.R\}$
begin

lemma δ: **assumes** $(q,a,q',b,d) \in \delta$

shows $q \in Q\ a\ k \in \Gamma\ q' \in Q\ b\ k \in \Gamma$
using *assms δ-set* **by** *auto*

lemma *fin-Σ*: *finite* Σ
using *fin-Γ Σ-sub-Γ* **by** (*metis finite-subset*)

lemma *fin-δ*: *finite δ*
by (*intro finite-subset*[*OF δ-set*] *finite-cartesian-product fin-funcsetI*, *insert fin-Q fin-Γ*, *auto*)

lemmas *tm* = *sQ Σ-sub-Γ blank*(*1*) *LE*(*1*)

fun *valid-config* :: ('*a*, '*q*, '*k*) *mt-config* ⇒ *bool* **where**
valid-config (*Config*$_M$ *q w n*) = (*q* ∈ *Q* ∧ (∀ *k*. *range* (*w k*) ⊆ Γ) ∧ (∀ *k*. *w k 0* = *LE*))

definition *init-config* :: '*a list* ⇒ ('*a*,'*q*,'*k*)*mt-config* **where**
init-config w = (*Config*$_M$ *s* (λ *k n*. *if n* = *0 then LE else if k* = *0* ∧ *n* ≤ *length w then w* ! (*n*−*1*) *else blank*) (λ -. *0*))

lemma *valid-init-config*: *set w* ⊆ Σ ⟹ *valid-config* (*init-config w*)
unfolding *init-config-def valid-config.simps* **using** *tm* **by** (*force simp*: *set-conv-nth*)

inductive-set *step* :: ('*a*, '*q*, '*k*) *mt-config rel* **where**
step: (*q*, (λ *k*. *ts k* (*n k*)), *q*', *a*, *dir*) ∈ *δ* ⟹
(*Config*$_M$ *q ts n*, *Config*$_M$ *q*' (λ *k*. (*ts k*)(*n k* := *a k*)) (λ *k*. *go-dir* (*dir k*) (*n k*)))
∈ *step*

lemma *valid-step*: **assumes** *step*: (α,β) ∈ *step*
and *val*: *valid-config* α
shows *valid-config* β
using *step*
proof (*cases rule*: *step.cases*)
case (*step q ts n q*' *a dir*)
from *δ*[*OF step*(*3*)] *val δLE step*(*3*)
show *?thesis* **unfolding** *step*(*1*−*2*) **by** *fastforce*
qed

definition *Lang* :: '*a list set* **where**
Lang = {*w* . *set w* ⊆ Σ ∧ (∃ *w' n*. (*init-config w*, *Config*$_M$ *t w' n*) ∈ *step*^∗)}

definition *deterministic* **where**
deterministic = (∀ *q a p1 b1 d1 p2 b2 d2*. (*q*,*a*,*p1*,*b1*,*d1*) ∈ *δ* ⟶ (*q*,*a*,*p2*,*b2*,*d2*)
∈ *δ* ⟶ (*p1*,*b1*,*d1*) = (*p2*,*b2*,*d2*))

definition *upper-time-bound* :: (*nat* ⇒ *nat*) ⇒ *bool* **where**
upper-time-bound f = (∀ *w c n*. *set w* ⊆ Σ ⟶ (*init-config w*, *c*) ∈ *step*^^*n* ⟶
n ≤ *f* (*length w*))
end

fun *valid-mttm* :: ('*q*,'*a*,'*k* :: {*finite*,*zero*})*mttm* ⇒ *bool* **where**
valid-mttm (*MTTM Q* Σ Γ *bl le* δ *s t r*) = *multitape-tm Q* Σ Γ *bl le* δ *s t r*

fun *Lang-mttm* :: ('*q*,'*a*,'*k* :: {*finite*,*zero*})*mttm* ⇒ '*a list set* **where**
Lang-mttm (*MTTM Q* Σ Γ *bl le* δ *s t r*) = *multitape-tm.Lang* Σ *bl le* δ *s t*

fun *det-mttm* :: ('*q*,'*a*,'*k* :: {*finite*,*zero*})*mttm* ⇒ *bool* **where**
det-mttm (*MTTM Q* Σ Γ *bl le* δ *s t r*) = *multitape-tm.deterministic* δ

fun *upperb-time-mttm* :: ('*q*,'*a*,'*k* :: {*finite*, *zero*})*mttm* ⇒ (*nat* ⇒ *nat*) ⇒ *bool* **where**
upperb-time-mttm (*MTTM Q* Σ Γ *bl le* δ *s t r*) *f* = *multitape-tm.upper-time-bound* Σ *bl le* δ *s f*

end

4 Singletape Turing Machines

theory *Singletape-TM*
imports
TM-Common
begin

Turing machines can be either defined via a datatype or via a locale. We use TMs with left endmarker and dedicated accepting and rejecting state from which no further transitions are allowed. Deterministic TMs can be partial.

datatype ('*q*,'*a*)*tm* = *TM*
(*Q-tm*: '*q set*)
'*a set*
(Γ-*tm*: '*a set*)
'*a*
'*a*
('*q* × '*a* × '*q* × '*a* × *dir*) *set*
'*q*
'*q*
'*q*

datatype ('*a*, '*q*) *st-config* = *Config*$_S$
'*q*
nat ⇒ '*a*
nat

locale *singletape-tm* =
fixes

$Q :: 'q\ set$ **and**
$\Sigma :: 'a\ set$ **and**
$\Gamma :: 'a\ set$ **and**
$blank :: 'a$ **and**
$LE :: 'a$ **and**
$\delta :: ('q \times 'a \times 'q \times 'a \times dir)\ set$ **and**
$s :: 'q$ **and**
$t :: 'q$ **and**
$r :: 'q$
assumes
fin-Q: *finite* Q **and**
fin-Γ: *finite* Γ **and**
Σ-*sub-*Γ: $\Sigma \subseteq \Gamma$ **and**
sQ: $s \in Q$ **and**
tQ: $t \in Q$ **and**
rQ: $r \in Q$ **and**
blank: $blank \in \Gamma\ blank \notin \Sigma$ **and**
LE: $LE \in \Gamma\ LE \notin \Sigma$ **and**
tr: $t \neq r$ **and**
δ-*set*: $\delta \subseteq (Q - \{t,r\}) \times \Gamma \times Q \times \Gamma \times UNIV$ **and**
δ*LE*: $(q,\ LE,\ q',\ a',\ d) \in \delta \Longrightarrow a' = LE \wedge d \in \{dir.N, dir.R\}$
begin

lemma δ: **assumes** $(q,a,q',b,d) \in \delta$
shows $q \in Q\ a \in \Gamma\ q' \in Q\ b \in \Gamma$
using *assms* δ-*set* **by** *auto*

lemma *fin*Σ: *finite* Σ
using *fin-*Γ Σ-*sub-*Γ **by** (*metis finite-subset*)

lemmas $tm = sQ\ \Sigma$-*sub-*$\Gamma\ blank(1)\ LE(1)$

fun *valid-config* :: $('a,\ 'q)$ *st-config* $\Rightarrow$ *bool* **where**
valid-config $(Config_S\ q\ w\ n) = (q \in Q \wedge range\ w \subseteq \Gamma)$

definition *init-config* :: $'a\ list\ \Rightarrow ('a,'q)$*st-config* **where**
init-config $w = (Config_S\ s\ (\lambda\ n.\ if\ n = 0\ then\ LE\ else\ if\ n \leq length\ w\ then\ w\ !\ (n-1)\ else\ blank)\ 0)$

lemma *valid-init-config*: *set* $w \subseteq \Sigma \Longrightarrow$ *valid-config* (*init-config* w)
unfolding *init-config-def valid-config.simps* **using** *tm* **by** (*force simp*: *set-conv-nth*)

inductive-set *step* :: $('a,\ 'q)$ *st-config rel* **where**
step: $(q,\ ts\ n,\ q',\ a,\ dir) \in \delta \Longrightarrow$
$(Config_S\ q\ ts\ n,\ Config_S\ q'\ (ts(n := a))\ (go\text{-}dir\ dir\ n)) \in step$

lemma *stepI*: $(q,\ a,\ q',\ b,\ dir) \in \delta \Longrightarrow ts\ n = a \Longrightarrow ts' = ts(n := b) \Longrightarrow n' = go\text{-}dir\ dir\ n \Longrightarrow q1 = q \Longrightarrow q2 = q'$
$\Longrightarrow (Config_S\ q1\ ts\ n,\ Config_S\ q2\ ts'\ n') \in step$

using *step*[*of q ts n q′ b dir*] **by** *auto*

lemma *valid-step*: **assumes** *step*: $(\alpha,\beta) \in step$
and *val*: *valid-config* α
shows *valid-config* β
using *step*
proof (*cases rule*: *step.cases*)
case (*step q ts n q′ a dir*)
from δ[*OF step*(*3*)] *val*
show *?thesis* **unfolding** *step*(*1−2*) **by** *auto*
qed

definition *Lang* :: *′a list set* **where**
Lang = {*w* . *set w* ⊆ Σ ∧ (∃ *w′ n*. (*init-config w*, *Config*$_S$ *t w′ n*) ∈ *step*^∗)}

definition *deterministic* **where**
deterministic = (∀ *q a p1 b1 d1 p2 b2 d2*. (*q*,*a*,*p1*,*b1*,*d1*) ∈ δ ⟶ (*q*,*a*,*p2*,*b2*,*d2*) ∈ δ ⟶ (*p1*,*b1*,*d1*) = (*p2*,*b2*,*d2*))

definition *upper-time-bound* :: (*nat* ⇒ *nat*) ⇒ *bool* **where**
upper-time-bound f = (∀ *w c n*. *set w* ⊆ Σ ⟶ (*init-config w*, *c*) ∈ *step*^^*n* ⟶ *n* ≤ *f* (*length w*))
end

fun *valid-tm* :: (*′q*,*′a*)*tm* ⇒ *bool* **where**
valid-tm (*TM Q* Σ Γ *bl le* δ *s t r*) = *singletape-tm Q* Σ Γ *bl le* δ *s t r*

fun *Lang-tm* :: (*′q*,*′a*)*tm* ⇒ *′a list set* **where**
Lang-tm (*TM Q* Σ Γ *bl le* δ *s t r*) = *singletape-tm.Lang* Σ *bl le* δ *s t*

fun *det-tm* :: (*′q*,*′a*)*tm* ⇒ *bool* **where**
det-tm (*TM Q* Σ Γ *bl le* δ *s t r*) = *singletape-tm.deterministic* δ

fun *upperb-time-tm* :: (*′q*,*′a*)*tm* ⇒ (*nat* ⇒ *nat*) ⇒ *bool* **where**
upperb-time-tm (*TM Q* Σ Γ *bl le* δ *s t r*) *f* = *singletape-tm.upper-time-bound* Σ *bl le* δ *s f*

context *singletape-tm*
begin

A deterministic step (in a potentially non-determistic TM) is a step without alternatives. This will be useful in the translation of multitape TMs. The simulation is mostly deterministic, and only at very specific points it is non-determistic, namely at the points where the multitape-TM transition is chosen.

inductive-set *dstep* :: (*′a*, *′q*) *st-config rel* **where**
dstep: (*q*, *ts n*, *q′*, *a*, *dir*) ∈ δ ⟹
(⋀ *q1′ a1 dir1*. (*q*, *ts n*, *q1′*, *a1*, *dir1*) ∈ δ ⟹ (*q1′*,*a1*,*dir1*) = (*q′*,*a*,*dir*)) ⟹
(*Config*$_S$ *q ts n*, *Config*$_S$ *q′* (*ts*(*n* := *a*)) (*go-dir dir n*)) ∈ *dstep*

lemma *dstepI*: $(q,\ a,\ q',\ b,\ dir) \in \delta \Longrightarrow ts\ n = a \Longrightarrow ts' = ts(n := b) \Longrightarrow n' =$ *go-dir dir n* $\Longrightarrow q1 = q \Longrightarrow q2 = q'$
$\Longrightarrow (\bigwedge q''\ b'\ dir'.\ (q,\ a,\ q'',\ b',\ dir') \in \delta \Longrightarrow (q'',\ b',\ dir') = (q',b,dir))$
$\Longrightarrow (Config_S\ q1\ ts\ n,\ Config_S\ q2\ ts'\ n') \in dstep$
using *dstep*[*of q ts n q' b dir*] **by** *blast*

lemma *dstep-step*: $dstep \subseteq step$
proof
fix *st*
assume *dstep*: $st \in dstep$
obtain *s t* **where** *st*: $st = (s,t)$ **by** *force*
have $(s,t) \in step$ **using** *dstep*[*unfolded st*]
proof (*cases rule*: *dstep.cases*)
case *1*: (*dstep q ts n q' a dir*)
show *?thesis* **unfolding** *1*(*1*−*2*) **by** (*rule stepI*[*OF 1*(*3*)], *auto*)
qed
thus $st \in step$ **using** *st* **by** *auto*
qed

lemma *dstep-inj*: **assumes** $(x,y) \in dstep$
and $(x,z) \in step$
shows $z = y$
using *assms*(*2*)
proof (*cases*)
case *1*: (*step q ts n p a d*)
show *?thesis* **using** *assms*(*1*) **unfolding** *1*(*1*)
proof *cases*
case *2*: (*dstep p' a' d'*)
from *2*(*3*)[*OF 1*(*3*)] **have** *id*: $p' = p\ a' = a\ d' = d$ **by** *auto*
show *?thesis* **unfolding** *1 2 id* **..**
qed
qed

lemma *dsteps-inj*: **assumes** $(x,y) \in dstep^{\frown\frown}n$
and $(x,z) \in step^{\frown\frown}m$
and $\neg\ (\exists\ u.\ (z,u) \in step)$
shows $\exists\ k.\ m = n + k \wedge (y,z) \in step^{\frown\frown}k$
using *assms*(*1*−*2*)
proof (*induct n arbitrary*: *m x*)
case (*Suc n m x*)
from *Suc*(*2*) **obtain** x' **where** *step*: $(x,x') \in dstep$ **and** *steps*: $(x',y) \in dstep^{\frown\frown}n$ **by** (*metis relpow-Suc-E2*)
from *step dstep-step* **have** $(x,x') \in step$ **by** *auto*
with *assms*(*3*) **have** $x \neq z$ **by** *auto*
with *Suc*(*3*) **obtain** *mm* **where** *m*: $m = Suc\ mm$ **by** (*cases m*, *auto*)
from *Suc*(*3*)[*unfolded this*] **obtain** x'' **where** *step'*: $(x,x'') \in step$ **and** *steps'*: $(x'',z) \in step^{\frown\frown}mm$ **by** (*metis relpow-Suc-E2*)
from *dstep-inj*[*OF step step'*] **have** *x''*: $x'' = x'$ **by** *auto*

from *Suc(1)*[*OF steps steps'*[*unfolded x''*]] **obtain** *k* **where** *mm*: *mm* = *n* + *k* **and** *steps*: (*y*, *z*) ∈ *step* ^^ *k* **by** *auto*
thus *?case* **unfolding** *m mm* **by** *auto*
qed *auto*

lemma *dsteps-inj'*: **assumes** (*x*,*y*) ∈ *dstep*^^*n*
and (*x*,*z*) ∈ *step*^^*m*
and *m* ≥ *n*
shows ∃ *k*. *m* = *n* + *k* ∧ (*y*,*z*) ∈ *step*^^*k*
using *assms*(*1*−*3*)
proof (*induct n arbitrary*: *m x*)
case (*Suc n m x*)
from *Suc(2)* **obtain** *x'* **where** *step*: (*x*,*x'*) ∈ *dstep* **and** *steps*: (*x'*,*y*) ∈ *dstep*^^*n* **by** (*metis relpow-Suc-E2*)
from *step dstep-step* **have** (*x*,*x'*) ∈ *step* **by** *auto*
with *Suc* **obtain** *mm* **where** *m*: *m* = *Suc mm* **by** (*cases m*, *auto*)
from *Suc(3)*[*unfolded this*] **obtain** *x''* **where** *step'*: (*x*,*x''*) ∈ *step* **and** *steps'*: (*x''*,*z*) ∈ *step*^^*mm* **by** (*metis relpow-Suc-E2*)
from *dstep-inj*[*OF step step'*] **have** *x''*: *x''* = *x'* **by** *auto*
from *Suc(1)*[*OF steps steps'*[*unfolded x''*]] *m Suc* **obtain** *k* **where** *mm*: *mm* = *n* + *k* **and** *steps*: (*y*, *z*) ∈ *step* ^^ *k* **by** *auto*
thus *?case* **unfolding** *m mm* **by** *auto*
qed *auto*
end
end

5 Renamings for Singletape Turing Machines

theory *STM-Renaming*
imports
Singletape-TM
begin

locale *renaming-of-singletape-tm* = *singletape-tm Q* Σ Γ *blank LE* δ *s t r*
for *Q* :: *'q set* **and** Σ :: *'a set* **and** Γ *blank LE* δ *s t r*
+ **fixes** *ra* :: *'a* ⇒ *'b*
and *rq* :: *'q* ⇒ *'p*
assumes *ra*: *inj-on ra* Γ
and *rq*: *inj-on rq Q*
begin

abbreviation *rd* **where** *rd* ≡ *map-prod rq* (*map-prod ra* (*map-prod rq* (*map-prod ra* (λ *d* :: *dir*. *d*))))

sublocale *ren*: *singletape-tm rq* ‘ *Q ra* ‘ Σ *ra* ‘ Γ *ra blank ra LE rd* ‘ δ *rq s rq t rq r*
proof (*unfold-locales*; (*intro finite-imageI imageI image-mono fin-Q fin-*Γ *tm sQ tQ rQ*)*?*)
show *ra LE* ∉ *ra* ‘ Σ **using** *ra tm LE* **by** (*simp add*: *inj-on-image-mem-iff*)

show *ra blank* $\notin$ *ra* ‘ Σ **using** *ra tm blank* **by** (*simp add*: *inj-on-image-mem-iff*)
show *rq t* $\neq$ *rq r* **using** *rq tQ rQ tr* **by** (*metis inj-on-contraD*)
show *rd* ‘ $\delta \subseteq$ (*rq* ‘ *Q* − {*rq t*, *rq r*}) × *ra* ‘ Γ × *rq* ‘ *Q* × *ra* ‘ Γ × *UNIV*
using δ*-set tQ rQ rq* **by** (*auto simp*: *inj-on-def*)
fix *p1 p2 b2 d*
assume (*p1*, *ra LE*, *p2*, *b2*, *d*) $\in$ *rd* ‘ δ
then obtain *q1 q2 a1 a2* **where** *mem*: (*q1*, *a1*, *q2*, *a2*, *d*) $\in \delta$ **and**
id: *p1* = *rq q1 ra LE* = *ra a1 p2* = *rq q2 b2* = *ra a2* **by** *auto*
from δ[*OF mem*] *id*(*2*) *LE ra* **have** *a1* = *LE* **by** (*simp add*: *inj-onD*)
with δ*LE*[*OF mem*[*unfolded this*]]
show *b2* = *ra LE* ∧ *d* $\in$ {*dir.N*, *dir.R*} **unfolding** *id* **by** *auto*
qed

fun *rc* :: (′*a*, ′*q*) *st-config* ⇒ (′*b*, ′*p*) *st-config* **where**
rc (*Config*$_S$ *q tc pos*) = *Config*$_S$ (*rq q*) (*ra o tc*) *pos*

lemma *ren-init*: *rc* (*init-config w*) = *ren.init-config* (*map ra w*)
unfolding *init-config-def ren.init-config-def rc.simps*
by *auto*

lemma *ren-step*: **assumes** (*c*,*c*′) $\in$ *step*
shows (*rc c*, *rc c*′) $\in$ *ren.step*
using *assms*
proof (*cases rule*: *step.cases*)
case (*step q ts n q*′ *a dir*)
from *step*(*3*) **have** *mem*: (*rq q*, *ra* (*ts n*), *rq q*′, *ra a*, *dir*) $\in$ *rd* ‘ δ **by** *force*
show *?thesis* **unfolding** *step rc.simps*
by (*intro ren.stepI*[*OF mem*], *auto*)
qed

lemma *ren-steps*: **assumes** (*c*,*c*′) $\in$ *step*$\widehat{}*$
shows (*rc c*, *rc c*′) $\in$ *ren.step*$\widehat{}*$
using *assms* **by** (*induct*, *insert ren-step*, *force*+)

lemma *ren-steps-count*: **assumes** (*c*,*c*′) $\in$ *step*$\widehat{}\widehat{}n$
shows (*rc c*, *rc c*′) $\in$ *ren.step*$\widehat{}\widehat{}n$
using *assms* **by** (*induct n arbitrary*: *c c*′, *insert ren-step*, *force*+)

lemma *ren-Lang-forward*: **assumes** *w* $\in$ *Lang*
shows *map ra w* $\in$ *ren.Lang*
proof −
from *assms*[*unfolded Lang-def*, *simplified*]
obtain *w*′ *n* **where** *w*: *set w* $\subseteq \Sigma$ **and** *steps*: (*init-config w*, *Config*$_S$ *t w*′ *n*) $\in$ *step*$\widehat{}*$
by *auto*
from *ren-steps*[*OF steps*, *unfolded ren-init*, *unfolded rc.simps*] *w*
show *map ra w* $\in$ *ren.Lang* **unfolding** *ren.Lang-def* **by** *auto*
qed

abbreviation *ira* **where** *ira* ≡ *the-inv-into* Γ *ra*
abbreviation *irq* **where** *irq* ≡ *the-inv-into Q rq*

interpretation *inv*: *renaming-of-singletape-tm rq* ‘ *Q ra* ‘ Σ *ra* ‘ Γ *ra blank ra LE rd* ‘ δ *rq s rq t rq r ira irq*
by (*unfold-locales*, *insert ra rq inj-on-the-inv-into*, *auto*)

lemmas *inv-simps*[*simp*] = *the-inv-into-f-f*[*OF ra*] *the-inv-into-f-f*[*OF rq*]

lemma *inv-ren-Sigma*: *ira* ‘ *ra* ‘ Σ = Σ **using** *inv-simps*(*1*)[*OF set-mp*[*OF* Σ-*sub*-Γ]]
by (*smt* (*verit*, *best*) *equalityI imageE image-subset-iff subsetI*)

lemma *inv-ren-Gamma*: *ira* ‘ *ra* ‘ Γ = Γ **using** *inv-simps*(*1*)
by (*smt* (*verit*, *best*) *equalityI imageE image-subset-iff subsetI*)

lemma *inv-ren-t*: *irq* (*rq t*) = *t* **using** *tQ* **by** *simp*
lemma *inv-ren-s*: *irq* (*rq s*) = *s* **using** *sQ* **by** *simp*
lemma *inv-ren-r*: *irq* (*rq r*) = *r* **using** *rQ* **by** *simp*
lemma *inv-ren-blank*: *ira* (*ra blank*) = *blank* **using** *tm* **by** *simp*
lemma *inv-ren-LE*: *ira* (*ra LE*) = *LE* **using** *tm* **by** *simp*

lemma *inv-ren-δ*: *inv.rd* ‘ *rd* ‘ δ = δ
proof −
{
fix *trans* :: (′*q* × ′*a* × ′*q* × ′*a* × *dir*)
obtain *q a p b d* **where** *trans*: *trans* = (*q*,*a*,*p*,*b*,*d*) **by** (*cases trans*, *auto*)
{
assume *t*: *trans* ∈ δ
note *mem* = δ[*OF this*[*unfolded trans*]]
from *t* **have** *inv.rd* (*rd trans*) ∈ *inv.rd* ‘ *rd* ‘ δ **by** *blast*
also have *inv.rd* (*rd trans*) = *trans* **unfolding** *trans* **using** *mem* **by** *auto*
finally have *trans* ∈ *inv.rd* ‘ *rd* ‘ δ **.**
}
moreover
{
assume *t*: *trans* ∈ *inv.rd* ‘ *rd* ‘ δ
then obtain *t*′ **where** *t*′*d*: *t*′ ∈ δ **and** *tra*: *trans* = *inv.rd* (*rd t*′) **by** *auto*
obtain *q*′ *a*′ *p*′ *b*′ *d*′ **where** *t*′: *t*′ = (*q*′,*a*′,*p*′,*b*′,*d*′) **by** (*cases t*′, *auto*)
note *mem* = δ[*OF t*′*d*[*unfolded t*′]]
from *tra*[*unfolded trans t*′] *mem*
have *id*: *q*′ = *q a*′ = *a p*′ = *p b*′ = *b d*′ = *d* **by** *auto*
with *trans t*′*d t*′ **have** *trans* ∈ δ **by** *auto*
}
ultimately have *trans* ∈ *inv.rd* ‘ *rd* ‘ δ ⟷ *trans* ∈ δ **by** *blast*
}
thus *?thesis* **by** *blast*
qed

lemmas *inv-ren* = *inv-ren-t inv-ren-s inv-ren-r inv-ren-δ inv-ren-Gamma inv-ren-Sigma*

inv-ren-blank inv-ren-LE

lemma *inv-ren-Lang*: *inv.ren.Lang* = *Lang* **unfolding** *inv-ren* **..**

lemma *ren-Lang-backward*: **assumes** *v* ∈ *ren.Lang*
shows ∃ *w*. *v* = *map ra w* ∧ *w* ∈ *Lang*
proof (*intro exI conjI*)
let *?w* = *map ira v*
from *inv.ren-Lang-forward*[*OF assms*, *unfolded inv-ren-Lang*]
show *?w* ∈ *Lang* **.**
show *v* = *map ra ?w* **unfolding** *map-map o-def*
proof (*subst map-idI*)
fix *b*
assume *b* ∈ *set v*
with *assms*[*unfolded ren.Lang-def*] Σ-*sub*-Γ **obtain** *a* **where** *a*: *a* ∈ Γ **and** *b*: *b* = *ra a* **by** *blast*
show *ra* (*ira b*) = *b* **unfolding** *b* **using** *a* **by** *simp*
qed *auto*
qed

lemma *ren-Lang*: *ren.Lang* = *map ra* ‘ *Lang*
proof
show *map ra* ‘ *Lang* ⊆ *ren.Lang* **using** *ren-Lang-forward* **by** *blast*
show *ren.Lang* ⊆ *map ra* ‘ *Lang* **using** *ren-Lang-backward* **by** *blast*
qed

lemma *ren-det*: **assumes** *deterministic*
shows *ren.deterministic*
unfolding *ren.deterministic-def*
proof (*intro allI impI*, *goal-cases*)
case (*1 q a p1 b1 d1 p2 b2 d2*)
let *?t1* = (*q*, *a*, *p1*, *b1*, *d1*)
let *?t2* = (*q*, *a*, *p2*, *b2*, *d2*)
from *1* **have** *t1*: *inv.rd ?t1* ∈ *inv.rd* ‘ *rd* ‘ δ **by** *force*
from *1* **have** *t2*: *inv.rd ?t2* ∈ *inv.rd* ‘ *rd* ‘ δ **by** *force*
from *t1 t2* **have** (*irq q*, *ira a*, *irq p1*, *ira b1*, *d1*) ∈ δ (*irq q*, *ira a*, *irq p2*, *ira b2*, *d2*) ∈ δ
unfolding *inv-ren* **by** *auto*
from *assms*[*unfolded deterministic-def*, *rule-format*, *OF this*]
have *id*: *irq p1* = *irq p2 ira b1* = *ira b2* **and** *d*: *d1* = *d2* **by** *auto*
from *inj-onD*[*OF inv.rq id*(*1*)] *ren.δ*[*OF 1*(*1*)] *ren.δ*[*OF 1*(*2*)]
have *p*: *p1* = *p2* **by** *auto*
from *inj-onD*[*OF inv.ra id*(*2*)] *ren.δ*[*OF 1*(*1*)] *ren.δ*[*OF 1*(*2*)]
have *b*: *b1* = *b2* **by** *auto*
show *?case* **unfolding** *b p d* **by** *simp*
qed

lemma *ren-upper-time*: **assumes** *upper-time-bound f*
shows *ren.upper-time-bound f*

```
  unfolding ren.upper-time-bound-def
proof (intro allI impI)
  fix w c n
  assume w: set w ⊆ ra ‘ Σ and steps: (ren.init-config w, c) ∈ ren.step ^^ n
  define v where v = map ira w
  from w have v: set v ⊆ Σ unfolding v-def
    using inv-ren-Sigma by fastforce
  from inv.ren-steps-count[OF steps]
  have (inv.rc (ren.init-config w), inv.rc c) ∈ inv.ren.step ^^ n .
  also have inv.ren.step = step using inv-ren-δ by presburger
  also have inv.rc (ren.init-config w) = init-config v unfolding v-def using v w
    by (simp add: inv.ren-init inv-ren-LE inv-ren-blank inv-ren-s)
  finally have (init-config v, inv.rc c) ∈ step ^^ n .
  with assms[unfolded upper-time-bound-def] v have n ≤ f (length v) by simp
  thus n ≤ f (length w) unfolding v-def by auto
qed

end

lemma tm-renaming: assumes valid-tm (tm :: ('q,'a)tm)
  and inj-on (ra :: 'a ⇒ 'b) (Γ-tm tm)
  and inj-on (rq :: 'q ⇒ 'p) (Q-tm tm)
shows ∃ tm' :: ('p,'b)tm.
  valid-tm tm' ∧
  Lang-tm tm' = map ra ‘ Lang-tm tm ∧
  (det-tm tm ⟶ det-tm tm') ∧
  (∀ f. upperb-time-tm tm f ⟶ upperb-time-tm tm' f)
proof (cases tm)
  case (TM Q Σ Γ bl le δ s t r)
  with assms interpret singletape-tm Q Σ Γ bl le δ s t r by auto
  interpret renaming-of-singletape-tm Q Σ Γ bl le δ s t r ra rq
    by (unfold-locales, insert assms TM, auto)
  let ?tm' = TM (rq ‘ Q) (ra ‘ Σ) (ra ‘ Γ) (ra bl) (ra le) (rd ‘ δ) (rq s) (rq t) (rq
r)
  show ?thesis
    by (rule exI[where x = ?tm'])
       (simp add: TM ren.singletape-tm-axioms ren-Lang ren-det ren-upper-time)
qed

end
```

6 Translating Multitape TMs to Singletape TMs

In this section we define the mapping from a multitape Turing machine to a singletape Turing machine. We further define soundness of the translation via several relations which establish a connection between configurations of both kinds of Turing machines.

The translation works both for deterministic and non-deterministic TMs.

Moreover, we verify a quadratic overhead in runtime.

theory *Multi-Single-TM-Translation*
imports
Multitape-TM
Singletape-TM
STM-Renaming
begin

6.1 Definition of the Translation

datatype *'a tuple-symbol* = *NO-HAT 'a* | *HAT 'a*
datatype *('a, 'k) st-tape-symbol* = *ST-LE* (‹⊢›) | *TUPLE 'k* ⇒ *'a tuple-symbol* | *INP 'a*
datatype *'a sym-or-bullet* = *SYM 'a* | *BULLET* (‹•›)

datatype *('a,'q,'k) st-states* =
R$_1$ *'a sym-or-bullet* |
R$_2$ |
S$_0$ *'q* |
S 'q 'k ⇒ *'a sym-or-bullet* |
S$_1$ *'q 'k* ⇒ *'a* |
E$_0$ *'q 'k* ⇒ *'a 'k* ⇒ *dir* |
E 'q 'k ⇒ *'a sym-or-bullet 'k* ⇒ *dir* |
Er 'q 'k ⇒ *'a sym-or-bullet 'k* ⇒ *dir 'k set* |
El 'q 'k ⇒ *'a sym-or-bullet 'k* ⇒ *dir 'k set* |
Em 'q 'k ⇒ *'a sym-or-bullet 'k* ⇒ *dir 'k set*

type-synonym *('a,'q,'k)mt-rule* = *'q* × (*'k* ⇒ *'a*) × *'q* × (*'k* ⇒ *'a*) × (*'k* ⇒ *dir*)

context *multitape-tm*
begin

definition *R1-Set* **where** *R1-Set* = *SYM* ‘ Σ ∪ {•}

definition *gamma-set* :: (*'k* ⇒ *'a tuple-symbol*) *set* **where**
gamma-set = (*UNIV* :: *'k set*) → *NO-HAT* ‘ Γ ∪ *HAT* ‘ Γ

definition Γ′ :: (*'a*, *'k*) *st-tape-symbol set* **where**
Γ′ = *TUPLE* ‘ *gamma-set* ∪ *INP* ‘ Σ ∪ {⊢}

definition *func-set* = (*UNIV* :: *'k set*) → *SYM* ‘ Γ ∪ {•}

definition *blank′* :: (*'a*, *'k*) *st-tape-symbol* **where** *blank′* = *TUPLE* (λ -. *NO-HAT blank*)
definition *hatLE′* :: (*'a*, *'k*) *st-tape-symbol* **where** *hatLE′* = *TUPLE* (λ -. *HAT LE*)
definition *encSym* :: *'a* ⇒ (*'a*, *'k*) *st-tape-symbol* **where** *encSym a* = (*TUPLE* (λ *i*. *if i* = *0 then NO-HAT a else NO-HAT blank*))

definition *add-inp* :: (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *'a sym-or-bullet*) ⇒ (*'k* ⇒ *'a sym-or-bullet*) **where**
add-inp inp inp2 = (λ *k*. *case inp k of HAT s* ⇒ *SYM s* | - ⇒ *inp2 k*)

definition *project-inp* :: (*'k* ⇒ *'a sym-or-bullet*) ⇒ (*'k* ⇒ *'a*) **where**
project-inp inp = (λ *k*. *case inp k of SYM s* ⇒ *s*)

definition *compute-idx-set* :: (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *'a sym-or-bullet*) ⇒ *'k set* **where**
compute-idx-set tup ys = {*i* . *tup i* ∈ *HAT* ' Γ ∧ *ys i* ∈ *SYM* ' Γ}

definition *update-ys* :: (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *'a sym-or-bullet*) ⇒ (*'k* ⇒ *'a sym-or-bullet*) **where**
update-ys tup ys = (λ *k*. *if k* ∈ (*compute-idx-set tup ys*) *then* • *else ys k*)

definition *replace-sym* :: (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *'a sym-or-bullet*) ⇒ (*'k* ⇒ *'a tuple-symbol*) **where**
replace-sym tup ys = (λ *k*. *if k* ∈ (*compute-idx-set tup ys*)
then (*case ys k of SYM a* ⇒ *NO-HAT a*)
else tup k)

definition *place-hats-to-dir* :: *dir* ⇒ (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *dir*) ⇒*'k set* ⇒ (*'k* ⇒ *'a tuple-symbol*) **where**
place-hats-to-dir dir tup ds I = (λ *k*. (*case tup k of*
NO-HAT a ⇒ *if k* ∈ *I* ∧ *ds k* = *dir*
then HAT a
else NO-HAT a
| *HAT a* ⇒ *HAT a*))

definition *place-hats-R* :: (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *dir*) ⇒*'k set* ⇒ (*'k* ⇒ *'a tuple-symbol*) **where**
place-hats-R = *place-hats-to-dir dir.R*

definition *place-hats-M* :: (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *dir*) ⇒*'k set* ⇒ (*'k* ⇒ *'a tuple-symbol*) **where**
place-hats-M = *place-hats-to-dir dir.N*

definition *place-hats-L* :: (*'k* ⇒ *'a tuple-symbol*) ⇒ (*'k* ⇒ *dir*) ⇒*'k set* ⇒ (*'k* ⇒ *'a tuple-symbol*) **where**
place-hats-L = *place-hats-to-dir dir.L*

definition *δ'* ::
((*'a*, *'q*, *'k*) *st-states* × (*'a*, *'k*) *st-tape-symbol* × (*'a*, *'q*, *'k*) *st-states* × (*'a*, *'k*) *st-tape-symbol* × *dir*)*set*
where
δ' = ({(*R*$_1$ •, ⊢, *R*$_1$ •, ⊢, *dir.R*)})
∪ (λ *x*. (*R*$_1$ •, *INP x*, *R*$_1$ (*SYM x*), *hatLE'*, *dir.R*)) ' Σ
∪ (λ (*a*,*x*). (*R*$_1$ (*SYM a*), *INP x*, *R*$_1$ (*SYM x*), *encSym a*, *dir.R*)) ' (Σ × Σ)

$\cup \{(R_1\ \bullet,\ blank',\ R_2,\ hatLE',\ dir.L)\}$
$\cup\ (\lambda\ a.\ (R_1\ (SYM\ a),\ blank',\ R_2,\ encSym\ a,\ dir.L))\ `\ \Sigma$
$\cup\ (\lambda\ x.\ (R_2,\ x,\ R_2,\ x,\ dir.L))\ `\ (\Gamma' - \{\vdash\})$
$\cup \{(R_2, \vdash, S_0\ s, \vdash, dir.N)\}$
$\cup\ (\lambda\ q.\ (S_0\ q, \vdash, S\ q\ (\lambda\ \text{-}.\ \bullet), \vdash, dir.R))\ `\ (Q - \{t,r\})$
$\cup\ (\lambda\ (q,inp,t).\ (S\ q\ inp,\ TUPLE\ t,\ S\ q\ (add\text{-}inp\ t\ inp),\ TUPLE\ t,\ dir.R))\ `\ (Q \times (func\text{-}set - (UNIV \to SYM\ `\ \Gamma)) \times gamma\text{-}set)$
$\cup\ (\lambda\ (q,inp,a).\ (S\ q\ inp,\ a,\ S_1\ q\ (project\text{-}inp\ inp),\ a,\ dir.L))\ `\ (Q \times (UNIV \to SYM\ `\ \Gamma) \times (\Gamma' - \{\vdash\}))$
$\cup\ (\lambda\ ((q,a,q',b,d),t).\ (S_1\ q\ a,\ t,\ E_0\ q'\ b\ d,\ t,\ dir.N))\ `\ (\delta \times \Gamma')$
$\cup\ (\lambda\ ((q,a,d),t).\ (E_0\ q\ a\ d,\ t,\ E\ q\ (SYM\ o\ a)\ d,\ t,\ dir.N))\ `\ ((Q \times (UNIV \to \Gamma) \times UNIV) \times \Gamma')$
$\cup\ (\lambda\ (q,d).\ (E\ q\ (\lambda\ \text{-}.\ \bullet)\ d, \vdash, S_0\ q, \vdash, dir.N))\ `\ (Q \times UNIV)$
$\cup\ (\lambda\ (q,ys,ds,t).\ \ (E\ \ q\ ys\ ds,\ \ \ TUPLE\ t,\ Er\ q\ (update\text{-}ys\ t\ ys)\ ds\ (compute\text{-}idx\text{-}set\ t\ ys),\ TUPLE(replace\text{-}sym\ t\ ys),\ dir.R))\ `\ (Q \times func\text{-}set \times UNIV \times gamma\text{-}set)$
$\cup\ (\lambda\ (q,ys,ds,I,t).\ (Er\ q\ ys\ ds\ I,\ TUPLE\ t,\ Em\ q\ ys\ ds\ I,\ TUPLE\ (place\text{-}hats\text{-}R\ t\ ds\ I),\ dir.L))\ `\ (Q \times func\text{-}set \times UNIV \times UNIV \times gamma\text{-}set)$
$\cup\ (\lambda\ (q,ys,ds,I,t).\ (Em\ q\ ys\ ds\ I,\ TUPLE\ t,\ El\ q\ ys\ ds\ I,\ TUPLE\ (place\text{-}hats\text{-}M\ t\ ds\ I),\ dir.L))\ `\ (Q \times func\text{-}set \times UNIV \times UNIV \times gamma\text{-}set)$
$\cup\ (\lambda\ (q,ys,ds,I,t).\ (El\ q\ ys\ ds\ I,\ TUPLE\ t,\ E\ \ q\ ys\ ds,\ \ \ TUPLE\ (place\text{-}hats\text{-}L\ t\ ds\ I),\ dir.N))\ `\ (Q \times func\text{-}set \times UNIV \times UNIV \times gamma\text{-}set)$
$\cup\ (\lambda\ (q,ys,ds,I).\ \ \ (El\ q\ ys\ ds\ I, \vdash, E\ q\ ys\ ds, \vdash, dir.N))\ `\ (Q \times func\text{-}set \times UNIV \times Pow(UNIV))$ — first switch into E state, so E phase is always finished in E state

definition $Q' =$
$R_1\ `\ R1\text{-}Set \cup \{R_2\} \cup$
$S_0\ `\ Q \cup (\lambda\ (q,inp).\ S\ q\ inp)\ `\ (Q \times func\text{-}set) \cup (\lambda\ (q,a).\ S_1\ q\ a)\ `\ (Q \times (UNIV \to \Gamma)) \cup$
$(\lambda\ (q,a,d).\ E_0\ q\ a\ d)\ `\ (Q \times (UNIV \to \Gamma) \times UNIV) \cup$
$(\lambda\ (q,a,d).\ E\ q\ a\ d)\ `\ (Q \times func\text{-}set \times UNIV) \cup$
$(\lambda\ (q,a,d,I).\ Er\ q\ a\ d\ I)\ `\ (Q \times func\text{-}set \times UNIV \times UNIV) \cup$
$(\lambda\ (q,a,d,I).\ Em\ q\ a\ d\ I)\ `\ (Q \times func\text{-}set \times UNIV \times UNIV) \cup$
$(\lambda\ (q,a,d,I).\ El\ q\ a\ d\ I)\ `\ (Q \times func\text{-}set \times UNIV \times UNIV)$

lemma *compute-idx-range*[*simp*,*intro*]:
assumes $tup \in gamma\text{-}set$
assumes $ys \in func\text{-}set$
shows $compute\text{-}idx\text{-}set\ tup\ ys \in UNIV$
by *auto*

lemma *update-ys-range*[*simp*,*intro*]:
assumes $tup \in gamma\text{-}set$
assumes $ys \in func\text{-}set$
shows $update\text{-}ys\ tup\ ys \in func\text{-}set$
by (*insert assms*, *fastforce simp*: *update-ys-def func-set-def*)

lemma *replace-sym-range*[*simp*,*intro*]:

assumes *tup* ∈ *gamma-set*
assumes *ys* ∈ *func-set*
shows *replace-sym tup ys* ∈ *gamma-set*
proof −
have ∀ *k*. (*if k* ∈ *compute-idx-set tup ys then case ys k of SYM x* ⇒ *NO-HAT x else tup k*) ∈ *NO-HAT* ‘ Γ ∪ *HAT* ‘ Γ
by(*intro allI*, *insert assms*, *cases k* ∈ *compute-idx-set tup ys*, *auto simp*: *func-set-def compute-idx-set-def gamma-set-def replace-sym-def*)
then show *?thesis*
using *assms* **unfolding** *replace-sym-def gamma-set-def* **by** *blast*
qed

lemma *tup-hat-content*:
assumes *tup* ∈ *gamma-set*
assumes *tup x* = *HAT a*
shows *a* ∈ Γ
proof −
have *range tup* ⊆ *NO-HAT* ‘ Γ ∪ *HAT* ‘ Γ
using *assms gamma-set-def* **by** *auto*
then show *?thesis*
using *assms*(*2*)
by (*metis UNIV-I Un-iff image-iff image-subset-iff tuple-symbol.distinct*(*1*) *tuple-symbol.inject*(*2*))
qed

lemma *tup-no-hat-content*:
assumes *tup* ∈ *gamma-set*
assumes *tup x* = *NO-HAT a*
shows *a* ∈ Γ
proof −
have *range tup* ⊆ *NO-HAT* ‘ Γ ∪ *HAT* ‘ Γ
using *assms gamma-set-def* **by** *auto*
then show *?thesis*
using *assms*(*2*)
by (*metis UNIV-I Un-iff image-iff image-subset-iff tuple-symbol.inject*(*1*) *tuple-symbol.simps*(*4*))
qed

lemma *place-hats-to-dir-range*[*simp*, *intro*]:
assumes *tup* ∈ *gamma-set*
shows *place-hats-to-dir d tup ds I* ∈ *gamma-set*
proof −
have ∀ *k*. (*case tup k of NO-HAT a* ⇒ *if k* ∈ *I* ∧ *ds k* = *d then HAT a else NO-HAT a* | *HAT x* ⇒ *HAT x*)
∈ *NO-HAT* ‘ Γ ∪ *HAT* ‘ Γ
proof
fix *k*
show (*case tup k of NO-HAT a* ⇒ *if k* ∈ *I* ∧ *ds k* = *d then HAT a else NO-HAT a* | *HAT x* ⇒ *HAT x*)

$\in$ *NO-HAT* ‘ $\Gamma \cup$ *HAT* ‘ Γ
by(*cases tup k*, *insert tup-hat-content*[*OF assms*(*1*)] *tup-no-hat-content*[*OF assms*(*1*)], *auto simp*: *gamma-set-def*)
qed
then show *?thesis*
using *assms*
unfolding *place-hats-to-dir-def gamma-set-def*
by *auto*
qed

lemma *place-hats-range*[*simp*,*intro*]:
assumes *tup* $\in$ *gamma-set*
shows *place-hats-R tup ds I* $\in$ *gamma-set* **and**
place-hats-L tup ds I $\in$ *gamma-set* **and**
place-hats-M tup ds I $\in$ *gamma-set*
by(*insert assms*, *auto simp*: *place-hats-R-def place-hats-L-def place-hats-M-def*)

lemma *fin-R1-Set*[*intro*,*simp*]: *finite R1-Set*
unfolding *R1-Set-def* **using** *fin-*Σ **by** *auto*

lemma *fin-gamma-set*[*intro*,*simp*]: *finite gamma-set*
unfolding *gamma-set-def* **using** *fin-*Γ
by (*intro fin-funcsetI*, *auto*)

lemma *fin-*Γ'[*intro*,*simp*]: *finite* Γ'
unfolding Γ'*-def* **using** *fin-*Σ **by** *auto*

lemma *fin-func-set*[*simp*,*intro*]: *finite func-set*
unfolding *func-set-def* **using** *fin-*Γ **by** *auto*

lemma *memberships*[*simp*,*intro*]: $\vdash \in \Gamma'$
$\cdot \in$ *R1-Set*
$x \in \Sigma \Longrightarrow$ *SYM* $x \in$ *R1-Set*
$x \in \Sigma \Longrightarrow$ *encSym* $x \in \Gamma'$
blank$' \in \Gamma'$
hatLE$' \in \Gamma'$
$x \in \Sigma \Longrightarrow$ *INP* $x \in \Gamma'$
$y \in$ *gamma-set* $\Longrightarrow$ *TUPLE* $y \in \Gamma'$
$(\lambda\text{-}.\ \cdot) \in$ *func-set*
$f \in$ *UNIV* $\to$ *SYM* ‘ $\Gamma \Longrightarrow f \in$ *func-set*
$g \in$ *UNIV* $\to \Gamma \Longrightarrow$ *SYM* $\circ\ g \in$ *func-set*
$f \in$ *UNIV* $\to$ *SYM* ‘ $\Gamma \Longrightarrow$ *project-inp* $f\ k \in \Gamma$
unfolding *R1-Set-def* Γ'*-def blank*$'$*-def hatLE*$'$*-def gamma-set-def encSym-def func-set-def project-inp-def*
using *LE blank tm funcset-mem*[*of f UNIV SYM* ‘ $\Gamma\ k$] **by** (*auto split*: *sym-or-bullet.splits*)

lemma *add-inp-func-set*[*simp*,*intro*]: $b \in$ *gamma-set* $\Longrightarrow a \in$ *func-set* $\Longrightarrow$ *add-inp* $b\ a \in$ *func-set*
unfolding *func-set-def gamma-set-def*

proof
fix x
assume a: $a \in UNIV \to SYM\ `\ \Gamma \cup \{\cdot\}$ **and** $b$: $b \in UNIV \to NO\text{-}HAT\ `\ \Gamma \cup HAT\ `\ \Gamma$
from a **have** a: $a\ x \in SYM\ `\ \Gamma \cup \{\cdot\}$ **by** *auto*
from b **have** b: $b\ x \in NO\text{-}HAT\ `\ \Gamma \cup HAT\ `\ \Gamma$ **by** *auto*
show *add-inp b a x* $\in SYM\ `\ \Gamma \cup \{\cdot\}$ **using** $a\ b$
unfolding *add-inp-def* **by** (*cases b x*, *auto simp*: *gamma-set-def*)
qed

lemma *automation*[*simp*]: $\bigwedge a\ b\ A\ B.\ (S\ a\ b \in (\lambda x.\ case\ x\ of\ (x1,\ x2) \Rightarrow S\ x1\ x2)\ `\ (A \times B)) \longleftrightarrow (a \in A \wedge b \in B)$
$\bigwedge a\ b\ A\ B.\ (S_1\ a\ b \in (\lambda x.\ case\ x\ of\ (x1,\ x2) \Rightarrow S_1\ x1\ x2)\ `\ (A \times B)) \longleftrightarrow (a \in A \wedge b \in B)$
$\bigwedge a\ b\ c\ A\ B\ C.\ (E_0\ a\ b\ c \in (\lambda x.\ case\ x\ of\ (x1,\ x2,\ x3) \Rightarrow E_0\ x1\ x2\ x3)\ `\ (A \times B \times C)) \longleftrightarrow (a \in A \wedge b \in B \wedge c \in C)$
$\bigwedge a\ b\ c\ A\ B\ C.\ (E\ a\ b\ c \in (\lambda x.\ case\ x\ of\ (x1,\ x2,\ x3) \Rightarrow E\ x1\ x2\ x3)\ `\ (A \times B \times C)) \longleftrightarrow (a \in A \wedge b \in B \wedge c \in C)$
$\bigwedge a\ b\ c\ d\ A\ B\ C.\ (Er\ a\ b\ c\ d \in (\lambda x.\ case\ x\ of\ (x1,\ x2,\ x3,\ x4) \Rightarrow Er\ x1\ x2\ x3\ x4)\ `\ (A \times B \times C)) \longleftrightarrow (a \in A \wedge b \in B \wedge (c,d) \in C)$
$\bigwedge a\ b\ c\ d\ A\ B\ C.\ (Em\ a\ b\ c\ d \in (\lambda x.\ case\ x\ of\ (x1,\ x2,\ x3,\ x4) \Rightarrow Em\ x1\ x2\ x3\ x4)\ `\ (A \times B \times C)) \longleftrightarrow (a \in A \wedge b \in B \wedge (c,d) \in C)$
$\bigwedge a\ b\ c\ d\ A\ B\ C.\ (El\ a\ b\ c\ d \in (\lambda x.\ case\ x\ of\ (x1,\ x2,\ x3,\ x4) \Rightarrow El\ x1\ x2\ x3\ x4)\ `\ (A \times B \times C)) \longleftrightarrow (a \in A \wedge b \in B \wedge (c,d) \in C)$
$blank' \neq \vdash$
$\vdash \neq blank'$
$blank' \neq INP\ x$
$INP\ x \neq blank'$
by (*force simp*: *blank'-def*)+

interpretation *st*: *singletape-tm* Q' $(INP\ `\ \Sigma)$ Γ' $blank' \vdash \delta'$ $R_1 \cdot S_0\ t\ S_0\ r$
proof
show *finite* Q'
unfolding *Q'-def* **using** *fin-Q fin-*Γ
by (*intro finite-UnI finite-imageI finite-cartesian-product*, *auto*)
show *finite* Γ' **by** (*rule fin-*Γ')
show $S_0\ t \in Q'$ **unfolding** *Q'-def* **using** *tQ* **by** *auto*
show $S_0\ r \in Q'$ **unfolding** *Q'-def* **using** *rQ* **by** *auto*
show $S_0\ t \neq S_0\ r$ **using** *tr* **by** *auto*
show $blank' \notin INP\ `\ \Sigma$ **unfolding** *blank'-def* **by** *auto*
show $R_1 \cdot \in Q'$ **unfolding** *Q'-def* **by** *auto*
show $\delta' \subseteq (Q' - \{S_0\ t,\ S_0\ r\}) \times \Gamma' \times Q' \times \Gamma' \times UNIV$
unfolding δ'*-def Q'-def* **using** *tm*
by (*auto dest*: δ)
show $(q, \vdash, q', a', d) \in \delta' \Longrightarrow a' = \vdash \wedge\ d \in \{dir.N,\ dir.R\}$ **for** $q\ q'\ a'\ d$
unfolding δ'*-def* **by** (*auto simp*: *hatLE'-def blank'-def*)
qed *auto*

lemma *valid-st*: *singletape-tm* Q' (*INP* ‘ Σ) Γ' *blank'* $\vdash$ δ' (R_1 $\cdot$) (S_0 t) (S_0 r) **..**

Determinism is preserved.

lemma *det-preservation*: *deterministic* $\Longrightarrow$ *st.deterministic*
unfolding *deterministic-def st.deterministic-def* **unfolding** δ'*-def*
by *auto*

6.2 Soundness of the Translation

lemma *range-mt-pos*:
$\exists$ *i*. *Max* (*range* (*mt-pos cm*)) = *mt-pos cm i*
finite (*range* (*mt-pos* (*cm* :: ('*a*, '*q*, '*k*) *mt-config*)))
range (*mt-pos cm*) $\neq$ {}
proof −
show *finite* (*range* (*mt-pos cm*)) **by** *auto*
moreover show *range* (*mt-pos cm*) $\neq$ {} **by** *auto*
ultimately show $\exists$ *i*. *Max* (*range* (*mt-pos cm*)) = *mt-pos cm i*
by (*meson Max-in imageE*)
qed

lemma *max-mt-pos-step*: **assumes** (*cm*,*cm'*) $\in$ *step*
shows *Max* (*range* (*mt-pos cm'*)) $\leq$ *Suc* (*Max* (*range* (*mt-pos cm*)))
proof −
from *range-mt-pos*(*1*)[*of cm'*] **obtain** *i'*
where *max1*: *Max* (*range* (*mt-pos cm'*)) = *mt-pos cm' i'* **by** *auto*
hence *Max* (*range* (*mt-pos cm'*)) $\leq$ *mt-pos cm' i'* **by** *auto*
also have ... $\leq$ *Suc* (*mt-pos cm i'*) **using** *assms*
proof (*cases*)
case (*step q ts n q' a dir*)
then show *?thesis* **by** (*cases dir i'*, *auto*)
qed
also have ... $\leq$ *Suc* (*Max* (*range* (*mt-pos cm*))) **using** *range-mt-pos*[*of cm*] **by** *simp*
finally show *?thesis* **.**
qed

lemma *max-mt-pos-init*: *Max* (*range* (*mt-pos* (*init-config w*))) = *0*
unfolding *init-config-def* **by** *auto*

lemma *INP-D*: **assumes** *set x* $\subseteq$ *INP* ‘ Σ
shows $\exists$ *w*. *x* = *map INP w* $\wedge$ *set w* $\subseteq$ Σ
using *assms*
proof (*induct x*)
case (*Cons x xs*)
then obtain *w* **where** *xs* = *map INP w* $\wedge$ *set w* $\subseteq$ Σ **by** *auto*
moreover from *Cons*(*2*) **obtain** *a* **where** *x* = *INP a* **and** *a* $\in$ Σ **by** *auto*
ultimately show *?case* **by** (*intro exI*[*of* - *a* # *w*], *auto*)
qed *auto*

6.2.1 R-Phase

fun *enc* :: ('*a*, '*q*, '*k*) *mt-config* ⇒ *nat* ⇒ ('*a*, '*k*) *st-tape-symbol*
where *enc* (*Config*$_M$ *q tc p*) *n* = *TUPLE* (λ *k*. *if p k* = *n then HAT* (*tc k n*) *else NO-HAT* (*tc k n*))

inductive *rel-R*$_1$ :: (('*a*, '*k*) *st-tape-symbol*,('*a*, '*q*, '*k*) *st-states*)*st-config* ⇒ '*a list* ⇒ *nat* ⇒ *bool* **where**
n = *length w* ⟹
tc′ *0* = ⊢ ⟹
p′ ≤ *n* ⟹
(⋀ *i*. *i* < *p*′ ⟹ *enc* (*init-config w*) *i* = *tc*′ (*Suc i*)) ⟹
(⋀ *i*. *i* ≥ *p*′ ⟹ *tc*′ (*Suc i*) = (*if i* < *n then INP* (*w* ! *i*) *else blank*′)) ⟹
(*p*′ = *0* ⟹ *q*′ = ⋅) ⟹
(⋀ *p*. *p*′ = *Suc p* ⟹ *q*′ = *SYM* (*w* ! *p*)) ⟹
rel-R$_1$ (*Config*$_S$ (*R*$_1$ *q*′) *tc*′ (*Suc p*′)) *w p*′

lemma *rel-R*$_1$*-init*: **shows** ∃ *cs1*. (*st.init-config* (*map INP w*), *cs1*) ∈ *st.dstep* ∧ *rel-R*$_1$ *cs1 w 0*
proof −
let *?INP* = *INP* :: '*a* ⇒ ('*a*, '*k*) *st-tape-symbol*
have *mem*: (*R*$_1$ ⋅, ⊢, *R*$_1$ ⋅, ⊢, *dir.R*) ∈ *δ*′ **unfolding** *δ*′*-def* **by** *auto*
let *?cs1* = *Config*$_S$ (*R*$_1$ ⋅) (λ*n*. *if n* = *0 then* ⊢ *else if n* ≤ *length* (*map ?INP w*) *then map ?INP w* ! (*n* − *1*) *else blank*′) (*Suc 0*)
have (*st.init-config* (*map INP w*), *?cs1*) ∈ *st.dstep*
unfolding *st.init-config-def* **by** (*rule st.dstepI*[*OF mem*], *auto simp*: *δ*′*-def blank*′*-def*)
moreover have *rel-R*$_1$ *?cs1 w 0*
by (*intro rel-R*$_1$*.intros*[*OF refl*], *auto*)
ultimately show *?thesis* **by** *blast*
qed

lemma *rel-R*$_1$*-R*$_1$: **assumes** *rel-R*$_1$ *cs0 w j*
and *j* < *length w*
and *set w* ⊆ Σ
shows ∃ *cs1*. (*cs0*, *cs1*) ∈ *st.dstep* ∧ *rel-R*$_1$ *cs1 w* (*Suc j*)
using *assms*(*1*)
proof (*cases rule*: *rel-R*$_1$*.cases*)
case (*1 n tc*′ *q*′)
note *cs0* = *1*(*1*)
from *assms* **have** *wj*: *w* ! *j* ∈ Σ **by** *auto*
show *?thesis*
proof (*cases j*)
case *0*
with *1* **have** *q*′: *q*′ = ⋅ **by** *auto*
from *1*(*6*)[*of 0*] *0 assms 1* **have** *tc*′*1*: *tc*′ (*Suc 0*) = *INP* (*w* ! *0*) **by** *auto*
have *mem*: (*R*$_1$ ⋅, *INP* (*w* ! *0*), *R*$_1$ (*SYM* (*w* ! *0*)), *hatLE*′, *dir.R*) ∈ *δ*′ **unfolding** *δ*′*-def*
using *wj 0* **by** *auto*

```
    let ?cs1 = Config_S (R_1 (SYM (w ! 0))) (tc'(Suc 0 := hatLE')) (Suc (Suc 0))
    have enc: enc (init-config w) 0 = hatLE' unfolding init-config-def hatLE'-def
by auto
    have (cs0, ?cs1) ∈ st.dstep unfolding cs0 0
      by (intro st.dstepI[OF mem], auto simp: q' tc'1 δ'-def blank'-def)
    moreover have rel-R_1 ?cs1 w (Suc 0)
      by (intro rel-R_1.intros, rule 1(2), insert 1 0 assms(2), auto simp: enc) (cases
w, auto)
    ultimately show ?thesis unfolding 0 by blast
  next
    case (Suc p)
    from 1(8)[OF Suc] have q': q' = SYM (w ! p) by auto
    from Suc assms(2) have p < length w by auto
    with assms(3) have w ! p ∈ Σ by auto
    with wj have (w ! p, w ! j) ∈ Σ × Σ by auto
    hence mem: (R_1 (SYM (w ! p)), INP (w ! j), R_1 (SYM (w ! j)), encSym (w !
p), dir.R) ∈ δ' unfolding δ'-def by auto
    have enc: enc (init-config w) j = encSym (w ! p) unfolding Suc using ‹p <
length w›
      by (auto simp: init-config-def encSym-def)
    from 1(6)[of j] assms 1 have tc': tc' (Suc j) = INP (w ! j) by auto
    let ?cs1 = Config_S (R_1 (SYM (w ! j))) (tc'(Suc j := encSym (w ! p))) (Suc
(Suc j))
    have (cs0, ?cs1) ∈ st.dstep unfolding cs0
      by (rule st.dstepI[OF mem], insert q' tc', auto simp: δ'-def blank'-def)
    moreover have rel-R_1 ?cs1 w (Suc j)
      by (intro rel-R_1.intros, insert 1 assms enc, auto)
    ultimately show ?thesis by blast
  qed
qed

inductive rel-R_2 :: (('a, 'k) st-tape-symbol,('a, 'q, 'k) st-states)st-config ⇒ 'a list
⇒ nat ⇒ bool where
  tc' 0 = ⊢ ⟹
  (⋀ i. enc (init-config w) i = tc' (Suc i)) ⟹
  p ≤ length w ⟹
  rel-R_2 (Config_S R_2 tc' p) w p


lemma rel-R_1-R_2: assumes rel-R_1 cs0 w (length w)
  and set w ⊆ Σ
shows ∃ cs1. (cs0, cs1) ∈ st.dstep ∧ rel-R_2 cs1 w (length w)
  using assms
proof (cases rule: rel-R_1.cases)
  case (1 n tc' q')
  note cs0 = 1(1)
  have enc: enc (init-config w) i = tc' (Suc i) if i ≠ length w for i
  proof (cases i < length w)
    case True
```

```
    thus ?thesis using 1(5)[of i] by auto
  next
    case False
    with that have i: i > length w by auto
    with 1(6)[of i] 1 have tc' (Suc i) = blank' by auto
     also have ... = enc (init-config w) i using i unfolding init-config-def by
(auto simp: blank'-def)
    finally show ?thesis by simp
  qed
  show ?thesis
  proof (cases length w)
    case 0
    with 1 have q': q' = • by auto
    from 1(6)[of 0] 0 1 have tc'1: tc' (Suc 0) = blank' by auto
    have mem: (R1 •, blank', R2, hatLE', dir.L) ∈ δ' unfolding δ'-def
      by auto
    let ?tc = tc'(Suc 0 := hatLE')
    let ?cs1 = Config_S R2 ?tc 0
   have enc0: enc (init-config w) 0 = hatLE' unfolding init-config-def hatLE'-def
by auto
    have enc: enc (init-config w) i = ?tc (Suc i) for i using enc[of i] enc0 using
0
      by (cases i, auto)
    have (cs0, ?cs1) ∈ st.dstep unfolding cs0 0
      by (intro st.dstepI[OF mem], auto simp: q' tc'1 δ'-def blank'-def)
    moreover have rel-R2 ?cs1 w (length w) unfolding 0
      by (intro rel-R2.intros enc, insert 1 0, auto)
    ultimately show ?thesis unfolding 0 by blast
  next
    case (Suc p)
    from 1(8)[OF Suc] have q': q' = SYM (w ! p) by auto
    from Suc have p < length w by auto
    with assms(2) have w ! p ∈ Σ by auto
     hence mem: (R1 (SYM (w ! p)), blank', R2, encSym (w ! p), dir.L) ∈ δ'
unfolding δ'-def by auto
    let ?tc = tc'(Suc (length w) := encSym (w ! p))
    have encW: enc (init-config w) (length w) = encSym (w ! p) unfolding Suc
using ‹p < length w›
      by (auto simp: init-config-def encSym-def)
   from 1(6)[of length w] assms 1 have tc': tc' (Suc (length w)) = blank' by auto
    let ?cs1 = Config_S R2 ?tc (length w)
    have enc: enc (init-config w) i = ?tc (Suc i) for i using enc[of i] encW by
auto
    have (cs0, ?cs1) ∈ st.dstep unfolding cs0 q'
      by (intro st.dstepI[OF mem] tc', auto simp: δ'-def blank'-def)
    moreover have rel-R2 ?cs1 w (length w)
      by (intro rel-R2.intros, insert 1 assms enc, auto)
    ultimately show ?thesis by blast
  qed
```

qed

lemma *rel-R_2-R_2*: **assumes** *rel-R_2 cs0 w (Suc j)*
and *set w ⊆ Σ*
shows ∃ *cs1*. *(cs0, cs1) ∈ st.dstep ∧ rel-R_2 cs1 w j*
using *assms*
proof *(cases rule: rel-R_2.cases)*
case *(1 tc')*
note *cs0 = 1(1)*
from *1* **have** *j*: *j < length w* **by** *auto*
have *tc*: *tc' (Suc j) ∈ Γ' − { ⊢ }* **unfolding** *1(3)[symmetric]* **using** *j assms(2)[unfolded set-conv-nth]* **unfolding** *init-config-def*
by *(force simp: Γ'-def gamma-set-def intro!: imageI LE blank set-mp[OF Σ-sub-Γ, of w ! (j − Suc 0)])*
hence *mem*: *(R_2, tc' (Suc j), R_2, tc' (Suc j), dir.L) ∈ δ'* **unfolding** *δ'-def* **by** *auto*
let *?cs1 = Config$_S$ R_2 tc' j*
have *(cs0, ?cs1) ∈ st.dstep* **unfolding** *cs0* **using** *tc*
by *(intro st.dstepI[OF mem], auto simp: δ'-def blank'-def)*
moreover have *rel-R_2 ?cs1 w j*
by *(intro rel-R_2.intros, insert 1, auto)*
ultimately show *?thesis* **by** *blast*
qed

inductive *rel-S_0* :: *(('a, 'k) st-tape-symbol,('a, 'q, 'k) st-states)st-config ⇒ ('a, 'q, 'k) mt-config ⇒ bool* **where**
tc' 0 = ⊢ ⟹
(⋀ i. tc' (Suc i) = enc (Config$_M$ q tc p) i) ⟹
valid-config (Config$_M$ q tc p) ⟹
rel-S_0 (Config$_S$ (S_0 q) tc' 0) (Config$_M$ q tc p)

lemma *rel-R_2-S_0*: **assumes** *rel-R_2 cs0 w 0*
and *set w ⊆ Σ*
shows ∃ *cs1*. *(cs0, cs1) ∈ st.dstep ∧ rel-S_0 cs1 (init-config w)*
using *assms*
proof *(cases rule: rel-R_2.cases)*
case *(1 tc')*
note *cs0 = 1(1)*
hence *mem*: *(R_2, ⊢, S_0 s, ⊢, dir.N) ∈ δ'* **unfolding** *δ'-def* **by** *auto*
let *?cs1 = Config$_S$ (S_0 s) tc' 0*
have *(cs0, ?cs1) ∈ st.dstep* **unfolding** *cs0*
by *(intro st.dstepI[OF mem], insert 1, auto simp: δ'-def blank'-def)*
moreover have *rel-S_0 ?cs1 (init-config w)* **using** *valid-init-config[OF assms(2)]* **unfolding** *init-config-def*
by *(intro rel-S_0.intros, insert 1(1,2,4−), auto simp: 1(3)[symmetric] init-config-def)*
ultimately show *?thesis* **by** *blast*
qed

If we start with a proper word w as input on the singletape TM, then via

the R-phase one can switch to the beginning of the S-phase ($rel\text{-}S_0$) for the initial configuration.

lemma *R-phase*: **assumes** *set w* $\subseteq \Sigma$
shows $\exists$ *cs*. (*st.init-config* (*map INP w*), *cs*) $\in$ *st.dstep*$\frown\frown$(*3* + *2* $*$ *length w*) $\wedge$ $rel\text{-}S_0$ *cs* (*init-config w*)
proof −
from $rel\text{-}R_1$*-init*[*of w*] **obtain** *cs1 n* **where**
step1: (*st.init-config* (*map INP w*), *cs1*) $\in$ *st.dstep* **and**
relR1: $rel\text{-}R_1$ *cs1 w n* **and**
n0: *n* = *0*
by *auto*
from *relR1*
have *n* + *k* $\leq$ *length w* $\Longrightarrow$ $\exists$ *cs2*. (*cs1*, *cs2*) $\in$ *st.dstep*$\frown\frown$*k* $\wedge$ $rel\text{-}R_1$ *cs2 w* (*n* + *k*) **for** *k*
proof (*induction k arbitrary*: *cs1 n*)
case (*Suc k cs1 n*)
hence *n* < *length w* **by** *auto*
from $rel\text{-}R_1\text{-}R_1$[*OF Suc*(*3*) *this assms*] **obtain** *cs3* **where**
step: (*cs1*, *cs3*) $\in$ *st.dstep* **and** *rel*: $rel\text{-}R_1$ *cs3 w* (*Suc n*) **by** *auto*
from *Suc.IH*[*OF - rel*] *Suc*(*2*) **obtain** *cs2* **where**
steps: (*cs3*, *cs2*) $\in$ *st.dstep* $\frown\frown$ *k* **and** *rel*: $rel\text{-}R_1$ *cs2 w* (*Suc n* + *k*)
by *auto*
from *relpow-Suc-I2*[*OF step steps*] *rel*
show *?case* **by** *auto*
qed *auto*
from *this*[*of length w*, *unfolded n0*]
obtain *cs2* **where** *steps2*: (*cs1*, *cs2*) $\in$ *st.dstep* $\frown\frown$ *length w* **and** *rel*: $rel\text{-}R_1$ *cs2 w* (*length w*) **by** *auto*
from $rel\text{-}R_1\text{-}R_2$[*OF rel assms*] **obtain** *cs3 n* **where** *step3*: (*cs2*, *cs3*) $\in$ *st.dstep*
and *rel*: $rel\text{-}R_2$ *cs3 w n* **and** *n*: *n* = *length w*
by *auto*
from *rel* **have** $\exists$ *cs*. (*cs3*, *cs*) $\in$ *st.dstep*$\frown\frown$*n* $\wedge$ $rel\text{-}R_2$ *cs w 0*
proof (*induction n arbitrary*: *cs3 rule*: *nat-induct*)
case (*Suc n cs3*)
from $rel\text{-}R_2\text{-}R_2$[*OF Suc*(*2*) *assms*] **obtain** *cs1* **where**
step: (*cs3*, *cs1*) $\in$ *st.dstep* **and** *rel*: $rel\text{-}R_2$ *cs1 w n* **by** *auto*
from *Suc.IH*[*OF rel*] **obtain** *cs* **where** *steps*: (*cs1*, *cs*) $\in$ *st.dstep* $\frown\frown$ *n* **and** *rel*: $rel\text{-}R_2$ *cs w 0* **by** *auto*
from *relpow-Suc-I2*[*OF step steps*] *rel* **show** *?case* **by** *auto*
qed *auto*
then obtain *cs4* **where** *steps4*: (*cs3*, *cs4*) $\in$ *st.dstep*$\frown\frown$(*length w*) **and** *rel*: $rel\text{-}R_2$ *cs4 w 0* **by** (*auto simp*: *n*)
from $rel\text{-}R_2\text{-}S_0$[*OF rel assms*] **obtain** *cs* **where** *step5*: (*cs4*, *cs*) $\in$ *st.dstep* **and**
rel: $rel\text{-}S_0$ *cs* (*init-config w*) **by** *auto*
from *relpow-Suc-I2*[*OF step1 relpow-transI*[*OF steps2 relpow-Suc-I2*[*OF step3 relpow-Suc-I*[*OF steps4 step5*]]]]
have (*st.init-config* (*map INP w*), *cs*) $\in$ *st.dstep* $\frown\frown$ *Suc* (*length w* + *Suc* (*Suc* (*length w*))) **.**
also have *Suc* (*length w* + *Suc* (*Suc* (*length w*))) = *3* + *2* $*$ *length w* **by** *simp*

finally show *?thesis* **using** *rel* **by** *auto*
qed

6.2.2 S-Phase

inductive *rel-S* :: ((*'a*, *'k*) *st-tape-symbol*,(*'a*, *'q*, *'k*) *st-states*)*st-config* ⇒ (*'a*, *'q*, *'k*) *mt-config* ⇒ *nat* ⇒ *bool* **where**
tc' 0 = ⊢ ⟹
(⋀ *i*. *tc'* (*Suc i*) = *enc* (*Config*$_M$ *q tc p*) *i*) ⟹
valid-config (*Config*$_M$ *q tc p*) ⟹
(⋀ *i*. *inp i* = (*if p i* < *p' then SYM* (*tc i* (*p i*)) *else* ·)) ⟹
rel-S (*Config*$_S$ (*S q inp*) *tc'* (*Suc p'*)) (*Config*$_M$ *q tc p*) *p'*

lemma *rel-S*$_0$*-S*: **assumes** *rel-S*$_0$ *cs0 cm*
and *mt-state cm* ∉ {*t*,*r*}
shows ∃ *cs1*. (*cs0*, *cs1*) ∈ *st.dstep* ∧ *rel-S cs1 cm 0*
using *assms*(*1*)
proof (*cases rule*: *rel-S*$_0$*.cases*)
case (*1 tc' q tc p*)
note *cs0* = *1*(*1*)
note *cm* = *1*(*2*)
from *assms*(*2*) *cm 1*(*5*) **have** *qtr*: *q* ∈ *Q* − {*t*,*r*} **by** *auto*
hence *mem*: (*S*$_0$ *q*, ⊢, *S q* (λ-. ·), ⊢, *dir.R*) ∈ *δ'* **unfolding** *δ'-def* **by** *auto*
let *?cs1* = *Config*$_S$ (*S q* (λ-. ·)) *tc'* (*Suc 0*)
have (*cs0*, *?cs1*) ∈ *st.dstep* **unfolding** *cs0*
by (*rule st.dstepI*[*OF mem*], *insert 1*, *auto simp*: *δ'-def blank'-def*)
moreover have *rel-S ?cs1 cm 0* **unfolding** *cm*
by (*intro rel-S.intros 1*, *auto*)
ultimately show *?thesis* **by** *blast*
qed

lemma *rel-S-mem*: **assumes** *rel-S* (*Config*$_S$ (*S q inp*) *tc' p'*) *cm j*
shows *inp* ∈ *func-set* ∧ *q* ∈ *Q* ∧ (∃ *t*. *tc'* (*Suc i*) = *TUPLE t* ∧ *t* ∈ *gamma-set*)

using *assms*(*1*)
proof (*cases rule*: *rel-S.cases*)
case (*1 tc p*)
from *1* **have** *q*: *q* ∈ *Q* **by** *auto*
have *inp*: *inp* ∈ *func-set* **unfolding** *func-set-def 1*(*6*) **using** *1*(*5*)
by *force*
have ∃ *t*. *tc'* (*Suc i*) = *TUPLE t* ∧ *t* ∈ *gamma-set* **using** *1*(*5*)
unfolding *1*(*4*) **by** (*force simp*: *gamma-set-def*)
with *q inp* **show** *?thesis* **by** *auto*
qed

lemma *rel-S-S*: **assumes** *rel-S cs0 cm p'*
p' ≤ *Max* (*range* (*mt-pos cm*))
shows ∃ *cs1*. (*cs0*, *cs1*) ∈ *st.dstep* ∧ *rel-S cs1 cm* (*Suc p'*)
using *assms*(*1*)

proof (*cases rule*: *rel-S.cases*)
case (*1 tc′ q tc p inp*)
note *cs0* = *1*(*1*)
note *cm* = *1*(*2*)
let *?Set* = *Q* × (*func-set* − (*UNIV* → *SYM* ‘ Γ)) × *gamma-set*
let *?f* = λ(*q*, *inp*, *t*). (*S q inp*, *TUPLE t*, *S q* (*add-inp t inp*), *TUPLE t*, *dir.R*)
obtain *i* **where** *mt-pos cm i* = *Max* (*range* (*mt-pos cm*)) **using** *range-mt-pos*(*1*)[*of cm*] **by** *auto*
with *assms 1* **have** *p′* ≤ *p i* **by** *auto*
with *1*(*6*)[*of i*] **have** *inp i* = · **by** *auto*
hence *inp*: *inp* ∉ (*UNIV* → *SYM* ‘ Γ)
by (*metis PiE UNIV-I image-iff sym-or-bullet.distinct*(*1*))
with *rel-S-mem*[*OF assms*(*1*)[*unfolded cs0*], *of p′*] **obtain** *t* **where**
(*q*,*inp*,*t*) ∈ *?Set* **and** *tc′*: *tc′* (*Suc p′*) = *TUPLE t* **by** *auto*
hence *?f* (*q*,*inp*,*t*) ∈ *δ′* **unfolding** *δ′-def* **by** *blast*
hence *mem*: (*S q inp*, *TUPLE t*, *S q* (*add-inp t inp*), *TUPLE t*, *dir.R*) ∈ *δ′* **by** *simp*
let *?cs1* = *Config*$_S$ (*S q* (*add-inp t inp*)) *tc′* (*Suc* (*Suc p′*))
have (*cs0*,*?cs1*) ∈ *st.dstep* **unfolding** *cs0* **using** *inp*
by (*intro st.dstepI*[*OF mem*], *auto simp*: *tc′ δ′-def blank′-def*)
moreover have *rel-S ?cs1 cm* (*Suc p′*) **unfolding** *cm*
proof (*intro rel-S.intros 1*)
from *1*(*4*)[*of p′*, *unfolded tc′*]
have *t*: *t* = (λ*k*. *if p k* = *p′ then HAT* (*tc k p′*) *else NO-HAT* (*tc k p′*)) **by** *auto*
show ⋀ *k*. *add-inp t inp k* = (*if p k* < *Suc p′ then SYM* (*tc k* (*p k*)) *else* ·)
unfolding *add-inp-def 1 t* **by** *auto*
qed
ultimately show *?thesis* **by** *blast*
qed

inductive *rel-S*$_1$ :: ((′*a*, ′*k*) *st-tape-symbol*,(′*a*, ′*q*, ′*k*) *st-states*)*st-config* ⇒ (′*a*, ′*q*, ′*k*) *mt-config* ⇒ *bool* **where**
tc′ 0 = ⊢ ⟹
(⋀ *i*. *tc′* (*Suc i*) = *enc* (*Config*$_M$ *q tc p*) *i*) ⟹
valid-config (*Config*$_M$ *q tc p*) ⟹
(⋀ *i*. *inp i* = *tc i* (*p i*)) ⟹
(⋀ *i*. *p i* < *p′*) ⟹
p′ = *Suc* (*Max* (*range p*)) ⟹
rel-S$_1$ (*Config*$_S$ (*S*$_1$ *q inp*) *tc′ p′*) (*Config*$_M$ *q tc p*)

lemma *rel-S-S*$_1$: **assumes** *rel-S cs0 cm p′*
p′ = *Suc* (*Max* (*range* (*mt-pos cm*)))
shows ∃ *cs1*. (*cs0*, *cs1*) ∈ *st.dstep* ∧ *rel-S*$_1$ *cs1 cm*
using *assms*(*1*)
proof (*cases rule*: *rel-S.cases*)
case (*1 tc′ q tc p inp*)
from *assms* **have** *p′Max*: *p′* > *Max* (*range* (*mt-pos cm*)) **by** *auto*
note *cs0* = *1*(*1*)

note *cm* = *1*(*2*)
from *p'Max range-mt-pos*(*2*−)[*of cm*] **have** *pip*: *p i* < *p'* **for** *i* **unfolding** *cm*
by *auto*
let *?SET* = *Q* × *func-set* × *gamma-set*
let *?Set* = *Q* × (*UNIV* → *SYM* ' Γ) × (Γ' − { ⊢ })
from *rel-S-mem*[*OF assms*(*1*)[*unfolded cs0*], *of p'*] **obtain** *t* **where**
mem: (*q*,*inp*,*t*) ∈ *?SET* **and** *tc'*: *tc'* (*Suc p'*) = *TUPLE t* **by** *auto*
hence *inp* ∈ *func-set* **by** *auto*
with *pip* **have** *inp*: *inp* ∈ *UNIV* → *SYM* ' Γ **unfolding** *func-set-def* **using** *1*(*6*)
by *auto*
with *mem* **have** (*q*,*inp*,*TUPLE t*) ∈ *?Set* **by** *auto*
hence (λ (*q*,*inp*,*a*). (*S q inp*, *a*, *S*$_1$ *q* (*project-inp inp*), *a*, *dir.L*)) (*q*,*inp*,*TUPLE*
t) ∈ *δ'* **unfolding** *δ'-def* **by** *blast*
hence *mem*: (*S q inp*, *TUPLE t*, *S*$_1$ *q* (*project-inp inp*), *TUPLE t*, *dir.L*) ∈ *δ'*
by *simp*
let *?cs1* = *Config*$_S$ (*S*$_1$ *q* (*project-inp inp*)) *tc' p'*
have (*cs0*,*?cs1*) ∈ *st.dstep* **unfolding** *cs0* **using** *inp*
by (*intro st.dstepI*[*OF mem*], *auto simp*: *tc' δ'-def blank'-def*)
moreover have *rel-S*$_1$ *?cs1 cm* **unfolding** *cm*
proof (*intro rel-S*$_1$*.intros 1 pip*)
fix *i*
from *inp* **have** *inp i* ∈ *SYM* ' Γ **by** *auto*
then obtain *g* **where** *inp i* = *SYM g* **and** *g* ∈ Γ **by** *auto*
thus *project-inp inp i* = *tc i* (*p i*) **using** *1*(*6*)[*of i*] **by** (*auto simp*: *project-inp-def*
split: *if-splits*)
show *p'* = *Suc* (*Max* (*range p*)) **unfolding** *assms*(*2*) **unfolding** *cm* **by** *simp*
qed
ultimately show *?thesis* **by** *auto*
qed

If we start the S-phase (in *rel-S*$_0$), and the multitape-TM is not in a final state, then we can move to the end of the S-phase (in *rel-S*$_1$).

lemma *S-phase*: **assumes** *rel-S*$_0$ *cs cm*
and *mt-state cm* ∉ {*t*, *r*}
shows ∃ *cs'*. (*cs*, *cs'*) ∈ *st.dstep*^^(*3* + *Max* (*range* (*mt-pos cm*))) ∧ *rel-S*$_1$ *cs'*
cm
proof −
let *?N* = *Max* (*range* (*mt-pos cm*))
from *rel-S*$_0$*-S*[*OF assms*] **obtain** *cs1 n* **where**
step1: (*cs*, *cs1*) ∈ *st.dstep* **and** *rel*: *rel-S cs1 cm n* **and** *n*: *n* = *0*
by *auto*
from *rel* **have** *n* + *k* ≤ *Suc ?N* ⟹ ∃ *cs2*. (*cs1*, *cs2*) ∈ *st.dstep* ^^ *k* ∧ *rel-S*
cs2 cm (*n* + *k*) **for** *k*
proof (*induction k arbitrary*: *cs1 n*)
case (*Suc k cs n*)
hence *n* ≤ *?N* **by** *auto*
from *rel-S-S*[*OF Suc*(*3*) *this*] **obtain** *cs1* **where** *step*: (*cs*, *cs1*) ∈ *st.dstep* **and**
rel: *rel-S cs1 cm* (*Suc n*) **by** *auto*
from *Suc* **have** *Suc n* + *k* ≤ *Suc ?N* **by** *auto*

from *Suc.IH*[*OF this rel*] **obtain** *cs2* **where** *steps*: (*cs1*, *cs2*) ∈ *st.dstep* ^^ *k* **and** *rel*: *rel-S cs2 cm* (*n* + *Suc k*) **by** *auto*
from *relpow-Suc-I2*[*OF step steps*] *rel*
show *?case* **by** *auto*
qed *auto*
from *this*[*of Suc ?N*, *unfolded n*] **obtain** *cs2* **where**
steps2: (*cs1*, *cs2*) ∈ *st.dstep* ^^ (*Suc ?N*) **and** *rel*: *rel-S cs2 cm* (*Suc ?N*) **by** *auto*
from *rel-S-S*$_1$[*OF rel*] **obtain** *cs3* **where** *step3*: (*cs2*,*cs3*) ∈ *st.dstep* **and** *rel*: *rel-S*$_1$ *cs3 cm* **by** *auto*
from *relpow-Suc-I2*[*OF step1 relpow-Suc-I*[*OF steps2 step3*]]
have (*cs*, *cs3*) ∈ *st.dstep* ^^ *Suc* (*Suc* (*Suc ?N*)) **by** *simp*
also have *Suc* (*Suc* (*Suc ?N*)) = *3* + *?N* **by** *simp*
finally show *?thesis* **using** *rel* **by** *blast*
qed

6.2.3 E-Phase

context
fixes *rule* :: ('*a*,'*q*,'*k*)*mt-rule*
begin
inductive-set *δstep* :: ('*a*, '*q*, '*k*) *mt-config rel* **where**
δstep: *rule* = (*q*, *a*, *q1*, *b*, *dir*) ⟹
rule ∈ *δ* ⟹
(⋀ *k*. *ts k* (*n k*) = *a k*) ⟹
(⋀ *k*. *ts'* *k* = (*ts k*)(*n k* := *b k*)) ⟹
(⋀ *k*. *n'* *k* = *go-dir* (*dir k*) (*n k*)) ⟹
(*Config*$_M$ *q ts n*, *Config*$_M$ *q1 ts' n'*) ∈ *δstep*
end

lemma *step-to-δstep*: (*c1*,*c2*) ∈ *step* ⟹ ∃ *rule*. (*c1*,*c2*) ∈ *δstep rule*
proof (*induct rule*: *step.induct*)
case (*step q ts n q' a dir*)
show *?case*
by (*rule exI*, *rule δstep.intros*[*OF refl step*], *auto*)
qed

lemma *δstep-to-step*: (*c1*,*c2*) ∈ *δstep rule* ⟹ (*c1*,*c2*) ∈ *step*
proof (*induct rule*: *δstep.induct*)
case ∗: (*δstep q a q' b dir ts n ts' n'*)
from ∗ **have** *a*: *a* = (λ *k*. *ts k* (*n k*)) **by** *auto*
from ∗ **have** *ts'*: *ts'* = (λ *k*. (*ts k*)(*n k* := *b k*)) **by** *auto*
from ∗ **have** *n'*: *n'* = (λ *k*. *go-dir* (*dir k*) (*n k*)) **by** *auto*
from ∗ **show** *?case* **using** *step.intros*[*of q ts n q' b dir*] **unfolding** *a ts' n'* **by** *auto*
qed

inductive *rel-E*$_0$ :: ((*'a*, *'k*) *st-tape-symbol*,(*'a*, *'q*, *'k*) *st-states*)*st-config*
⇒ (*'a*, *'q*, *'k*) *mt-config* ⇒ (*'a*, *'q*, *'k*) *mt-config* ⇒ (*'a*,*'q*,*'k*)*mt-rule* ⇒ *bool* **where**

tc′ 0 = ⊢ ⟹
(⋀ i. tc′ (Suc i) = enc (Config$_M$ q tc p) i) ⟹
valid-config (Config$_M$ q tc p) ⟹
rule = (q,a,q1,b,d) ⟹
(Config$_M$ q tc p, Config$_M$ q1 tc1 p1) ∈ δstep rule ⟹
(⋀ i. p i < p′) ⟹
p′ = Suc (Max (range p)) ⟹
rel-E$_0$ (Config$_S$ (E$_0$ q1 b d) tc′ p′) (Config$_M$ q tc p) (Config$_M$ q1 tc1 p1) rule

For the transition between S and E phase we do not have deterministic steps. Therefore we add two lemmas: the former one is for showing that multitape can be simulated by singletape, and the latter one is for the inverse direction.

lemma *rel-S$_1$-E$_0$-step*: **assumes** *rel-S$_1$ cs cm*
and *(cm,cm1) ∈ step*
shows *∃ rule cs1. (cs, cs1) ∈ st.step ∧ rel-E$_0$ cs1 cm cm1 rule*
proof −
from *step-to-δstep[OF assms(2)]* **obtain** *rule* **where** *rstep*: *(cm, cm1) ∈ δstep rule* **by** *auto*
show *?thesis* **using** *assms(1)*
proof *(cases rule*: *rel-S$_1$.cases)*
case *(1 tc′ q tc p inp p′)*
note *cs = 1(1)*
note *cm = 1(2)*
have *tc′*: *tc′ p′ ∈ Γ′* **unfolding** *1(8,4) enc.simps Γ′-def gamma-set-def* **using** *1(5)*
by *(force intro!*: *imageI)*
show *?thesis* **using** *rstep[unfolded cm]*
proof *(cases rule*: *δstep.cases)*
case *2*: *(δstep a q1 b dir ts′ n′)*
note *rule = 2(2)*
note *cm1 = 2(1)*
have *(λ((q, a, q′, b, d), t). (S$_1$ q a, t, E$_0$ q′ b d, t, dir.N)) (rule,tc′ p′) ∈ δ′*
unfolding *δ′-def* **using** *tc′ 2(3)* **by** *blast*
hence *mem*: *(S$_1$ q a, tc′ p′, E$_0$ q1 b dir, tc′ p′, dir.N) ∈ δ′* **by** *(auto simp*: *rule)*
have *inp-a*: *inp = a* **using** *2(4)[folded 1(6)]* **by** *auto*
let *?cs1 = Config$_S$ (E$_0$ q1 b dir) tc′ p′*
have *step*: *(cs, ?cs1) ∈ st.step* **unfolding** *cs*
by *(intro st.stepI[OF mem], insert inp-a, auto)*
moreover have *rel-E$_0$?cs1 cm cm1 rule* **unfolding** *cm cm1*
by *(intro rel-E$_0$.intros[OF - - - rule], insert 1 2 assms rstep, auto)*
ultimately show *?thesis* **by** *blast*
qed
qed
qed

lemma *rel-S$_1$-E$_0$-st-step*: **assumes** *rel-S$_1$ cs cm*
and *(cs,cs1) ∈ st.step*

shows $\exists$ *cm1 rule*. (*cm*, *cm1*) $\in$ *step* $\wedge$ *rel-E*$_0$ *cs1 cm cm1 rule*
using *assms*(*1*)
proof (*cases rule*: *rel-S*$_1$.*cases*)
case (*1 tc' q tc p inp p'*)
note *cs* = *1*(*1*)
note *cm* = *1*(*2*)
have *tc'*: *tc' p'* $\in$ Γ' **unfolding** *1*(*8*,*4*) *enc.simps* Γ'*-def gamma-set-def* **using** *1*(*5*)
by (*force intro*!: *imageI*)
show *?thesis* **using** *assms*(*2*)[*unfolded cs*]
proof (*cases rule*: *st.step.cases*)
case *2*: (*step qq bb ddir*)
from *2*(*2*)[*unfolded* δ'*-def*]
have (*S*$_1$ *q inp*, *tc' p'*, *qq*, *bb*, *ddir*) $\in$ (λ((*q*, *a*, *q'*, *b*, *d*), *t*). (*S*$_1$ *q a*, *t*, *E*$_0$ *q' b d*, *t*, *dir.N*)) ‘ (δ $\times$ Γ') **by** *auto*
then obtain *q' b dir* **where** *mem*: (*q*,*inp*,*q'*,*b*,*dir*) $\in$ δ **and** *qq*: *qq* = *E*$_0$ *q' b dir* **and** *ddir*: *ddir* = *dir.N*
and *bb*: *bb* = *tc' p'* **by** *auto*
hence *cs1*: *cs1* = *Config*$_S$ (*E*$_0$ *q' b dir*) *tc' p'* **unfolding** *2 qq ddir bb* **by** *auto*
let *?rule* = (*q*,*inp*,*q'*,*b*,*dir*)
let *?cm1* = *Config*$_M$ *q'* (λ *k*. (*tc k*)(*p k* := *b k*)) (λ *k*. *go-dir* (*dir k*) (*p k*))
have δ*step*: (*cm*, *?cm1*) $\in$ δ*step ?rule* **unfolding** *cm*
by (*intro* δ*step.intros*[*OF refl mem*], *auto simp*: *1*(*6*))
from δ*step-to-step*[*OF this*]
have (*cm*, *?cm1*) $\in$ *step* **.**
moreover have *rel-E*$_0$ *cs1 cm ?cm1 ?rule* **unfolding** *cm cs1*
by (*intro rel-E*$_0$*.intros* δ*step*[*unfolded cm*], *insert 1 2*, *auto*)
ultimately show *?thesis* **by** *blast*
qed
qed

fun *enc2* :: (*'a*, *'q*, *'k*) *mt-config* $\Rightarrow$ (*'a*, *'q*, *'k*) *mt-config* $\Rightarrow$ *nat* $\Rightarrow$ *nat* $\Rightarrow$ (*'a*, *'k*) *st-tape-symbol*
where *enc2* (*Config*$_M$ *q tc p*) (*Config*$_M$ *q1 tc1 p1*) *p' n* = *TUPLE* (λ *k*. *if p k* < *p'*
then if p k = *n then HAT* (*tc k n*) *else NO-HAT* (*tc k n*)
else if p1 k = *n then HAT* (*tc1 k n*) *else NO-HAT* (*tc1 k n*))

inductive *rel-E* :: ((*'a*, *'k*) *st-tape-symbol*,(*'a*, *'q*, *'k*) *st-states*)*st-config*
$\Rightarrow$ (*'a*, *'q*, *'k*) *mt-config* $\Rightarrow$ (*'a*, *'q*, *'k*) *mt-config* $\Rightarrow$ (*'a*,*'q*,*'k*)*mt-rule* $\Rightarrow$ *nat* $\Rightarrow$ *bool* **where**
tc' 0 = $\vdash$ $\Longrightarrow$
($\bigwedge$ *i*. *tc'* (*Suc i*) = *enc2* (*Config*$_M$ *q tc p*) (*Config*$_M$ *q1 tc1 p1*) *p' i*) $\Longrightarrow$
valid-config (*Config*$_M$ *q tc p*) $\Longrightarrow$
rule = (*q*,*a*,*q1*,*b*,*d*) $\Longrightarrow$
(*Config*$_M$ *q tc p*, *Config*$_M$ *q1 tc1 p1*) $\in$ δ*step rule* $\Longrightarrow$
bo = (λ *k*. *if p k* < *p' then SYM* (*b k*) *else* $\cdot$) $\Longrightarrow$
rel-E (*Config*$_S$ (*E q1 bo d*) *tc' p'*) (*Config*$_M$ *q tc p*) (*Config*$_M$ *q1 tc1 p1*) *rule p'*

lemma *rel-E_0-E*: **assumes** *rel-E_0 cs cm cm1 rule*
shows $\exists$ *cs1*. (*cs*, *cs1*) $\in$ *st.dstep* $\wedge$ *rel-E cs1 cm cm1 rule* (*Suc* (*Max* (*range* (*mt-pos cm*))))
using *assms*(*1*)
proof (*cases rule*: *rel-E_0.cases*)
case (*1 tc′ q tc p a q1 b d tc1 p1 p′*)
note *cs* = *1*(*1*)
note *cm* = *1*(*2*)
note *cm1* = *1*(*3*)
note *rule* = *1*(*7*)
let *?rule* = (*q*, *a*, *q1*, *b*, *d*)
have *tc′*: *tc′ p′* $\in$ Γ' **unfolding** *1*(*10*,*5*) *enc.simps* Γ'*-def gamma-set-def* **using** *1*(*6*)
by (*force intro*!: *imageI*)
have *rmem*: *?rule* $\in$ δ **using** *1*(*8*,*7*) **by** (*cases rule*: δ*step.cases*, *auto*)
note *elem* = δ[*OF this*]
have ((*q1*,*b*,*d*), *tc′ p′*) $\in$ (*Q* $\times$ (*UNIV* $\to$ Γ) $\times$ *UNIV*) $\times$ Γ'
using *elem tc′* **by** *auto*
hence (λ((*q*, *a*, *d*), *t*). (*E_0 q a d*, *t*, *E q* (*SYM* $\circ$ *a*) *d*, *t*, *dir.N*)) ((*q1*,*b*,*d*), *tc′ p′*) $\in$ δ'
unfolding δ'*-def* **by** *blast*
hence *mem*: (*E_0 q1 b d*, *tc′ p′*, *E q1* (*SYM* $\circ$ *b*) *d*, *tc′ p′*, *dir.N*) $\in$ δ' **by** *simp*
have *Max*: *Suc* (*Max* (*range* (*mt-pos cm*))) = *p′* **unfolding** *cm* **using** *1* **by** *auto*
let *?cs1* = *Config$_S$* (*E q1* (*SYM* $\circ$ *b*) *d*) *tc′ p′*
have (*cs*, *?cs1*) $\in$ *st.dstep* **unfolding** *cs*
by (*intro st.dstepI*[*OF mem*] *refl*, *auto simp*: δ'*-def*)
moreover have *rel-E ?cs1 cm cm1 rule* (*Suc* (*Max* (*range* (*mt-pos cm*))))
unfolding *Max* **unfolding** *cm cm1 rule*
by (*intro rel-E.intros*, *insert 1*, *auto*)
ultimately show *?thesis* **by** *blast*
qed

lemma *rel-E-S_0*: **assumes** *rel-E cs cm cm1 rule 0*
shows $\exists$ *cs1*. (*cs*,*cs1*) $\in$ *st.dstep* $\wedge$ *rel-S_0 cs1 cm1*
using *assms*(*1*)
proof (*cases rule*: *rel-E.cases*)
case (*1 tc′ q tc p q1 tc1 p1 a b d bo*)
note *cs* = *1*(*1*)
note *cm* = *1*(*2*)
note *cm1* = *1*(*3*)
from *valid-step*[*OF* δ*step-to-step*[*OF 1*(*8*)] *1*(*6*)]
have *valid*: *valid-config* (*Config$_M$ q1 tc1 p1*) .
from *valid* **have** *q1*: *q1* $\in$ *Q* **by** *auto*
hence *mem*: (*E q1* (λ -. $\cdot$) *d*, $\vdash$, *S_0 q1*, $\vdash$, *dir.N*) $\in$ δ' **unfolding** δ'*-def* **by** *auto*
let *?cs1* = *Config$_S$* (*S_0 q1*) *tc′ 0*
have (*cs*, *?cs1*) $\in$ *st.dstep* **unfolding** *cs*
by (*intro st.dstepI*[*OF mem*], *insert 1*, *auto simp*: δ'*-def*)
moreover have *rel-S_0 ?cs1 cm1* **unfolding** *cm1*
by (*intro rel-S_0.intros valid*, *insert 1*, *auto*)

ultimately show *?thesis* **by** *blast*
qed

lemma *dsteps-to-steps*: $a \in st.dstep \hat{\ }\hat{\ } n \Longrightarrow a \in st.step \hat{\ }\hat{\ } n$
using *relpow-mono*[*OF st.dstep-step*] **by** *auto*

lemma δ'*-mem*: **assumes** *tup* $\in A$
and f ‘ $A \subseteq \delta'$
shows f *tup* $\in \delta'$
using *assms* **by** *auto*

lemma *rel-E-E*: **assumes** *rel-E cs cm cm1 rule* (*Suc p'*)
shows $\exists$ *cs1*. (*cs*,*cs1*) $\in$ *st.dstep*$\hat{\ }\hat{\ }$*4* $\wedge$ *rel-E cs1 cm cm1 rule p'*
using *assms*
proof(*cases rule*: *rel-E.cases*)
case (*1 tc' q tc p q1 tc1 p1 a b d bo*)
let *?rule* = (*q*, *a*, *q1*, *b*, *d*)
have *valid-next*: *valid-config*(*Config*$_M$ *q1 tc1 p1*)
using *1*(*8*,*6*) δ*step-to-step valid-step* **by** *blast*
have *trans*: (λ(*q*, *ys*, *ds*, *t*). (*E q ys ds*, *TUPLE t*, *Er q* (*update-ys t ys*) *ds* (*compute-idx-set t ys*),
TUPLE (*replace-sym t ys*), *dir.R*)) ‘ (*Q* × *func-set* × *UNIV* × *gamma-set*) $\subseteq \delta'$
(λ(*q*, *ys*, *ds*, *I*, *t*). (*Er q ys ds I*, *TUPLE t*, *Em q ys ds I*, *TUPLE* (*place-hats-R t ds I*), *dir.L*))
‘ (*Q* × *func-set* × *UNIV* × *UNIV* × *gamma-set*) $\subseteq \delta'$
(λ(*q*, *ys*, *ds*, *I*, *t*). (*Em q ys ds I*, *TUPLE t*, *El q ys ds I*, *TUPLE* (*place-hats-M t ds I*), *dir.L*))
‘ (*Q* × *func-set* × *UNIV* × *UNIV* × *gamma-set*) $\subseteq \delta'$
(λ(*q*, *ys*, *ds*, *I*). (*El q ys ds I*, $\vdash$, *E q ys ds*, $\vdash$, *dir.N*))
‘ (*Q* × *func-set* × *UNIV* × *Pow UNIV*) $\subseteq \delta'$
(λ (*q*,*ys*,*ds*,*I*,*t*). (*El q ys ds I*, *TUPLE t*, *E q ys ds*, *TUPLE* (*place-hats-L t ds I*), *dir.N*))
‘ (*Q* × *func-set* × *UNIV* × *UNIV* × *gamma-set*) $\subseteq \delta'$
unfolding δ'*-def*
by(*blast*, *blast*, *blast*, *blast*, *blast*)

obtain *tup* **where** *tup*: *tc'* (*Suc p'*) = *TUPLE tup*
unfolding *1*(*5*) Γ'*-def gamma-set-def enc2.simps* **by** *auto*
have *tup-mem*: *tup* $\in$ *gamma-set*
using *tup 1*(*6*) *valid-next* **unfolding** *gamma-set-def 1*(*5*) *enc2.simps valid-config.simps*
by (*smt* (*z3*) *Pi-iff UnI1 UnI2 image-iff range-subsetD st-tape-symbol.simps*(*1*))
have *bo-set*: *bo* $\in$ *func-set*
using *1* δ(*4*) δ*step.simps* **unfolding** *func-set-def* **by** *fastforce*
have *rmem*: *?rule* $\in \delta$ **using** *1*(*8*,*7*) **by** (*cases rule*: δ*step.cases*, *auto*)
note *elem* = δ[*OF this*]
let *?rep-tup* = *TUPLE* (*replace-sym tup bo*)
let *?tc1* = (*tc'*(*Suc p'* := *?rep-tup*))
let *?I* = *compute-idx-set tup bo*

let *?ys′ = update-ys tup bo*
let *?er = Er q1 ?ys′ d ?I*
let *?cs1 = Config$_S$?er ?tc1 (Suc(Suc p′))*
have *(q1,bo,d,tup) ∈ Q × func-set × UNIV × gamma-set* **using** *elem tup-mem bo-set* **by** *blast*
hence *mem: (E q1 bo d, tc′ (Suc p′), ?er, ?rep-tup, dir.R) ∈ δ′*
using *δ′-mem[OF - trans(1)]* **unfolding** *split tup* **by** *fast*
note *dstep-help = st.dstep[of E q1 bo d tc′ (Suc p′) ?er ?rep-tup dir.R]*
have *to-r: (Config$_S$ (E q1 bo d) tc′ (Suc p′), ?cs1) ∈ st.dstep*
using *dstep-help[OF mem]* **unfolding** *δ′-def go-dir.simps tup* **by** *fast*

obtain *tup2* **where** *tup2: tc′ (Suc(Suc p′)) = TUPLE tup2*
unfolding *1(5) Γ′-def gamma-set-def enc2.simps* **by** *auto*
have *tup2-mem: tup2 ∈ gamma-set*
using *tup2 1(6) valid-next*
unfolding *gamma-set-def 1(5) enc2.simps valid-config.simps*
by *(smt (z3) Pi-iff UnI1 UnI2 imageI range-subsetD st-tape-symbol.inject(1))*
let *?em = Em q1 ?ys′ d ?I*
let *?tc2 = (?tc1(Suc(Suc p′) := TUPLE (place-hats-R tup2 d ?I)))*
let *?cs2 = Config$_S$?em ?tc2 (Suc p′)*
have *(q1,?ys′,d,?I,tup2) ∈ Q × func-set × UNIV × UNIV × gamma-set*
using *update-ys-range[OF tup-mem bo-set] elem tup2-mem* **by** *blast*
hence *mem2: (?er, ?tc1 (Suc(Suc p′)), Em q1 ?ys′ d ?I, TUPLE (place-hats-R tup2 d ?I), dir.L) ∈ δ′*
using *δ′-mem[OF - trans(2)] tup2* **unfolding** *split* **by** *auto*
note *dstep-help2 = st.dstep[of ?er ?tc1 Suc(Suc p′) ?em TUPLE (place-hats-R tup2 d ?I) dir.L]*
have *to-m: (?cs1, ?cs2) ∈ st.dstep*
using *dstep-help2[OF mem2] tup2* **unfolding** *δ′-def go-dir.simps* **by** *fastforce*

have *(q1,?ys′,d,?I,replace-sym tup bo) ∈ Q × func-set × UNIV × UNIV × gamma-set*
using *update-ys-range[OF tup-mem bo-set] replace-sym-range[OF tup-mem bo-set] elem(3)* **by** *blast*
hence *mem3: (?em, ?tc2 (Suc p′), El q1 ?ys′ d ?I, TUPLE (place-hats-M (replace-sym tup bo) d ?I), dir.L) ∈ δ′*
using *δ′-mem[OF - trans(3)]* **by** *auto*
note *dstep-help3 = st.dstep[of ?em ?tc2 Suc p′ El q1 ?ys′ d ?I TUPLE (place-hats-M (replace-sym tup bo) d ?I) dir.L]*
let *?el = El q1 (update-ys tup bo) d (compute-idx-set tup bo)*
let *?tc3 = tc′(Suc p′ := TUPLE (replace-sym tup bo),*
Suc (Suc p′) := TUPLE (place-hats-R tup2 d (compute-idx-set tup bo)),
Suc p′ := TUPLE (place-hats-M (replace-sym tup bo) d (compute-idx-set tup bo)))
let *?cs3 = Config$_S$?el ?tc3 p′*
have *to-l: (?cs2, ?cs3) ∈ st.dstep*
using *dstep-help3[OF mem3]* **unfolding** *δ′-def go-dir.simps* **by** *fastforce*

have *steps3*: $(cs,\ ?cs3) \in st.dstep\ ^{\frown\frown}\ 3$ **unfolding** *numeral-3-eq-3* **using** *to-l to-m to-r 1(1)* **by** *auto*

have *tc1-def*: $\bigwedge k.\ tc1\ k = (tc\ k)(p\ k := b\ k)$
using *1(8)* **unfolding** *1(7)* **by** (*simp add*: *δstep.simps old.prod.inject*)
have *p1-def*: $\bigwedge k.\ p1\ k = go\text{-}dir\ (d\ k)\ (p\ k)$
using *1(8)* **unfolding** *1(7)* **by** (*simp add*: *δstep.simps old.prod.inject*)
have *not-I-mem-current-pos*: $\forall\ k'.\ k' \notin ?I \longrightarrow p\ k' \neq p'$
by(*intro allI impI*, *insert tup elem 1(6)*, *fastforce simp*: *1 compute-idx-set-def*)
have *I-mem-current-pos*: $\forall\ k.\ k \in ?I \longrightarrow p\ k = p'$
using *compute-idx-set-def 1(5,9) tup* **by**(*simp*, *fastforce*)
have *I-mem-eq-cur-pos*: $\forall\ k.\ k \in ?I \longleftrightarrow p\ k = p'$
using *I-mem-current-pos not-I-mem-current-pos* **by** *auto*
show *?thesis*
proof(*cases p′*)
case *p-zero*: *0*
hence *tc3-tup*: *?tc3 p′* $= \vdash$ **using** *1(4)* **by** *simp*
have (*q1*,*?ys′*,*d*,*?I*) $\in Q \times$ *func-set* $\times$ *UNIV* $\times$ *UNIV*
using *update-ys-range*[*OF tup-mem bo-set*] *replace-sym-range*[*OF tup-mem bo-set*] *elem(3)* **by** *blast*
hence *mem4*: (*El q1 ?ys′ d ?I*, *?tc3 p′*, *E q1 ?ys′ d*, $\vdash$, *dir.N*) $\in \delta'$
using *δ′-mem*[*OF - trans(4)*] **unfolding** *tc3-tup* **by** *auto*
let *?tc4* $=$ *?tc3*$(p' := \vdash)$
let *?cs4* $=$ $Config_S$ (*E q1 ?ys′ d*) *?tc4 p′*
note *dstep-help4* $=$ *st.dstep*[*of El q1 ?ys′ d ?I ?tc3 p′ E q1 ?ys′ d* $\vdash$ *dir.N*]
have (*?cs3*, *?cs4*) $\in$ *st.dstep* $^{\frown\frown}$ *1*
using *dstep-help4*[*OF mem4*] **unfolding** *δ′-def go-dir.simps relpow-1 tc3-tup* **by** *fastforce*
hence *steps*: $(cs,\ ?cs4) \in$ *st.dstep* $^{\frown\frown}$ *4*
using *relpow-transI*[*OF steps3*] **by** *fastforce*
note *intro-helper* $=$ *rel-E.intros*[*of ?tc4 q tc p q1 tc1 p1 p′ rule a b d update-ys tup bo*]
have *valid-subs*: $(\forall\ i.\ (tc'(Suc\ p' := TUPLE\ (replace\text{-}sym\ tup\ bo),$
$Suc\ (Suc\ p') := TUPLE\ (place\text{-}hats\text{-}R\ tup2\ d\ (compute\text{-}idx\text{-}set\ tup\ bo)),$
$Suc\ p' := TUPLE\ (place\text{-}hats\text{-}M\ (replace\text{-}sym\ tup\ bo)\ d\ (compute\text{-}idx\text{-}set\ tup\ bo)),$
$p' := \vdash))\ (Suc\ i) = enc2\ (Config_M\ q\ tc\ p)\ (Config_M\ q1\ tc1\ p1)\ p'\ i)$
proof
fix *i*
consider (*zer*) $i = 0$ | (*suc*) $i = Suc\ 0$ | (*ge-one*) $i > Suc\ 0$ **by** *linarith*
then show $(tc'(Suc\ p' := TUPLE\ (replace\text{-}sym\ tup\ bo),$
$Suc\ (Suc\ p') := TUPLE\ (place\text{-}hats\text{-}R\ tup2\ d\ (compute\text{-}idx\text{-}set\ tup\ bo)),$
$Suc\ p' := TUPLE\ (place\text{-}hats\text{-}M\ (replace\text{-}sym\ tup\ bo)\ d\ (compute\text{-}idx\text{-}set\ tup\ bo)),$
$p' := \vdash))\ (Suc\ i) = enc2\ (Config_M\ q\ tc\ p)\ (Config_M\ q1\ tc1\ p1)\ p'\ i$
proof(*cases*)
case *zer*
have (*case replace-sym tup bo k of*

NO-HAT a ⇒ if k ∈ compute-idx-set tup bo ∧ d k = dir.N then HAT a else NO-HAT a
| *HAT x ⇒ HAT x*) = (*if p1 k = 0 then HAT* (*tc1 k 0*) *else NO-HAT* (*tc1 k 0*)) **for** *k*
proof(*cases k ∈ ?I*)
case *k-in-I*: *True*
then obtain *x* **where** *rep-no-hat*: *replace-sym tup bo k = NO-HAT x*
unfolding *replace-sym-def compute-idx-set-def* **by** *auto*
have *pk-zero*: *p k = 0*
using *k-in-I less-Suc0 p-zero* **unfolding** *compute-idx-set-def 1*(*9*) **by** *fastforce*
show *?thesis*
proof(*cases d k = dir.N*)
case *False*
moreover have *tc k* (*p k*) = *LE*
using *1*(*6*) *pk-zero 1*(*8*) **by** *auto*
moreover have *tc k* (*p k*) = *a k*
using *1*(*7*,*8*) *pk-zero* **unfolding** *δstep.simps* **by** *blast*
ultimately have *d k = dir.R*
using *δLE*[*OF rmem*] **by** *auto*
then show *?thesis*
by(*insert k-in-I p1-def tc1-def*, *simp*, *insert rep-no-hat*, *auto simp*: *replace-sym-def 1*(*9*) *p-zero pk-zero*)
qed(*insert k-in-I rep-no-hat pk-zero 1*(*9*), *auto simp*: *replace-sym-def tc1-def p1-def*)
next
case *False*
show *?thesis*
using *tup False 1*(*5*) *p-zero not-I-mem-current-pos p1-def tc1-def*
unfolding *p-zero replace-sym-def* **by** *fastforce*
qed
then show *?thesis*
unfolding *zer p-zero place-hats-M-def place-hats-to-dir-def* **by** *simp*
next
case *suc*
have (*case tup2 k of*
NO-HAT a ⇒ if k ∈ compute-idx-set tup bo ∧ d k = dir.R then HAT a else NO-HAT a
| *HAT x ⇒ HAT x*) = (*if p1 k = Suc 0 then HAT* (*tc1 k* (*Suc 0*)) *else NO-HAT* (*tc1 k* (*Suc 0*))) **for** *k*
using *tup2 p-zero elem*(*4*) *1*(*5*,*6*,*9*) *gr-zeroI tm*(*4*) *tup*
by (*auto simp*: *compute-idx-set-def tc1-def p1-def*, *smt* (*verit*, *best*) *diff-0-eq-0 go-dir.elims not-gr0*)
then show *?thesis* **unfolding** *suc p-zero place-hats-R-def place-hats-to-dir-def* **by** *simp*
next
case *ge-one*
have (*if p k = 0 then if p k = i then HAT* (*tc k i*) *else NO-HAT* (*tc k i*)
else if p1 k = i then HAT (*tc1 k i*) *else NO-HAT* (*tc1 k i*)) = (*if p1 k = i*

then HAT (tc1 k i) else NO-HAT (tc1 k i)) **for** *k*
using *insert ge-one p1-def tc1-def*
by (*smt* (*verit*, *ccfv-threshold*) *diff-0-eq-0 fun-upd-other go-dir.elims less-irrefl-nat less-nat-zero-code*)
then show *?thesis* **using** *ge-one p-zero 1(5)*[*of i*] *enc2.simps* **by** *simp*
qed
qed
have *only-hats*: $\bigwedge$ *k. p k = 0* $\longrightarrow$ *tup k* $\in$ *HAT* ‘ Γ
using *tup* **unfolding** *p-zero 1(5)*[*of 0*] *enc2.simps* **by** (*simp*, *meson imageI tup-hat-content tup-mem*)
have (*if k* $\in$ *compute-idx-set tup bo then* $\cdot$ *else bo k*) = $\cdot$ **for** *k*
using *only-hats elem(4) 1(9)* **by** (*auto simp*: *compute-idx-set-def p-zero*)
hence *replaced-all*: *update-ys tup bo* = (λ*k. if p k < p′ then SYM* (*b k*) *else* $\cdot$)
unfolding *update-ys-def p-zero* **by** *auto*
have *invs*: *rel-E ?cs4 cm cm1 rule p′*
using *valid-subs p-zero intro-helper*[*OF - - 1(6) 1(7) 1(8) replaced-all*] *1(2,3,7)* **by** *auto*
then show *?thesis*
by(*insert steps invs*, *intro exI conjI*, *auto*)
next
case (*Suc nat*)
obtain *tup3* **where** *tc3-p′*: *?tc3 p′* = *TUPLE tup3* **and**
tup3-def: *tup3* = (λ*k. if p k < Suc* (*Suc nat*) *then if p k = nat then HAT* (*tc k nat*) *else NO-HAT* (*tc k nat*)
else if p1 k = nat then HAT (*tc1 k nat*) *else NO-HAT* (*tc1 k nat*))
using *1(5)*[*of nat*] **unfolding** *Suc enc2.simps* **by** *simp*
have *tup3-mem*: *tup3* $\in$ *gamma-set*
using *tup3-def 1(6) valid-next* **unfolding** *gamma-set-def 1(5) enc2.simps valid-config.simps*
by (*smt* (*z3*) *Pi-I UnI1 UnI2 imageI range-subsetD st-tape-symbol.inject*(*1*))
let *?a4* = *TUPLE* (*place-hats-L tup3 d* (*compute-idx-set tup bo*))
let *?tc4* = *?tc3*(*p′* := *?a4*)
let *?cs4* = *Config*$_S$ (*E q1 ?ys′ d*) *?tc4 p′*
have *step-mem*:(*q1*, *?ys′*, *d*, *?I*, *tup3*) $\in$ *Q* $\times$ *func-set* $\times$ *UNIV* $\times$ *UNIV* $\times$ *gamma-set*
using *update-ys-range*[*OF tup-mem bo-set*] *replace-sym-range*[*OF tup-mem bo-set*] *elem(3) tup3-mem* **by** *blast*
have *mem5*: (*El q1 ?ys′ d ?I*, *?tc3 p′*, *E q1 ?ys′ d*, *TUPLE* (*place-hats-L tup3 d* (*compute-idx-set tup bo*)), *dir.N*) $\in$ δ'
using δ'*-mem*[*OF step-mem trans*(*5*)] **unfolding** *split tc3-p′* **.**
note *dstep-help5* = *st.dstep*[*of El q1 ?ys′ d ?I ?tc3 p′ E q1 ?ys′ d ?a4 dir.N*]
note *intros-helper2* = *rel-E.intros*[*of ?tc4 q tc p q1 tc1 p1 p′ rule a b d update-ys tup bo*]
have *correct-shift*: (*tc′*(*Suc p′* := *TUPLE* (*replace-sym tup bo*),
Suc (*Suc p′*) := *TUPLE* (*place-hats-R tup2 d* (*compute-idx-set tup bo*)),
Suc p′ := *TUPLE* (*place-hats-M* (*replace-sym tup bo*) *d* (*compute-idx-set tup bo*)),
p′ := *TUPLE* (*place-hats-L tup3 d* (*compute-idx-set tup bo*))))
(*Suc i*) = *enc2* (*Config*$_M$ *q tc p*) (*Config*$_M$ *q1 tc1 p1*) *p′ i* **for** *i*

proof −
consider (*one*) *Suc i = Suc nat*
| (*two*) *Suc i = Suc*(*Suc nat*)
| (*three*) *Suc i = Suc*(*Suc*(*Suc nat*))
| (*else*) *Suc i* ∉ {*Suc nat* ,*Suc*(*Suc nat*), *Suc*(*Suc*(*Suc nat*))} **by** *blast*
then show *?thesis*
proof *cases*
case *one*
have (*case tup3 k of*
NO-HAT a ⇒ *if k* ∈ *compute-idx-set tup bo* ∧ *d k = dir.L then HAT a else NO-HAT a*
| *HAT x* ⇒ *HAT x*) = (*if p k < Suc nat then if p k = i then HAT* (*tc k i*) *else NO-HAT* (*tc k i*)
else if p1 k = i then HAT (*tc1 k i*) *else NO-HAT* (*tc1 k i*)) **for** *k*
using *one I-mem-eq-cur-pos Suc nat-less-le*
by (*cases d k*, *auto simp*: *tc1-def p1-def tup3-def compute-idx-set-def*)
then show *?thesis*
using *one* **unfolding** *Suc place-hats-L-def place-hats-to-dir-def* **by** *auto*
next
case *two*
have (*case replace-sym tup bo k of*
NO-HAT a ⇒ *if k* ∈ *compute-idx-set tup bo* ∧ *d k = dir.N then HAT a else NO-HAT a*
| *HAT x* ⇒ *HAT x*) = (*if p k < Suc nat then if p k = i then HAT* (*tc k i*) *else NO-HAT* (*tc k i*)
else if p1 k = i then HAT (*tc1 k i*) *else NO-HAT* (*tc1 k i*)) **for** *k*
using *two 1*(*5*,*9*) *Suc tup elem*(*4*) *not-I-mem-current-pos*
by (*cases d k*, *auto simp*: *replace-sym-def compute-idx-set-def p1-def tc1-def*)
then show *?thesis*
unfolding *two Suc enc2.simps place-hats-M-def place-hats-to-dir-def* **by** *simp*
next
case *three*
have (*case tup2 k of*
NO-HAT a ⇒ *if k* ∈ *compute-idx-set tup bo* ∧ *d k = dir.R then HAT a else NO-HAT a*
| *HAT x* ⇒ *HAT x*) = (*if p k < Suc nat then if p k = i then HAT* (*tc k i*) *else NO-HAT* (*tc k i*)
else if p1 k = i then HAT (*tc1 k i*) *else NO-HAT* (*tc1 k i*)) **for** *k*
using *three p1-def tc1-def compute-idx-set-def tup2 Suc 1*(*9*) *elem*(*4*) *I-mem-eq-cur-pos less-SucE*
unfolding *1*(*5*) *enc2.simps* **by** (*cases d k*, *auto*)
then show *?thesis*
unfolding *three Suc enc2.simps place-hats-R-def place-hats-to-dir-def* **by** *simp*
next
case *else*
have (*if p k < Suc* (*Suc nat*) *then if p k = i then HAT* (*tc k i*) *else NO-HAT* (*tc k i*)

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        else if p1 k = i then HAT (tc1 k i) else NO-HAT (tc1 k i)) =
       (if p k < Suc nat then if p k = i then HAT (tc k i) else NO-HAT (tc k i)
        else if p1 k = i then HAT (tc1 k i) else NO-HAT (tc1 k i)) for k
         unfolding 1(5) enc2.simps Suc
         using else  p1-def tc1-def
         by (cases d k) auto
       then show ?thesis
         using else Suc 1(5) enc2.simps by auto
     qed
   qed
   have correct-replace: update-ys tup bo = (λk. if p k < p' then SYM (b k) else
·)
     by(insert I-mem-eq-cur-pos 1(9), auto simp: Suc update-ys-def)
   have step: (?cs3, ?cs4) ∈ st.dstep ^^ 1
     using mem5 dstep-help5[OF mem5]
     unfolding δ'-def go-dir.simps relpow-1 Suc by fastforce
   hence (cs, ?cs4) ∈ st.dstep ^^ 4
     using relpow-transI[OF steps3 step] by simp
   moreover have rel-E ?cs4 cm cm1 rule p'
    using Suc 1 intros-helper2[OF - - 1(6) 1(7) 1(8) correct-replace] correct-shift
by simp
   ultimately show ?thesis by blast
 qed
qed

lemma E-phase: assumes rel-E0 cs cm cm1 rule
 shows ∃ cs'. (cs,cs') ∈ st.dstep ^^ (6 + 4 * Max (range (mt-pos cm))) ∧ rel-S0
cs' cm1
proof −
 from rel-E0-E[OF assms] obtain n cs1 where step1: (cs, cs1) ∈ st.dstep
   and n: n = Suc (Max (range (mt-pos cm)))
   and rel: rel-E cs1 cm cm1 rule n
   by auto
 from rel have ∃ cs2. (cs1,cs2) ∈ st.dstep^^(4 * n) ∧ rel-E cs2 cm cm1 rule 0
 proof (induction n arbitrary: cs1 rule: nat-induct)
   case (Suc n)
   from rel-E-E[OF Suc.prems] obtain cs' where
     step4: (cs1, cs') ∈ st.dstep ^^ 4 and rel: rel-E cs' cm cm1 rule n by auto
   from Suc.IH[OF rel] obtain cs2 where
     steps: (cs', cs2) ∈ st.dstep ^^ (4 * n) and rel: rel-E cs2 cm cm1 rule 0
     by auto
   from relpow-transI[OF step4 steps] rel show ?case by auto
 qed auto
 then obtain cs2 where steps2: (cs1,cs2) ∈ st.dstep^^(4 * n) and rel: rel-E
cs2 cm cm1 rule 0 by auto
 from rel-E-S0[OF rel] obtain cs' where step3: (cs2, cs') ∈ st.dstep and rel:
rel-S0 cs' cm1 by auto
 from relpow-Suc-I2[OF step1 relpow-Suc-I[OF steps2 step3]]
 have (cs, cs') ∈ st.dstep ^^ Suc (Suc (4 * n)) by simp
```

also have *Suc (Suc (4 * n)) = 6 + 4 * Max (range (mt-pos cm))* **unfolding** *n*
by *simp*
finally show *?thesis* **using** *rel* **by** *auto*
qed

6.2.4 Simulation of multitape TM by singletape TM

lemma *step-simulation*: **assumes** *rel-S_0 cs cm*
and *(cm, cm') ∈ step*
shows *∃ cs'. (cs,cs') ∈ st.step ^^ (10 + 5 * Max (range (mt-pos cm))) ∧ rel-S_0 cs' cm'*
proof −
let *?n = Max (range (mt-pos cm))*
from *assms(2)* **have** *mt-state cm ∉ {t, r}* **using** *δ-set*
by *(cases, auto)*
from *S-phase[OF assms(1) this]* **obtain** *cs1* **where**
steps1: *(cs, cs1) ∈ st.dstep ^^ (3 + ?n)* **and** *rel*: *rel-S_1 cs1 cm*
by *auto*
from *rel-S_1-E_0-step[OF rel assms(2)]* **obtain** *r cs2* **where**
step2: *(cs1, cs2) ∈ st.step* **and** *rel*: *rel-E_0 cs2 cm cm' r*
by *auto*
from *E-phase[OF rel]* **obtain** *cs'* **where**
steps3: *(cs2, cs') ∈ st.dstep ^^ (6 + 4 * ?n)* **and** *rel*: *rel-S_0 cs' cm'*
by *auto*
from *relpow-transI[OF dsteps-to-steps[OF steps1] relpow-Suc-I2[OF step2 dsteps-to-steps[OF steps3]]]*
have *(cs, cs') ∈ st.step ^^ ((3 + ?n) + Suc (6 + 4 * ?n))* **by** *simp*
also have *((3 + ?n) + Suc (6 + 4 * ?n)) = 10 + 5 * ?n* **by** *simp*
finally show *?thesis* **using** *rel* **by** *auto*
qed

lemma *steps-simulation-main*: **assumes** *rel-S_0 cs cm*
and *Max (range (mt-pos cm)) ≤ N*
and *(cm, cm') ∈ step^^n*
shows *∃ m cs'. (cs,cs') ∈ st.step^^m ∧ rel-S_0 cs' cm' ∧ m ≤ sum (λ i. 10 + 5 * (N + i)) {..< n} ∧ Max (range (mt-pos cm')) ≤ N + n*
using *assms(3,1,2)*
proof *(induct n arbitrary: cm' N)*
case *0*
show *?case*
by *(intro exI[of - 0] exI[of - cs], insert 0, auto)*
next
case *(Suc n cm' N)*
from *Suc(2)* **obtain** *cm''* **where** *(cm,cm'') ∈ step^^n* **and** *step*: *(cm'', cm') ∈ step* **by** *auto*
from *Suc(1)[OF this(1) Suc(3−4)]* **obtain** *m cs''* **where**
steps: *(cs, cs'') ∈ st.step ^^ m* **and** *m*: *m ≤ (∑ i < n. 10 + 5 * (N + i))* **and** *rel*: *rel-S_0 cs'' cm''* **and** *max*: *Max (range (mt-pos cm'')) ≤ N + n*
by *auto*

from *step-simulation*[*OF rel step*] **obtain** *cs'* **where**
steps2: $(cs'', cs') \in st.step \hat{}\hat{} (10 + 5 * Max\ (range\ (mt\text{-}pos\ cm'')))$ **and** *rel*: *rel-S*$_0$ *cs' cm'* **by** *auto*
let *?m* = $m + (10 + 5 * Max\ (range\ (mt\text{-}pos\ cm'')))$
from *relpow-transI*[*OF steps steps2*]
have *steps*: $(cs, cs') \in st.step \hat{}\hat{} ?m$ **by** *auto*
show *?case*
proof (*intro exI conjI*, *rule steps*, *rule rel*)
from *max-mt-pos-step*[*OF step*] *max*
show $Max\ (range\ (mt\text{-}pos\ cm')) \leq N + Suc\ n$ **by** *linarith*
have *id*: $\{..<Suc\ n\} = insert\ n\ \{..<n\}$ **by** *auto*
have $?m \leq m + (10 + 5 * (N + n))$ **using** *max* **by** *presburger*
also have $\ldots \leq (\sum i < Suc\ n.\ 10 + 5 * (N + i))$ **using** *m* **unfolding** *id* **by** *auto*
finally show $?m \leq (\sum i < Suc\ n.\ 10 + 5 * (N + i))$ **by** *auto*
qed
qed

lemma *steps-simulation-rel-S*$_0$: **assumes** *rel-S*$_0$ *cs* (*init-config w*)
and $(init\text{-}config\ w, cm') \in step\hat{}\hat{}n$
shows $\exists\ m\ cs'.\ (cs,cs') \in st.step\hat{}\hat{}m \wedge$ *rel-S*$_0$ *cs' cm'* $\wedge\ m \leq 3 * n\hat{}2 + 7 * n$
proof −
from *steps-simulation-main*[*OF assms*(1) - *assms*(2), *unfolded max-mt-pos-init*, *OF le-refl*]
obtain *m cs'* **where** *steps*: $(cs, cs') \in st.step \hat{}\hat{} m$ **and** *rel*: *rel-S*$_0$ *cs' cm'* **and** *m*: $m \leq (\sum i{<}n.\ 10 + 5 * i)$
by *auto*
have $m \leq (\sum i{<}n.\ 10 + 5 * i)$ **by** *fact*
also have $\ldots \leq 3 * n\hat{}2 + 7 * n$ **using** *aux-sum-formula* **.**
finally show *?thesis* **using** *steps rel* **by** *auto*
qed

lemma *simulation-with-complexity*: **assumes** *w*: *set w* $\subseteq \Sigma$
and *steps*: $(init\text{-}config\ w, Config_M\ q\ mtape\ p) \in step\hat{}\hat{}n$
shows $\exists$ *stape k*. $(st.init\text{-}config\ (map\ INP\ w), Config_S\ (S_0\ q)\ stape\ 0) \in st.step\hat{}\hat{}k$ $\wedge\ k \leq 2 * length\ w + 3 * n\hat{}2 + 7 * n + 3$
proof −
let *?INP* = *INP* :: *'a* ⇒ (*'a*, *'k*) *st-tape-symbol*
let *?initm* = *init-config w*
define *x* **where** *x* = *map ?INP w*
from *R-phase*[*OF w*, *folded x-def*] **obtain** *cs* **where**
steps1: $(st.init\text{-}config\ x, cs) \in st.dstep \hat{}\hat{} (3 + 2 * length\ w)$ **and** *rel*: *rel-S*$_0$ *cs ?initm*
by *auto*
from *steps-simulation-rel-S*$_0$[*of - w*, *OF rel steps*] **obtain** *k' cs'* **where**
steps2: $(cs, cs') \in st.step\hat{}\hat{}k'$ **and**
rel: *rel-S*$_0$ *cs'* $(Config_M\ q\ mtape\ p)$ **and**
k': $k' \leq 3 * n\hat{}2 + 7 * n$ **by** *auto*
let *?k* = $3 + 2 * length\ w + k'$

from *relpow-transI*[*OF dsteps-to-steps*[*OF steps1*] *steps2*]
have *steps*: (*st.init-config x*, *cs'*) ∈ *st.step* ^^ *?k* **.**
from *rel* **obtain** *stape* **where** *cs'*: *cs'* = *Config*$_S$ (*S*$_0$ *q*) *stape 0*
by (*cases*, *auto*)
show *?thesis*
by (*intro exI*[*of - stape*] *exI*[*of - ?k*], *insert steps cs' k'*, *auto simp*: *x-def*)
qed

lemma *simulation*: *map INP ' Lang* ⊆ *st.Lang*
proof
fix *x* :: ('*a*, '*k*) *st-tape-symbol list*
assume *x* ∈ *map INP ' Lang*
then obtain *w* **where** *mem*: *w* ∈ *Lang* **and** *x*: *x* = *map INP w* **by** *auto*
define *cm* **where** *cm* = *init-config w*
from *mem*[*unfolded Lang-def*] **obtain** *w' n* **where** *w*: *set w* ⊆ Σ **and** *steps*: (*cm*, *Config*$_M$ *t w' n*) ∈ *step*^* **by** (*auto simp*: *cm-def*)
from *rtrancl-imp-relpow*[*OF steps*] **obtain** *num* **where** *steps*: (*cm*, *Config*$_M$ *t w' n*) ∈ *step*^^*num* **by** *auto*
from *simulation-with-complexity*[*OF w*, *folded cm-def*, *OF steps*] **obtain** *stape*
where *steps*: (*st.init-config* (*map INP w*), *Config*$_S$ (*S*$_0$ *t*) *stape 0*) ∈ *st.step*^*
using *relpow-imp-rtrancl* **by** *blast*
show *x* ∈ *st.Lang* **using** *steps w* **unfolding** *x st.Lang-def* **by** *auto*
qed

6.2.5 Simulation of singletape TM by multitape TM

lemma *rev-simulation*: *st.Lang* ⊆ *map INP ' Lang*
proof
fix *x* :: ('*a*, '*k*) *st-tape-symbol list*
let *?INP* = *INP* :: '*a* ⇒ ('*a*, '*k*) *st-tape-symbol*
assume *x* ∈ *st.Lang*
from *this*[*unfolded st.Lang-def*] **obtain** *ts p* **where** *x*: *set x* ⊆ *?INP ' Σ*
and *steps*: (*st.init-config x*, *Config*$_S$ (*S*$_0$ *t*) *ts p*) ∈ *st.step*^* **by** *force*
let *?NF* = *Config*$_S$ (*S*$_0$ *t*) *ts p*
have *NF*: ¬ (∃ *c*. (*?NF*, *c*) ∈ *st.step*)
proof
assume ∃ *c*. (*?NF*, *c*) ∈ *st.step*
then obtain *c* **where** (*?NF*, *c*) ∈ *st.step* **by** *auto*
thus *False*
by (*cases rule*: *st.step.cases*, *insert st.δ-set*, *auto*)
qed
from *INP-D*[*OF x*] **obtain** *w* **where** *x*: *x* = *map ?INP w* **and** *w*: *set w* ⊆ Σ **by** *auto*
define *cm* **where** *cm* = *init-config w*
from *R-phase*[*OF w*, *folded x*] **obtain** *cs* **where**
dsteps: (*st.init-config x*, *cs*) ∈ *st.dstep* ^^ (*3* + *2* ∗ *length w*) **and** *rel*: *rel-S*$_0$ *cs cm*
by (*auto simp*: *cm-def*)

from *steps* **obtain** *k* **where** (*st.init-config x*, *?NF*) ∈ *st.step*^^*k* **using** *rtrancl-power* **by** *blast*
from *st.dsteps-inj*[*OF dsteps this NF*] **obtain** *n* **where** *ssteps*: (*cs*, *?NF*) ∈ *st.step* ^^ *n* **by** *auto*
from *rel ssteps* **have** ∃ *cm'*. (*cm*,*cm'*) ∈ *step*^* ∧ *rel-S*$_0$ *?NF cm'*
proof (*induct n arbitrary*: *cs cm rule*: *less-induct*)
case (*less n cs cm*)
note *rel* = *less*(*2*)
note *steps* = *less*(*3*)
show *?case*
proof (*cases mt-state cm* ∈ {*t*, *r*})
case *True*
with *rel* **obtain** *ts' p' q* **where** *cs*: *cs* = *Config*$_S$ (*S*$_0$ *q*) *ts' p'* **and** *q*: *q* ∈ {*t*,*r*}
by (*cases*, *auto*)
have *NF*: *False* **if** (*cs*, *cs'*) ∈ *st.step* **for** *cs'* **using** *that* **unfolding** *cs* **using** *q*
by (*cases rule*: *st.step.cases*, *insert st.δ-set*, *auto*)
have *cs* = *?NF*
proof (*cases n*)
case *0*
thus *?thesis* **using** *steps* **by** *auto*
next
case (*Suc m*)
from *NF relpow-Suc-E2*[*OF steps*[*unfolded this*]] **show** *?thesis* **by** *auto*
qed
thus *?thesis* **using** *rel* **by** *auto*
next
case *False*
define *N* **where** *N* = *Max* (*range* (*mt-pos cm*))
from *S-phase*[*OF rel False*] **obtain** *cs1* **where** *dsteps*: (*cs*, *cs1*) ∈ *st.dstep* ^^ (*3* + *N*) **and** *rel*: *rel-S*$_1$ *cs1 cm* **by** (*auto simp*: *N-def*)
from *st.dsteps-inj*[*OF dsteps steps NF*] **obtain** *k1* **where** *n*: *n* = *3* + *N* + *k1* **and** *steps*: (*cs1*, *?NF*) ∈ *st.step* ^^ *k1* **by** *auto*
from *rel* **have** *cs1* ≠ *?NF* **by** (*cases*, *auto*)
then obtain *k* **where** *k1*: *k1* = *Suc k* **using** *steps* **by** (*cases k1*, *auto*)
from *relpow-Suc-E2*[*OF steps*[*unfolded this*]] **obtain** *cs2* **where** *step*: (*cs1*, *cs2*) ∈ *st.step* **and** *steps*: (*cs2*,*?NF*) ∈ *st.step* ^^ *k* **by** *auto*
from *rel-S*$_1$-*E*$_0$-*st-step*[*OF rel step*] **obtain** *cm1 rule* **where** *mstep*: (*cm*, *cm1*) ∈ *step* **and** *rel*: *rel-E*$_0$ *cs2 cm cm1 rule* **by** *auto*
from *E-phase*[*OF rel*] **obtain** *cs3* **where** *dsteps*: (*cs2*, *cs3*) ∈ *st.dstep* ^^ (*6* + *4* ∗ *N*) **and** *rel*: *rel-S*$_0$ *cs3 cm1* **by** (*auto simp*: *N-def*)
from *st.dsteps-inj*[*OF dsteps steps NF*] **obtain** *m* **where** *k*: *k* = *6* + *4* ∗ *N* + *m* **and** *steps*: (*cs3*, *Config*$_S$ (*S*$_0$ *t*) *ts p*) ∈ *st.step* ^^ *m*
by *auto*
have *m* < *n* **unfolding** *n k1 k* **by** *auto*
from *less*(*1*)[*OF this rel steps*] **obtain** *cm'* **where** *msteps*: (*cm1*, *cm'*) ∈ *step*^* **and** *rel*: *rel-S*$_0$ *?NF cm'* **by** *auto*
from *mstep msteps* **have** (*cm*, *cm'*) ∈ *step*^* **by** *auto*

```
    with rel show ?thesis by auto
   qed
  qed
  then obtain cm' where msteps: (cm, cm') ∈ step^* and rel: rel-S₀ ?NF cm'
by auto
  from rel obtain tc p where cm': cm' = Config_M t tc p by (cases, auto)
  from msteps have w ∈ Lang unfolding cm-def cm' Lang-def using w by auto
  thus x ∈ map INP ‘ Lang unfolding x by auto
qed

lemma rev-simulation-complexity: assumes w: set w ⊆ Σ
  and steps: (st.init-config (map INP w), cs) ∈ st.step^^n
  and n: n ≥ 2 * length w + 3 * k^2 + 7 * k + 3
shows ∃ cm. (init-config w, cm) ∈ step^^k
proof −
  let ?INP = INP :: 'a ⇒ ('a, 'k) st-tape-symbol
  define cm1 where cm1 = init-config w
  define x where x = map ?INP w
  from R-phase[OF w, folded x-def] obtain cs1 where
   steps1: (st.init-config x, cs1) ∈ st.dstep ^^ (3 + 2 * length w) and rel1: rel-S₀
cs1 cm1
    by (auto simp: cm1-def)
  from st.dsteps-inj'[OF steps1 steps[folded x-def]] obtain n1 where
   nn1: n = 3 + 2 * length w + n1 and
   ssteps1: (cs1, cs) ∈ st.step ^^ n1
   using n by auto
  define M where M = (0 :: nat)
  have r: Max (range (mt-pos cm1)) ≤ M unfolding M-def cm1-def by (simp
add: max-mt-pos-init)
  from nn1 n have n1 ≥ 3 * k^2 + 7 * k by auto
  hence n1: n1 ≥ sum (λ i. 10 + 5 * (M + i)) {..< k} unfolding M-def
   using aux-sum-formula[of k] by simp
  from ssteps1 rel1 n1 r show ?thesis unfolding cm1-def[symmetric]
  proof (induct k arbitrary: cs1 cm1 M n1)
   case (Suc k cs1 cm1 M n1)
   let ?M = Max (range (mt-pos cm1))
   define n where n = (∑ i<k. 10 + 5 * (Suc M + i))
   from Suc(4) have n1 ≥ n + 10 + M * 5 unfolding n-def
    by (simp add: algebra-simps sum.distrib)
   with Suc(5) have n1: n1 ≥ n + 10 + 5 * ?M by linarith
   show ?case
   proof (cases mt-state cm1 ∈ {t, r})
    case False
    from S-phase[OF Suc(3) False]
    obtain cs2 where steps2: (cs1, cs2) ∈ st.dstep ^^ (3 + ?M) and rel2: rel-S₁
cs2 cm1 by auto
     from st.dsteps-inj'[OF steps2 Suc(2)] n1 obtain n2 where
      n12: n1 = 3 + ?M + n2 and
      steps2: (cs2, cs) ∈ st.step ^^ n2
```

by *auto*
from *n12 n1* **obtain** *n3* **where** *n23*: *n2* = *Suc n3* **by** (*cases n2*, *auto*)
from *steps2* **obtain** *cs3* **where** *step*: (*cs2*, *cs3*) ∈ *st.step* **and** *steps3*: (*cs3*,*cs*) ∈ *st.step* ^^ *n3* **unfolding** *n23* **by** (*metis relpow-Suc-E2*)
from *rel-S_1-E_0-st-step*[*OF rel2 step*] **obtain** *cm2 rule* **where** *step*: (*cm1*, *cm2*) ∈ *step* **and** *rel3*: *rel-E_0 cs3 cm1 cm2 rule* **by** *auto*
let *?M2* = *Max* (*range* (*mt-pos cm2*))
from *n1 n12 n23* **have** *n3*: *6* + *4* ∗ *?M* ≤ *n3* **by** *auto*
from *E-phase*[*OF rel3*] **obtain** *cs4* **where** *dsteps*: (*cs3*, *cs4*) ∈ *st.dstep* ^^ (*6* + *4* ∗ *?M*) **and** *rel4*: *rel-S_0 cs4 cm2* **by** *auto*
from *st.dsteps-inj'*[*OF dsteps steps3 n3*] **obtain** *n4* **where** *n34*: *n3* = *6* + *4* ∗ *?M* + *n4*
and *steps*: (*cs4*, *cs*) ∈ *st.step* ^^ *n4* **by** *auto*
from *max-mt-pos-step*[*OF step*] *Suc*(*5*)
have *M2*: *?M2* ≤ *Suc M* **by** *linarith*
have *n4*: *n* ≤ *n4* **using** *n34 n12 n23 n1* **by** *simp*
from *Suc*(*1*)[*OF steps rel4 n4*[*unfolded n-def*] *M2*] **obtain** *cm* **where** (*cm2*, *cm*) ∈ *step* ^^ *k* **..**
with *step* **have** (*cm1*, *cm*) ∈ *step* ^^ (*Suc k*) **by** (*metis relpow-Suc-I2*)
thus *?thesis* **..**
next
case *True*
from *n1* **obtain** *n2* **where** *n1* = *Suc n2* **by** (*cases n1*, *auto*)
from *relpow-Suc-E2*[*OF Suc*(*2*)[*unfolded this*]]
obtain *cs2* **where** *step*: (*cs1*, *cs2*) ∈ *st.step* **by** *auto*
from *rel-S_0.cases*[*OF Suc*(*3*)] **obtain** *tc' q tc p* **where**
cs1: *cs1* = *Config$_S$* (*S_0 q*) *tc' 0* **and**
cm1: *cm1* = *Config$_M$ q tc p*
by *metis*
with *True* **have** *q*: *q* ∈ {*t*,*r*} **by** *auto*
from *st.step.cases*[*OF step*] **obtain** *ts q' a dir* **where** *rule*: (*S_0 q*, *ts*, *q'*, *a*, *dir*) ∈ *δ'*
unfolding *cs1* **by** *fastforce*
with *q* **have** *False* **unfolding** *δ'-def* **by** *auto*
thus *?thesis* **by** *simp*
qed
qed *auto*
qed

6.2.6 Main Results

theorem *language-equivalence*: *st.Lang* = *map INP* ‘ *Lang*
using *simulation rev-simulation* **by** *auto*

theorem *upper-time-bound-quadratic-increase*: **assumes** *upper-time-bound f*
shows *st.upper-time-bound* (λ *n*. *3* ∗ (*f n*)^*2* + *13* ∗ *f n* + *2* ∗ *n* + *12*)
unfolding *st.upper-time-bound-def*
proof (*intro allI impI*, *rule ccontr*)
fix *ww c n*

assume *set ww* $\subseteq$ *INP* ‘ Σ **and** *steps*: (*st.init-config ww*, *c*) $\in$ *st.step* $\widehat{\ }\widehat{\ }$ *n*
and *bnd*: $\neg$ *n* $\leq$ *3* $*$ (*f* (*length ww*))^2 + *13* $*$ (*f* (*length ww*)) + *2* $*$ *length ww* + *12*
from *INP-D*[*OF this*(*1*)] **obtain** *w* **where** *w*: *set w* $\subseteq$ Σ **and** *ww*: *ww* = *map INP w* **by** *auto*
let *?lw* = *length w*
from *bnd* **have** *n* $\geq$ *2* $*$ *?lw* + *3* $*$ (*f ?lw* + *1*)^2 + *7* $*$ (*f ?lw* + *1*) + *3*
by (*auto simp*: *ww power2-eq-square*)
from *rev-simulation-complexity*[*OF w steps*[*unfolded ww*] *this*]
obtain *cm* **where** (*init-config w*, *cm*) $\in$ *step* $\widehat{\ }\widehat{\ }$ (*f ?lw* + *1*) **by** *auto*
from *assms*[*unfolded upper-time-bound-def*, *rule-format*, *OF w this*] **show** *False* **by** *simp*
qed
end

6.3 Main Results with Proper Renamings

By using the renaming capabilities we can get rid of the *map INP* in the language equivalence theorem. We just assume that there will always be enough symbols for the renaming, i.e., an infinite supply of fresh names is available.

theorem *multitape-to-singletape*: **assumes** *valid-mttm* (*mttm* :: (*'p*,*'a*,*'k* :: {*finite*,*zero*})*mttm*)

and *infinite* (*UNIV* :: *'q set*)
and *infinite* (*UNIV* :: *'a set*)
shows $\exists$ *tm* :: (*'q*,*'a*)*tm*. *valid-tm tm* $\wedge$
Lang-mttm mttm = *Lang-tm tm* $\wedge$
(*det-mttm mttm* $\longrightarrow$ *det-tm tm*) $\wedge$
(*upperb-time-mttm mttm f* $\longrightarrow$ *upperb-time-tm tm* (λ *n*. *3* $*$ (*f n*)^*2* + *13* $*$ *f n* + *2* $*$ *n* + *12*))
proof (*cases mttm*)
let *?INP* = *INP* :: *'a* $\Rightarrow$ (*'a*, *'k*) *st-tape-symbol*
case (*MTTM Q* Σ Γ *bl le* δ *s t r*)
from *assms*(*1*)[*unfolded this*]
interpret *multitape-tm Q* Σ Γ *bl le* δ *s t r* **by** *simp*
let *?TM1* = *TM Q'* (*?INP* ‘ Σ) Γ' *blank'* $\vdash$ δ' (R_1 $\cdot$) (S_0 *t*) (S_0 *r*)
have *valid*: *valid-tm ?TM1* **unfolding** *valid-tm.simps* **using** *valid-st* **.**
interpret *st*: *singletape-tm Q' ?INP* ‘ Σ Γ' *blank'* $\vdash$ δ' R_1 $\cdot$ S_0 *t* S_0 *r* **using** *valid-st* **.**
from *language-equivalence*
have *id*: *Lang-tm ?TM1* = *map INP* ‘ *Lang-mttm mttm* **unfolding** *MTTM* **by** *auto*
have *finite Q'* **using** *st.fin-Q* **.**
with *assms*(*2*) **have** $\exists$ *tq* :: ((*'a*, *'p*, *'k*) *st-states* $\Rightarrow$ *'q*). *inj-on tq Q'* **by** (*metis finite-infinite-inj-on*)
then obtain *tq* :: - $\Rightarrow$ *'q* **where** *inj-on tq Q'* **by** *blast*
hence *tq*: *inj-on tq* (*Q-tm ?TM1*) **by** *simp*

```
  from st.fin-Γ have finG': finite Γ' .
  from fin-Σ assms(3) have infinite (UNIV − Σ) by auto
  then obtain B :: 'a set where B: finite B card B = card Γ' B ⊆ UNIV − Σ
    by (meson infinite-arbitrarily-large)
  from st.finΣ have finS': finite (?INP ‘ Σ) .
  from finG' B obtain ta' where bij: bij-betw ta' Γ' B
    by (metis bij-betw-iff-card)
  define ta where ta x = (if x ∈ ?INP ‘ Σ then (case x of INP y ⇒ y) else ta' x)
for x
  have ta: inj-on ta (Γ-tm ?TM1) using bij B(3)
    by (auto simp: bij-betw-def inj-on-def ta-def split: st-tape-symbol.splits)
  obtain tm' :: ('q,'a)tm where valid: valid-tm tm' and lang: Lang-tm tm' = map
ta ‘ map INP ‘ Lang-mttm mttm
    and det: st.deterministic ⟹ det-tm tm'
    and upper: ⋀ f. st.upper-time-bound f ⟹ upperb-time-tm tm' f
    using tm-renaming[OF valid ta tq, unfolded id] by auto
   note lang also have map ta ‘ map INP ‘ Lang-mttm mttm = (λ w. w) ‘
Lang-mttm mttm
    unfolding image-comp o-def map-map
  proof (rule image-cong[OF refl])
    fix w
    assume w ∈ Lang-mttm mttm
    hence w: set w ⊆ Σ unfolding Lang-def MTTM Lang-mttm.simps by auto
    show map (λx. ta (INP x)) w = w
      by (intro map-idI, insert w, auto simp: ta-def)
  qed
  finally have lang: Lang-tm tm' = Lang-mttm mttm by simp
  {
    assume det-mttm mttm
    hence deterministic unfolding MTTM by simp
    from det-preservation[OF this] have st.deterministic by auto
    from det[OF this] have det-tm tm' .
  } note det = this
  {
    assume upperb-time-mttm mttm f
    hence upper-time-bound f unfolding MTTM by simp
    from upper[OF upper-time-bound-quadratic-increase[OF this]]
    have upperb-time-tm tm' (λn. 3 * (f n)^2 + 13 * f n + 2 * n + 12) .
  } note upper = this
  from valid lang det upper show ?thesis by blast
qed


end
```

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