

AutoFocus Stream Processing for Single-Clocking and Multi-Clocking Semantics

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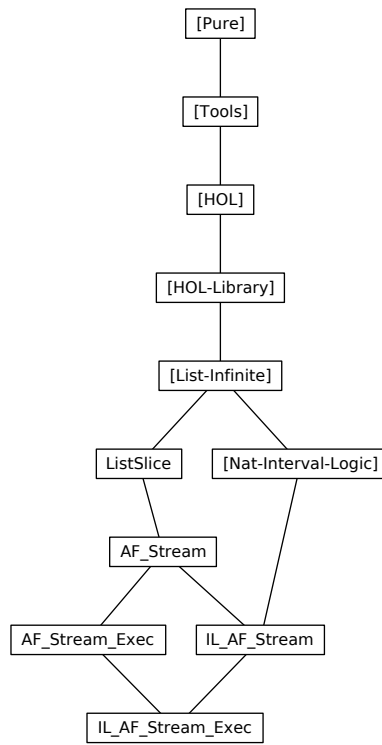
Abstract

We formalize the AutoFocus Semantics (a time-synchronous subset of the Focus formalism) as stream processing functions on finite and infinite message streams represented as finite/infinite lists. The formalization comprises both the conventional single-clocking semantics (uniform global clock for all components and communications channels) and its extension to multi-clocking semantics (internal execution clocking of a component may be a multiple of the external communication clocking). The semantics is defined by generic stream processing functions making it suitable for simulation/code generation in Isabelle/HOL. Furthermore, a number of AutoFocus semantics properties are formalized using definitions from the Nat-Interval-Logic theories.

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1 Additional definitions and results for lists

```
theory ListSlice
imports List-Infinite.ListInf
begin
```

1.1 Slicing lists into lists of lists

definition *ilist-slice* :: 'a ilist $\Rightarrow$ nat $\Rightarrow$ 'a list ilist
where *ilist-slice* $f\ k \equiv \lambda x. \text{map } f\ [x * k..< \text{Suc } x * k]$

primrec *list-slice-aux* :: 'a list $\Rightarrow$ nat $\Rightarrow$ nat $\Rightarrow$ 'a list list
where
list-slice-aux $xs\ k\ 0 = []$
 $| \text{list-slice-aux } xs\ k\ (\text{Suc } n) = \text{take } k\ xs \# \text{list-slice-aux } (xs \uparrow k)\ k\ n$

definition *list-slice* :: 'a list $\Rightarrow$ nat $\Rightarrow$ 'a list list
where *list-slice* $xs\ k \equiv \text{list-slice-aux } xs\ k\ (\text{length } xs \text{ div } k)$

definition *list-slice2* :: 'a list $\Rightarrow$ nat $\Rightarrow$ 'a list list
where *list-slice2* $xs\ k \equiv$
list-slice $xs\ k\ @\ (\text{if } \text{length } xs \bmod k = 0 \text{ then } [] \text{ else } [xs \uparrow (\text{length } xs \text{ div } k * k)])$

No function *list-unslice* for finite lists is needed because the corresponding functionality is already provided by *concat*. Therefore, only a *ilist-unslice* function for infinite lists is defined.

definition *ilist-unslice* :: 'a list ilist $\Rightarrow$ 'a ilist
where *ilist-unslice* $f \equiv \lambda n. f\ (n \text{ div } \text{length } (f\ 0))\ !\ (n \bmod \text{length } (f\ 0))$

lemma *list-slice-aux-length*: $\bigwedge xs. \text{length } (\text{list-slice-aux } xs\ k\ n) = n$
 $\langle \text{proof} \rangle$

lemma *list-slice-aux-nth*:
 $\bigwedge m\ xs. m < n \implies (\text{list-slice-aux } xs\ k\ n)\ !\ m = (xs \uparrow (m * k) \downarrow k)$
 $\langle \text{proof} \rangle$

lemma *list-slice-length*: $\text{length } (\text{list-slice } xs\ k) = \text{length } xs \text{ div } k$
 $\langle \text{proof} \rangle$

lemma *list-slice-0*: $\text{list-slice } xs\ 0 = []$
 $\langle \text{proof} \rangle$

lemma *list-slice-1*: $\text{list-slice } xs\ (\text{Suc } 0) = \text{map } (\lambda x. [x])\ xs$
 $\langle \text{proof} \rangle$

lemma *list-slice-less*: $\text{length } xs < k \implies \text{list-slice } xs\ k = []$
 $\langle \text{proof} \rangle$

lemma *list-slice-Nil*: $list\text{-}slice\ []\ k = []$
 $\langle proof \rangle$

lemma *list-slice-nth*:
 $m < length\ xs\ div\ k \implies list\text{-}slice\ xs\ k\ !\ m = xs\ \uparrow\ (m * k)\ \downarrow\ k$
 $\langle proof \rangle$

lemma *list-slice-nth-length*:
 $m < length\ xs\ div\ k \implies length\ ((list\text{-}slice\ xs\ k)\ !\ m) = k$
 $\langle proof \rangle$

lemma *list-slice-nth-eq-sublist-list*:
 $m < length\ xs\ div\ k \implies list\text{-}slice\ xs\ k\ !\ m = sublist\text{-}list\ xs\ [m * k..<m * k + k]$
 $\langle proof \rangle$

lemma *list-slice-nth-nth*:
 $\llbracket m < length\ xs\ div\ k; n < k \rrbracket \implies$
 $(list\text{-}slice\ xs\ k)\ !\ m\ !\ n = xs\ !\ (m * k + n)$
 $\langle proof \rangle$

lemma *list-slice-nth-nth-rev*:
 $n < length\ xs\ div\ k * k \implies$
 $(list\text{-}slice\ xs\ k)\ !\ (n\ div\ k)\ !\ (n\ mod\ k) = xs\ !\ n$
 $\langle proof \rangle$

lemma *list-slice-eq-list-slice-take*:
 $list\text{-}slice\ (xs\ \downarrow\ (length\ xs\ div\ k * k))\ k = list\text{-}slice\ xs\ k$
 $\langle proof \rangle$

lemma *list-slice-append-mult*:
 $\bigwedge xs. length\ xs = m * k \implies$
 $list\text{-}slice\ (xs\ @\ ys)\ k = list\text{-}slice\ xs\ k\ @\ list\text{-}slice\ ys\ k$
 $\langle proof \rangle$

lemma *list-slice-append-mod*:
 $length\ xs\ mod\ k = 0 \implies$
 $list\text{-}slice\ (xs\ @\ ys)\ k = list\text{-}slice\ xs\ k\ @\ list\text{-}slice\ ys\ k$
 $\langle proof \rangle$

lemma *list-slice-div-eq-1*[*rule-format*]:
 $length\ xs\ div\ k = Suc\ 0 \implies list\text{-}slice\ xs\ k = [take\ k\ xs]$
 $\langle proof \rangle$

lemma *list-slice-div-eq-Suc*[*rule-format*]:
 $length\ xs\ div\ k = Suc\ n \implies$
 $list\text{-}slice\ xs\ k = list\text{-}slice\ (xs\ \downarrow\ (n * k))\ k\ @\ [xs\ \uparrow\ (n * k)\ \downarrow\ k]$
 $\langle proof \rangle$

lemma *list-slice2-mod-0*:

$length\ xs \bmod k = 0 \implies list_slice2\ xs\ k = list_slice\ xs\ k$
 <proof>

lemma *list-slice2-mod-gr0*:

$0 < length\ xs \bmod k \implies list_slice2\ xs\ k = list_slice\ xs\ k @ [xs \uparrow (length\ xs \div k * k)]$
 <proof>

lemma *list-slice2-length*:

$length\ (list_slice2\ xs\ k) = ($
 $if\ length\ xs \bmod k = 0\ then\ length\ xs \div k\ else\ Suc\ (length\ xs \div k))$
 <proof>

lemma *list-slice2-0*:

$list_slice2\ xs\ 0 = (if\ (length\ xs = 0)\ then\ []\ else\ [xs])$
 <proof>

lemma *list-slice2-1*: $list_slice2\ xs\ (Suc\ 0) = map\ (\lambda x. [x])\ xs$

<proof>

lemma *list-slice2-le*:

$length\ xs \leq k \implies list_slice2\ xs\ k = (if\ length\ xs = 0\ then\ []\ else\ [xs])$
 <proof>

lemma *list-slice2-Nil*: $list_slice2\ []\ k = []$

<proof>

lemma *list-slice2-list-slice-nth*:

$m < length\ xs \div k \implies list_slice2\ xs\ k ! m = list_slice\ xs\ k ! m$
 <proof>

lemma *list-slice2-last*:

$[length\ xs \bmod k > 0; m = length\ xs \div k] \implies$
 $list_slice2\ xs\ k ! m = xs \uparrow (length\ xs \div k * k)$
 <proof>

lemma *list-slice2-nth*:

$[m < length\ xs \div k] \implies$
 $list_slice2\ xs\ k ! m = xs \uparrow (m * k) \downarrow k$
 <proof>

lemma *list-slice2-nth-length-eq1*:

$m < length\ xs \div k \implies length\ (list_slice2\ xs\ k ! m) = k$
 <proof>

lemma *list-slice2-nth-length-eq2*:

$[length\ xs \bmod k > 0; m = length\ xs \div k] \implies$
 $length\ (list_slice2\ xs\ k ! m) = length\ xs \bmod k$
 <proof>

lemma *list-slice2-nth-nth-eq1*:

$\llbracket m < \text{length } xs \text{ div } k; n < k \rrbracket \implies$
 $(\text{list-slice2 } xs \ k) ! m ! n = xs ! (m * k + n)$
 $\langle \text{proof} \rangle$

lemma *list-slice2-nth-nth-eq2*:

$\llbracket m = \text{length } xs \text{ div } k; n < \text{length } xs \text{ mod } k \rrbracket \implies$
 $(\text{list-slice2 } xs \ k) ! m ! n = xs ! (m * k + n)$
 $\langle \text{proof} \rangle$

lemma *list-slice2-nth-nth-rev*:

$n < \text{length } xs \implies (\text{list-slice2 } xs \ k) ! (n \text{ div } k) ! (n \text{ mod } k) = xs ! n$
 $\langle \text{proof} \rangle$

lemma *list-slice2-append-mult*:

$\text{length } xs = m * k \implies$
 $\text{list-slice2 } (xs @ ys) \ k = \text{list-slice2 } xs \ k @ \text{list-slice2 } ys \ k$
 $\langle \text{proof} \rangle$

lemma *list-slice2-append-mod*:

$\text{length } xs \text{ mod } k = 0 \implies$
 $\text{list-slice2 } (xs @ ys) \ k = \text{list-slice2 } xs \ k @ \text{list-slice2 } ys \ k$
 $\langle \text{proof} \rangle$

lemma *ilist-slice-nth*:

$(\text{ilist-slice } f \ k) \ m = \text{map } f \ [m * k .. \text{Suc } m * k]$
 $\langle \text{proof} \rangle$

lemma *ilist-slice-nth-length*: $\text{length } ((\text{ilist-slice } f \ k) \ m) = k$

$\langle \text{proof} \rangle$

lemma *ilist-slice-nth-nth*:

$n < k \implies (\text{ilist-slice } f \ k) \ m ! n = f \ (m * k + n)$
 $\langle \text{proof} \rangle$

lemma *ilist-slice-nth-nth-rev*:

$0 < k \implies (\text{ilist-slice } f \ k) \ (n \text{ div } k) ! (n \text{ mod } k) = f \ n$
 $\langle \text{proof} \rangle$

lemma *list-slice-concat*:

$\text{concat } (\text{list-slice } xs \ k) = xs \downarrow (\text{length } xs \text{ div } k * k)$
 $(\text{is } ?P \ xs \ k)$
 $\langle \text{proof} \rangle$

lemma *list-slice-unslice-mult*:

$\text{length } xs = m * k \implies \text{concat } (\text{list-slice } xs \ k) = xs$
 $\langle \text{proof} \rangle$

lemma *ilist-slice-unslice*: $0 < k \implies \text{ilist-unslice } (\text{ilist-slice } f \ k) = f$
 $\langle \text{proof} \rangle$

lemma *i-take-ilist-slice-eq-list-slice*:
 $0 < k \implies \text{ilist-slice } f \ k \Downarrow n = \text{list-slice } (f \Downarrow (n * k)) \ k$
 $\langle \text{proof} \rangle$

lemma *list-slice-i-take-eq-i-take-ilist-slice*:
 $\text{list-slice } (f \Downarrow n) \ k = \text{ilist-slice } f \ k \Downarrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *ilist-slice-i-append-mod*:
 $\text{length } xs \bmod k = 0 \implies$
 $\text{ilist-slice } (xs \frown f) \ k = \text{list-slice } xs \ k \frown \text{ilist-slice } f \ k$
 $\langle \text{proof} \rangle$

corollary *ilist-slice-append-mult*:
 $\text{length } xs = m * k \implies$
 $\text{ilist-slice } (xs \frown f) \ k = \text{list-slice } xs \ k \frown \text{ilist-slice } f \ k$
 $\langle \text{proof} \rangle$

end

2 AutoFocus message streams

theory *AF-Stream*
imports *ListSlice*
begin

2.1 Basic definitions

2.1.1 Time-synchronous streams

datatype *'a message-af* = *NoMsg* | *Msg 'a*

notation (*latex*)
 $\text{NoMsg} \ (\langle \varepsilon \rangle)$ **and**
 $\text{Msg} \ (\langle \text{Msg} \rangle)$

Abbreviation for finite streams

type-synonym *'a fstream-af* = *'a message-af list*

Abbreviation for infinite streams

type-synonym *'a istream-af* = *'a message-af ilist*

lemma *not-NoMsg-eq*: $(m \neq \varepsilon) = (\exists x. m = \text{Msg } x)$
 $\langle \text{proof} \rangle$

lemma *not-Msg-eq*: $(\forall x. m \neq \text{Msg } x) = (m = \varepsilon)$
 $\langle \text{proof} \rangle$

primrec *the-af* :: $'a \text{ message-af} \Rightarrow 'a$
where *the-af* ($\text{Msg } x$) = x

By this definition one can determine, whether data elements of different data structures with messages, especially product types of arbitrary sizes and records, are pointwise equal to NoMsg, i.e., contain only NoMsg entries.

consts *is-NoMsg* :: $'a \Rightarrow \text{bool}$

overloading *is-NoMsg* $\equiv$ *is-NoMsg* :: $'a \text{ message-af} \Rightarrow \text{bool}$
begin

primrec *is-NoMsg* :: $'a \text{ message-af} \Rightarrow \text{bool}$
where
 $\text{is-NoMsg } \varepsilon = \text{True}$
 $|\text{ is-NoMsg } (\text{Msg } x) = \text{False}$

end

overloading *is-NoMsg* $\equiv$ *is-NoMsg* :: $('a \times 'b) \Rightarrow \text{bool}$
begin

definition *is-NoMsg-tuple-def* :
 $\text{is-NoMsg } (p :: 'a \times 'b) \equiv (\text{is-NoMsg } (\text{fst } p) \wedge \text{is-NoMsg } (\text{snd } p))$

end

overloading *is-NoMsg* $\equiv$ *is-NoMsg* :: $'a \text{ set} \Rightarrow \text{bool}$
begin

definition *is-NoMsg-set-def* :
 $\text{is-NoMsg } (A :: 'a \text{ set}) \equiv (\forall x \in A. \text{is-NoMsg } x)$

end

record *SomeRecordExample* =
 $\text{Field1} :: \text{nat message-af}$
 $\text{Field2} :: \text{int message-af}$
 $\text{Field3} :: \text{int message-af}$

overloading *is-NoMsg* $\equiv$ *is-NoMsg* :: $'a \text{ SomeRecordExample-scheme} \Rightarrow \text{bool}$
begin

definition *is-NoMsg-SomeRecordExample-def* :
 $\text{is-NoMsg } (r :: 'a \text{ SomeRecordExample-scheme}) \equiv$
 $\text{Field1 } r = \varepsilon \wedge \text{Field2 } r = \varepsilon \wedge \text{Field3 } r = \varepsilon$

end

definition $is_Msg :: 'a \Rightarrow bool$
where $is_Msg\ x \equiv (\neg\ is_NoMsg\ x)$

lemma $is_NoMsg_message_af_conv$: $is_NoMsg\ m = (case\ m\ of\ \varepsilon \Rightarrow True \mid Msg\ x \Rightarrow False)$
 $\langle proof \rangle$

lemma $is_NoMsg_message_af_conv2$: $is_NoMsg\ m = (m = \varepsilon)$
 $\langle proof \rangle$

lemma $is_Msg_message_af_conv$: $is_Msg\ m = (case\ m\ of\ \varepsilon \Rightarrow False \mid Msg\ x \Rightarrow True)$
 $\langle proof \rangle$

lemma $is_Msg_message_af_conv2$: $is_Msg\ m = (m \neq \varepsilon)$
 $\langle proof \rangle$

Collection for definitions for is_NoMsg .

named-theorems is_NoMsg_defs

declare

$is_NoMsg_tuple_def[is_NoMsg_defs]$
 $is_NoMsg_set_def\ [is_NoMsg_defs]$
 $is_NoMsg_SomeRecordExample_def[is_NoMsg_defs]$
 $is_Msg_def[is_NoMsg_defs]$

lemma not_is_NoMsg : $(\neg\ is_NoMsg\ m) = is_Msg\ m$
 $\langle proof \rangle$

lemma not_is_Msg : $(\neg\ is_Msg\ m) = is_NoMsg\ m$
 $\langle proof \rangle$

lemma $is_NoMsg\ (\varepsilon :: (nat\ message_af))$
 $\langle proof \rangle$

lemma $is_NoMsg\ (\varepsilon :: (nat\ message_af), \varepsilon :: (nat\ message_af))$
 $\langle proof \rangle$

lemma $is_NoMsg\ (\varepsilon :: (nat\ message_af), \varepsilon :: (nat\ message_af), \varepsilon :: (nat\ message_af))$
 $\langle proof \rangle$

lemma $is_Msg\ (\varepsilon :: (nat\ message_af), Msg\ (1 :: nat), \varepsilon :: (nat\ message_af))$
 $\langle proof \rangle$

lemma $is_NoMsg\ \{\varepsilon :: (nat\ message_af), \varepsilon\}$
 $\langle proof \rangle$

lemma *is-Msg* { $\varepsilon :: (\text{nat message-af}), \text{Msg } 1$ }
 $\langle \text{proof} \rangle$

lemma *is-NoMsg* ($\mid \text{Field1} = \varepsilon, \text{Field2} = \varepsilon, \text{Field3} = \varepsilon \mid$)
 $\langle \text{proof} \rangle$

lemma *is-Msg* ($\mid \text{Field1} = \varepsilon, \text{Field2} = \text{Msg } 1, \text{Field3} = \varepsilon \mid$)
 $\langle \text{proof} \rangle$

2.1.2 Time abstraction

primrec *untime* :: 'a fstream-af $\Rightarrow$ 'a list

where

untime [] = []
 $\mid \text{untime } (x \# xs) =$
 (if $x = \varepsilon$
 then (*untime* xs)
 else (*the-af* x) # (*untime* xs))

lemma *untime-eq-filter*[rule-format]:

$\text{map } (\lambda x. \text{Msg } x) (\text{untime } s) = \text{filter } (\lambda x. x \neq \varepsilon) s$
 $\langle \text{proof} \rangle$

The following lemma involves *the-af* function and thus is some more limited than the previous lemma

corollary *untime-eq-filter2*[rule-format]:

$\text{untime } s = \text{map } (\lambda x. \text{the-af } x) (\text{filter } (\lambda x. x \neq \varepsilon) s)$
 $\langle \text{proof} \rangle$

definition *untime-length* :: 'a fstream-af $\Rightarrow$ nat

where *untime-length* $s \equiv \text{length } (\text{untime } s)$

primrec *untime-length-cnt* :: 'a fstream-af $\Rightarrow$ nat

where

untime-length-cnt [] = 0
 $\mid \text{untime-length-cnt } (x \# xs) =$
 (if $x = \varepsilon$ then 0 else *Suc* 0) + *untime-length-cnt* xs

lemma *untime-length-eq-untime-length-cnt*:

$\text{untime-length } s = \text{untime-length-cnt } s$
 $\langle \text{proof} \rangle$

definition *untime-length-filter* :: 'a fstream-af $\Rightarrow$ nat

where *untime-length-filter* $s \equiv \text{length } (\text{filter } (\lambda x. x \neq \varepsilon) s)$

lemma *untime-length-filter-eq-untime-length*:

$\text{untime-length-filter } s = \text{untime-length } s$
 $\langle \text{proof} \rangle$

lemma *untime-empty-conv*: $(untime\ s = []) = (\forall n < length\ s. s\ !\ n = \varepsilon)$
 $\langle proof \rangle$

lemma *untime-not-empty-conv*: $(untime\ s \neq []) = (\exists n < length\ s. s\ !\ n \neq \varepsilon)$
 $\langle proof \rangle$

corollary *untime-empty-imp-NoMsg[rule-format]*:
 $\llbracket\ untime\ s = [];\ n < length\ s\ \rrbracket \implies s\ !\ n = \varepsilon$
 $\langle proof \rangle$

lemma *untime-nth-eq-filter*:
 $n < untime-length\ s \implies$
 $Msg\ (untime\ s\ !\ n) = (filter\ (\lambda x. x \neq \varepsilon)\ s)\ !\ n$
 $\langle proof \rangle$

corollary *untime-nth-eq-filter2*:
 $n < untime-length\ s \implies$
 $untime\ s\ !\ n = the-af\ ((filter\ (\lambda x. x \neq \varepsilon)\ s)\ !\ n)$
 $\langle proof \rangle$

lemma *untime-hd-eq-filter-hd*:
 $untime\ s \neq [] \implies$
 $Msg\ (hd\ (untime\ s)) = hd\ (filter\ (\lambda x. x \neq \varepsilon)\ s)$
 $\langle proof \rangle$

corollary *untime-hd-eq-filter-hd2*:
 $untime\ s \neq [] \implies$
 $hd\ (untime\ s) = the-af\ (hd\ (filter\ (\lambda x. x \neq \varepsilon)\ s))$
 $\langle proof \rangle$

lemma *untime-last-eq-filter-last*:
 $untime\ s \neq [] \implies$
 $Msg\ (last\ (untime\ s)) = last\ (filter\ (\lambda x. x \neq \varepsilon)\ s)$
 $\langle proof \rangle$

corollary *untime-last-eq-filter-last2*:
 $untime\ s \neq [] \implies$
 $last\ (untime\ s) = the-af\ (last\ (filter\ (\lambda x. x \neq \varepsilon)\ s))$
 $\langle proof \rangle$

2.2 Expanding and compressing lists and streams

2.2.1 Expanding message streams

primrec *f-expand* :: $'a\ fstream-af \Rightarrow nat \Rightarrow 'a\ fstream-af\ (\mathbf{infixl}\ \langle \odot_f \rangle\ 100)$
where

f-expand-Nil: $[] \odot_f k = []$
 | *f-expand-Cons*: $(x \# xs) \odot_f k =$
 $(\text{if } 0 < k \text{ then } x \# \varepsilon^k - \text{Suc } 0 @ (xs \odot_f k) \text{ else } [])$

definition *i-expand* :: $'a \text{ istream-af} \Rightarrow \text{nat} \Rightarrow 'a \text{ istream-af}$ (**infixl** $\langle \odot_i \rangle$ 100)

where

i-expand $\equiv \lambda f k n.$
 $(\text{if } k = 0 \text{ then } \varepsilon \text{ else}$
 $\text{if } n \bmod k = 0 \text{ then } f (n \text{ div } k) \text{ else } \varepsilon)$

primrec *f-expand-Suc* :: $'a \text{ fstream-af} \Rightarrow \text{nat} \Rightarrow 'a \text{ fstream-af}$ (**infixl** $\langle \odot_{f\text{Suc}} \rangle$ 100)

where

f-expand-Suc $[] k = []$
 | *f-expand-Suc* $(x \# xs) k = x \# \varepsilon^k @ (f\text{-expand-Suc } xs k)$

definition *i-expand-Suc* :: $'a \text{ istream-af} \Rightarrow \text{nat} \Rightarrow 'a \text{ istream-af}$ (**infixl** $\langle \odot_{i\text{Suc}} \rangle$ 100)

where *i-expand-Suc* $\equiv \lambda f k n.$ *if* $n \bmod (\text{Suc } k) = 0$ *then* $f (n \text{ div } (\text{Suc } k))$ *else* ε

notation

f-expand (**infixl** $\langle \odot \rangle$ 100) **and**
i-expand (**infixl** $\langle \odot \rangle$ 100)

lemma *length-f-expand-Suc[simp]*: $\text{length } (f\text{-expand-Suc } xs k) = \text{length } xs * \text{Suc } k$
 $\langle \text{proof} \rangle$

lemma *i-expand-if*:

$f \odot_i k = (\text{if } k = 0 \text{ then } (\lambda n. \varepsilon) \text{ else}$
 $(\lambda n. \text{if } n \bmod k = 0 \text{ then } f (n \text{ div } k) \text{ else } \varepsilon))$
 $\langle \text{proof} \rangle$

lemma *f-expand-one*: $0 < k \implies [a] \odot_f k = a \# \varepsilon^k - \text{Suc } 0$
 $\langle \text{proof} \rangle$

lemma *f-expand-0[simp]*: $xs \odot_f 0 = []$
 $\langle \text{proof} \rangle$

corollary *f-expand-0-is-zero-element*: $xs \odot_f 0 = ys \odot_f 0$
 $\langle \text{proof} \rangle$

lemma *i-expand-0[simp]*: $f \odot_i 0 = (\lambda n. \varepsilon)$
 $\langle \text{proof} \rangle$

corollary *i-expand-0-is-zero-element*: $f \odot_i 0 = g \odot_i 0$
 $\langle \text{proof} \rangle$

lemma *f-expand-gr0-f-expand-Suc*: $0 < k \implies xs \odot_f k = f\text{-expand-Suc } xs (k - \text{Suc } 0)$
 $\langle \text{proof} \rangle$

lemma *i-expand-gr0-i-expand-Suc*: $0 < k \implies f \odot_i k = i\text{-expand-Suc } f (k - \text{Suc } 0)$

$\langle \text{proof} \rangle$

lemma *i-expand-gr0*:

$0 < k \implies f \odot_i k = (\lambda n. \text{ if } n \bmod k = 0 \text{ then } f (n \operatorname{div} k) \text{ else } \varepsilon)$

$\langle \text{proof} \rangle$

lemma *f-expand-1[simp]*: $xs \odot_f \operatorname{Suc} 0 = xs$

$\langle \text{proof} \rangle$

lemma *i-expand-1[simp]*: $f \odot_i \operatorname{Suc} 0 = f$

$\langle \text{proof} \rangle$

lemma *f-expand-length[simp]*: $\text{length } (xs \odot_f k) = \text{length } xs * k$

$\langle \text{proof} \rangle$

lemma *f-expand-empty-conv*: $(xs \odot_f k = []) = (xs = [] \vee k = 0)$

$\langle \text{proof} \rangle$

lemma *f-expand-not-empty-conv*: $(xs \odot_f k \neq []) = (xs \neq [] \wedge 0 < k)$

$\langle \text{proof} \rangle$

lemma *f-expand-Cons*:

$0 < k \implies (x \# xs) \odot_f k = x \# \varepsilon^k - \operatorname{Suc} 0 @ (xs \odot_f k)$

$\langle \text{proof} \rangle$

lemma *f-expand-append[simp]*: $\bigwedge ys. (xs @ ys) \odot_f k = (xs \odot_f k) @ (ys \odot_f k)$

$\langle \text{proof} \rangle$

lemma *f-expand-snoc*:

$0 < k \implies (xs @ [x]) \odot_f k = xs \odot_f k @ x \# \text{replicate } (k - \operatorname{Suc} 0) \varepsilon$

$\langle \text{proof} \rangle$

lemma *f-expand-nth-mult*: $\bigwedge n.$

$\llbracket n < \text{length } xs; 0 < k \rrbracket \implies (xs \odot_f k) ! (n * k) = xs ! n$

$\langle \text{proof} \rangle$

lemma *i-expand-nth-mult*: $0 < k \implies (f \odot_i k) (n * k) = f n$

$\langle \text{proof} \rangle$

lemma *f-expand-nth-if*: $\bigwedge n.$

$n < \text{length } xs * k \implies$

$(xs \odot_f k) ! n = (\text{if } n \bmod k = 0 \text{ then } xs ! (n \operatorname{div} k) \text{ else } \varepsilon)$

$\langle \text{proof} \rangle$

corollary *f-expand-nth-mod-eq-0*:

$\llbracket n < \text{length } xs * k; n \bmod k = 0 \rrbracket \implies (xs \odot_f k) ! n = xs ! (n \operatorname{div} k)$

$\langle \text{proof} \rangle$

corollary *f-expand-nth-mod-neq-0*:

$\llbracket n < \text{length } xs * k; 0 < n \bmod k \rrbracket \implies (xs \odot_f k) ! n = \varepsilon$

$\langle \text{proof} \rangle$

lemma *f-expand-nth-0-upto-k-minus-1-if*:

$\llbracket t < \text{length } xs; n = t * k + i; i < k \rrbracket \implies$

$(xs \odot_f k) ! n = (\text{if } i = 0 \text{ then } xs ! t \text{ else } \varepsilon)$
 $\langle \text{proof} \rangle$

lemma *f-expand-take-mult*: $xs \odot_f k \downarrow (n * k) = (xs \downarrow n) \odot_f k$
 $\langle \text{proof} \rangle$

lemma *f-expand-take-mod*:
 $n \bmod k = 0 \implies xs \odot_f k \downarrow n = xs \downarrow (n \text{ div } k) \odot_f k$
 $\langle \text{proof} \rangle$

lemma *f-expand-drop-mult*: $xs \odot_f k \uparrow (n * k) = (xs \uparrow n) \odot_f k$
 $\langle \text{proof} \rangle$

lemma *f-expand-drop-mod*:
 $n \bmod k = 0 \implies xs \odot_f k \uparrow n = xs \uparrow (n \text{ div } k) \odot_f k$
 $\langle \text{proof} \rangle$

lemma *f-expand-take-mult-Suc*:
 $\llbracket n < \text{length } xs; i < k \rrbracket \implies$
 $xs \odot_f k \downarrow (n * k + \text{Suc } i) = (xs \downarrow n) \odot_f k @ (xs ! n \# \varepsilon^i)$
 $\langle \text{proof} \rangle$

lemma *f-expand-take-Suc*:
 $n < \text{length } xs * k \implies$
 $xs \odot_f k \downarrow \text{Suc } n = (xs \downarrow (n \text{ div } k)) \odot_f k @ (xs ! (n \text{ div } k) \# \varepsilon^{n \bmod k})$
 $\langle \text{proof} \rangle$

lemma *i-expand-nth-if*:
 $0 < k \implies (f \odot_i k) n = (\text{if } n \bmod k = 0 \text{ then } f (n \text{ div } k) \text{ else } \varepsilon)$
 $\langle \text{proof} \rangle$

corollary *i-expand-nth-mod-eq-0*:
 $\llbracket 0 < k; n \bmod k = 0 \rrbracket \implies (f \odot_i k) n = f (n \text{ div } k)$
 $\langle \text{proof} \rangle$

corollary *i-expand-nth-mod-neq-0*:
 $0 < n \bmod k \implies (f \odot_i k) n = \varepsilon$
 $\langle \text{proof} \rangle$

lemma *i-expand-nth-0-upto-k-minus-1-if*:
 $\llbracket n = t * k + i; i < k \rrbracket \implies$
 $(f \odot_i k) n = (\text{if } i = 0 \text{ then } f t \text{ else } \varepsilon)$
 $\langle \text{proof} \rangle$

lemma *i-expand-i-take-mult*: $f \odot_i k \Downarrow (n * k) = (f \Downarrow n) \odot_f k$
 $\langle \text{proof} \rangle$

lemma *i-expand-i-take-mod*:
 $n \bmod k = 0 \implies f \odot_i k \Downarrow n = f \Downarrow (n \text{ div } k) \odot_f k$
 $\langle \text{proof} \rangle$

lemma *i-expand-i-drop-mult*: $(f \odot_i k) \uparrow (n * k) = (f \uparrow n) \odot_i k$
 $\langle \text{proof} \rangle$

lemma *i-expand-i-drop-mod*:
 $n \bmod k = 0 \implies f \odot_i k \uparrow n = f \uparrow (n \text{ div } k) \odot_i k$
 $\langle \text{proof} \rangle$

lemma *i-expand-i-take-mult-Suc*:
 $i < k \implies f \odot_i k \downarrow (n * k + \text{Suc } i) = (f \downarrow n) \odot_f k @ (f n \# \varepsilon^i)$
 $\langle \text{proof} \rangle$

lemma *i-expand-i-take-Suc*:
 $0 < k \implies f \odot_i k \downarrow \text{Suc } n = (f \downarrow (n \text{ div } k)) \odot_f k @ (f (n \text{ div } k) \# \varepsilon^{n \bmod k})$
 $\langle \text{proof} \rangle$

lemma *f-expand-nth-interval-eq-nth-append-replicate-NoMsg[rule-format]*:
 $\llbracket 0 < k; t < \text{length } xs; t * k \leq t1; t1 \leq t * k + k - \text{Suc } 0 \rrbracket \implies$
 $xs \odot_f k \downarrow \text{Suc } t1 \uparrow (t * k) = xs ! t \# \varepsilon^{t1 - t * k}$
 $\langle \text{proof} \rangle$

lemma *f-expand-nth-interval-eq-replicate-NoMsg*:
 $\llbracket 0 < k; t * k < t1; t1 \leq t2; t2 \leq t * k + k; t2 \leq \text{length } xs * k \rrbracket \implies$
 $xs \odot_f k \downarrow t2 \uparrow t1 = \varepsilon^{t2 - t1}$
 $\langle \text{proof} \rangle$

lemma *i-expand-nth-interval-eq-nth-append-replicate-NoMsg[rule-format]*:
 $\llbracket 0 < k; t * k \leq t1; t1 \leq t * k + k - \text{Suc } 0 \rrbracket \implies$
 $f \odot_i k \downarrow \text{Suc } t1 \uparrow (t * k) = f t \# \varepsilon^{t1 - t * k}$
 $\langle \text{proof} \rangle$

lemma *i-expand-nth-interval-eq-replicate-NoMsg*:
 $\llbracket 0 < k; t * k < t1; t1 \leq t2; t2 \leq t * k + k \rrbracket \implies$
 $f \odot_i k \downarrow t2 \uparrow t1 = \varepsilon^{t2 - t1}$
 $\langle \text{proof} \rangle$

lemma *f-expand-replicate-NoMsg[simp]*: $(\varepsilon^n) \odot_f k = \varepsilon^{n * k}$
 $\langle \text{proof} \rangle$

lemma *i-expand-const-NoMsg[simp]*: $(\lambda n. \varepsilon) \odot_i k = (\lambda n. \varepsilon)$
 $\langle \text{proof} \rangle$

lemma *f-expand-assoc*: $xs \odot_f a \odot_f b = xs \odot_f (a * b)$
 $\langle \text{proof} \rangle$

lemma *i-expand-assoc*: $f \odot_i a \odot_i b = f \odot_i (a * b)$
 $\langle \text{proof} \rangle$

lemma *f-expand-commute*: $xs \odot_f a \odot_f b = xs \odot_f b \odot_f a$
 $\langle proof \rangle$

lemma *i-expand-commute*: $f \odot_i a \odot_i b = f \odot_i b \odot_i a$
 $\langle proof \rangle$

lemma *i-expand-i-append*: $(xs \frown f) \odot_i k = xs \odot_f k \frown (f \odot_i k)$
 $\langle proof \rangle$

lemma *f-expand-eq-conv*:
 $0 < k \implies (xs \odot_f k = ys \odot_f k) = (xs = ys)$
 $\langle proof \rangle$

lemma *i-expand-eq-conv*:
 $0 < k \implies (f \odot_i k = g \odot_i k) = (f = g)$
 $\langle proof \rangle$

lemma *f-expand-eq-conv'*:
 $(xs' \odot_f k = xs) =$
 $(length\ xs' * k = length\ xs \wedge$
 $(\forall i < length\ xs. xs ! i = (if\ i\ mod\ k = 0\ then\ xs' ! (i\ div\ k)\ else\ \varepsilon)))$
 $\langle proof \rangle$

lemma *i-expand-eq-conv'*:
 $0 < k \implies (f' \odot_i k = f) =$
 $(\forall i. f\ i = (if\ i\ mod\ k = 0\ then\ f'\ (i\ div\ k)\ else\ \varepsilon))$
 $\langle proof \rangle$

2.2.2 Aggregating lists

definition *f-aggregate* :: $'a\ list \Rightarrow nat \Rightarrow ('a\ list \Rightarrow 'a) \Rightarrow 'a\ list$
where *f-aggregate* $s\ k\ ag \equiv map\ ag\ (list-slice\ s\ k)$

definition *i-aggregate* :: $'a\ ilist \Rightarrow nat \Rightarrow ('a\ list \Rightarrow 'a) \Rightarrow 'a\ ilist$
where *i-aggregate* $s\ k\ ag \equiv \lambda n. ag\ (s\ \uparrow\ (n * k)\ \downarrow\ k)$

lemma *f-aggregate-0[simp]*: *f-aggregate* $xs\ 0\ ag = []$
 $\langle proof \rangle$

lemma *f-aggregate-1*:
 $(\bigwedge x. ag\ [x] = x) \implies$
 $f-aggregate\ xs\ (Suc\ 0)\ ag = xs$
 $\langle proof \rangle$

lemma *f-aggregate-Nil[simp]*: *f-aggregate* $[]\ k\ ag = []$
 $\langle proof \rangle$

lemma *f-aggregate-length[simp]*: $\text{length } (f\text{-aggregate } xs \ k \ ag) = \text{length } xs \ \text{div } k$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-empty-conv*:
 $0 < k \implies (f\text{-aggregate } xs \ k \ ag = []) = (\text{length } xs < k)$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-one*:
 $\llbracket 0 < k; \text{length } xs = k \rrbracket \implies f\text{-aggregate } xs \ k \ ag = [ag \ xs]$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-Cons*:
 $\llbracket 0 < k; \text{length } xs = k \rrbracket \implies$
 $f\text{-aggregate } (xs @ ys) \ k \ ag = ag \ xs \ \# \ (f\text{-aggregate } ys \ k \ ag)$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-eq-f-aggregate-take*:
 $f\text{-aggregate } (xs \downarrow (\text{length } xs \ \text{div } k * k)) \ k \ ag = f\text{-aggregate } xs \ k \ ag$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-nth*:
 $n < \text{length } xs \ \text{div } k \implies$
 $(f\text{-aggregate } xs \ k \ ag) ! n = ag \ (xs \uparrow (n * k) \downarrow k)$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-nth-eq-sublist-list*:
 $n < \text{length } xs \ \text{div } k \implies$
 $(f\text{-aggregate } xs \ k \ ag) ! n = ag \ (\text{sublist-list } xs \ [n * k..<n * k + k])$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-take-nth*:
 $\bigwedge xs \ m. \llbracket n < \text{length } xs \ \text{div } k; n < m \ \text{div } k \rrbracket \implies$
 $f\text{-aggregate } (xs \downarrow m) \ k \ ag ! n = f\text{-aggregate } xs \ k \ ag ! n$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-hd*:
 $\llbracket 0 < k; k \leq \text{length } xs \rrbracket \implies$
 $hd \ (f\text{-aggregate } xs \ k \ ag) = ag \ (xs \downarrow k)$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-append-mod*:
 $\text{length } xs \ \text{mod } k = 0 \implies$
 $f\text{-aggregate } (xs @ ys) \ k \ ag =$
 $f\text{-aggregate } xs \ k \ ag @ f\text{-aggregate } ys \ k \ ag$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-append-mult*:
 $\text{length } xs = m * k \implies$
 $f\text{-aggregate } (xs @ ys) \ k \ ag =$
 $f\text{-aggregate } xs \ k \ ag @ f\text{-aggregate } ys \ k \ ag$

$\langle \text{proof} \rangle$

lemma *f-aggregate-snoc*:

$\llbracket 0 < k; \text{length } ys = k; \text{length } xs \bmod k = 0 \rrbracket \implies$
 $f\text{-aggregate } (xs @ ys) k ag = f\text{-aggregate } xs k ag @ [ag ys]$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-take*:

$f\text{-aggregate } (xs \downarrow n) k ag = f\text{-aggregate } xs k ag \downarrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-take-mult*:

$f\text{-aggregate } (xs \downarrow (n * k)) k ag = f\text{-aggregate } xs k ag \downarrow n$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-drop-mult*:

$f\text{-aggregate } (xs \uparrow (n * k)) k ag = f\text{-aggregate } xs k ag \uparrow n$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-drop-mod*:

$n \bmod k = 0 \implies f\text{-aggregate } (xs \uparrow n) k ag = f\text{-aggregate } xs k ag \uparrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-assoc*:

$(\bigwedge xs. \text{length } xs \bmod a = 0 \implies ag (f\text{-aggregate } xs a ag) = ag xs) \implies$
 $f\text{-aggregate } (f\text{-aggregate } xs a ag) b ag = f\text{-aggregate } xs (a * b) ag$
 $\langle \text{proof} \rangle$

lemma *f-aggregate-commute*:

$\llbracket \bigwedge xs. \text{length } xs \bmod a = 0 \implies ag (f\text{-aggregate } xs a ag) = ag xs;$
 $\bigwedge xs. \text{length } xs \bmod b = 0 \implies ag (f\text{-aggregate } xs b ag) = ag xs \rrbracket \implies$
 $f\text{-aggregate } (f\text{-aggregate } xs a ag) b ag = f\text{-aggregate } (f\text{-aggregate } xs b ag) a ag$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-0[simp]*: $i\text{-aggregate } f 0 ag = (\lambda x. ag [])$

$\langle \text{proof} \rangle$

lemma *i-aggregate-1*: $(\bigwedge x. ag [x] = x) \implies i\text{-aggregate } f (Suc 0) ag = f$

$\langle \text{proof} \rangle$

lemma *i-aggregate-nth*: $i\text{-aggregate } f k ag n = ag (f \uparrow (n * k) \downarrow k)$

$\langle \text{proof} \rangle$

lemma *i-aggregate-hd*: $i\text{-aggregate } f k ag 0 = ag (f \downarrow k)$

$\langle \text{proof} \rangle$

lemma *i-aggregate-nth-eq-map*: $i\text{-aggregate } f k ag n = ag (\text{map } f [n * k..<n * k + k])$

$\langle \text{proof} \rangle$

lemma *i-aggregate-i-append-mod*:

$\text{length } xs \bmod k = 0 \implies$
 $i\text{-aggregate } (xs \frown f) k ag = f\text{-aggregate } xs k ag \frown i\text{-aggregate } f k ag$

$\langle \text{proof} \rangle$

lemma *i-aggregate-i-append-mult:*

$\text{length } xs = m * k \implies$
 $i\text{-aggregate } (xs \frown f) \ k \ ag = f\text{-aggregate } xs \ k \ ag \frown i\text{-aggregate } f \ k \ ag$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-Cons:*

$\llbracket 0 < k; \text{length } xs = k \rrbracket \implies$
 $i\text{-aggregate } (xs \frown f) \ k \ ag = [ag \ xs] \frown (i\text{-aggregate } f \ k \ ag)$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-take-nth:*

$n < m \text{ div } k \implies f\text{-aggregate } (f \Downarrow m) \ k \ ag \ ! \ n = i\text{-aggregate } f \ k \ ag \ n$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-i-take:*

$f\text{-aggregate } (f \Downarrow n) \ k \ ag = i\text{-aggregate } f \ k \ ag \Downarrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-i-take-mult:*

$0 < k \implies f\text{-aggregate } (f \Downarrow (n * k)) \ k \ ag = i\text{-aggregate } f \ k \ ag \Downarrow n$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-i-drop-mult:*

$i\text{-aggregate } (f \Uparrow (n * k)) \ k \ ag = i\text{-aggregate } f \ k \ ag \Uparrow n$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-i-drop-mod:*

$n \text{ mod } k = 0 \implies$
 $i\text{-aggregate } (f \Uparrow n) \ k \ ag = i\text{-aggregate } f \ k \ ag \Uparrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-assoc:*

$\llbracket 0 < a; 0 < b; \bigwedge xs. \text{length } xs \text{ mod } a = 0 \implies ag \ (f\text{-aggregate } xs \ a \ ag) = ag \ xs \rrbracket \implies$
 $i\text{-aggregate } (i\text{-aggregate } f \ a \ ag) \ b \ ag = i\text{-aggregate } f \ (a * b) \ ag$
 $\langle \text{proof} \rangle$

lemma *i-aggregate-commute:*

$\llbracket 0 < a; 0 < b; \bigwedge xs. \text{length } xs \text{ mod } a = 0 \implies ag \ (f\text{-aggregate } xs \ a \ ag) = ag \ xs; \bigwedge xs. \text{length } xs \text{ mod } b = 0 \implies ag \ (f\text{-aggregate } xs \ b \ ag) = ag \ xs \rrbracket \implies$
 $i\text{-aggregate } (i\text{-aggregate } xs \ a \ ag) \ b \ ag = i\text{-aggregate } (i\text{-aggregate } xs \ b \ ag) \ a \ ag$
 $\langle \text{proof} \rangle$

2.2.3 Compressing message streams

Determines the last non-empty message.

primrec *last-message* :: 'a fstream-af $\Rightarrow$ 'a message-af

where

last-message [] = ε
 | *last-message* (x # xs) = (if *last-message* xs = ε then x else *last-message* xs)

definition *f-shrink* :: 'a fstream-af $\Rightarrow$ nat $\Rightarrow$ 'a fstream-af (infixl $\langle \div_f \rangle$ 100)

where *f-shrink* xs k $\equiv$ *f-aggregate* xs k *last-message*

definition *i-shrink* :: 'a istream-af $\Rightarrow$ nat $\Rightarrow$ 'a istream-af (infixl $\langle \div_i \rangle$ 100)

where *i-shrink* f k $\equiv$ *i-aggregate* f k *last-message*

notation

f-shrink (infixl $\langle \div \rangle$ 100) and
i-shrink (infixl $\langle \div \rangle$ 100)

lemmas *f-shrink-defs* = *f-shrink-def* *f-aggregate-def*

lemmas *i-shrink-defs* = *i-shrink-def* *i-aggregate-def*

lemma *last-message-Nil*: *last-message* [] = ε
 $\langle \text{proof} \rangle$

lemma *last-message-one*: *last-message* [m] = m
 $\langle \text{proof} \rangle$

lemma *last-message-replicate*: $0 < n \implies \text{last-message } (m^n) = m$
 $\langle \text{proof} \rangle$

lemma *last-message-replicate-NoMsg*: *last-message* (ε^n) = ε
 $\langle \text{proof} \rangle$

lemma *last-message-Cons-NoMsg*: *last-message* ($\varepsilon \# xs$) = *last-message* xs
 $\langle \text{proof} \rangle$

lemma *last-message-append-one*:
last-message (xs @ [m]) = (if m = ε then *last-message* xs else m)
 $\langle \text{proof} \rangle$

lemma *last-message-append*: $\bigwedge xs.$
last-message (xs @ ys) = (
 if *last-message* ys = ε then *last-message* xs else *last-message* ys)
 $\langle \text{proof} \rangle$

corollary *last-message-append-replicate-NoMsg*:
last-message (xs @ ε^n) = *last-message* xs
 $\langle \text{proof} \rangle$

lemma *last-message-replicate-NoMsg-append*:

$last_message (\varepsilon^n @ xs) = last_message xs$
 $\langle proof \rangle$

lemma *last-message-NoMsg-conv*:
 $(last_message xs = \varepsilon) = (\forall i < length\ xs. xs ! i = \varepsilon)$
 $\langle proof \rangle$

lemma *last-message-not-NoMsg-conv*:
 $(last_message xs \neq \varepsilon) = (\exists i < length\ xs. xs ! i \neq \varepsilon)$
 $\langle proof \rangle$

lemma *not-NoMsg-imp-last-message*:
 $\llbracket i < length\ xs; xs ! i \neq \varepsilon \rrbracket \implies last_message xs \neq \varepsilon$
 $\langle proof \rangle$

lemma *last-message-exists-nth*:
 $last_message xs \neq \varepsilon \implies$
 $\exists i < length\ xs. last_message xs = xs ! i \wedge (\forall j < length\ xs. i < j \longrightarrow xs ! j = \varepsilon)$
 $\langle proof \rangle$

lemma *last-message-exists-nth'*:
 $last_message xs \neq \varepsilon \implies \exists i < length\ xs. last_message xs = xs ! i$
 $\langle proof \rangle$

lemma *last-messageI2-aux*: $\bigwedge i.$
 $\llbracket i < length\ xs; xs ! i \neq \varepsilon;$
 $\forall j. i < j \wedge j < length\ xs \longrightarrow xs ! j = \varepsilon \rrbracket \implies$
 $last_message xs = xs ! i$
 $\langle proof \rangle$

lemma *last-messageI2*:
 $\llbracket i < length\ xs; xs ! i \neq \varepsilon;$
 $\bigwedge j. \llbracket i < j; j < length\ xs \rrbracket \implies xs ! j = \varepsilon \rrbracket \implies$
 $last_message xs = xs ! i$
 $\langle proof \rangle$

lemma *last-messageI*:
 $\llbracket m \neq \varepsilon; i < length\ xs; xs ! i = m;$
 $\bigwedge j. \llbracket i < j; j < length\ xs \rrbracket \implies xs ! j = \varepsilon \rrbracket \implies$
 $last_message xs = m$
 $\langle proof \rangle$

lemma *last-message-Msg-eq-last*:
 $\llbracket xs \neq []; last\ xs \neq \varepsilon \rrbracket \implies last_message xs = last\ xs$
 $\langle proof \rangle$

lemma *last-message-conv*:
 $m \neq \varepsilon \implies$
 $(last_message xs = m) =$

$(\exists i < \text{length } xs. xs ! i = m \wedge (\forall j < \text{length } xs. i < j \longrightarrow xs ! j = \varepsilon))$
 $\langle \text{proof} \rangle$

lemma *last-message-conv-if*:

$(\text{last-message } xs = m) =$
 $(\text{if } m = \varepsilon \text{ then } \forall i < \text{length } xs. xs ! i = \varepsilon$
 $\text{else } \exists i < \text{length } xs. xs ! i = m \wedge (\forall j < \text{length } xs. i < j \longrightarrow xs ! j = \varepsilon))$
 $\langle \text{proof} \rangle$

lemma *last-message-not-NoMsg-eq-conv*:

$\llbracket \text{last-message } xs \neq \varepsilon; \text{last-message } ys \neq \varepsilon \rrbracket \implies$
 $(\text{last-message } xs = \text{last-message } ys) =$
 $(\exists i j. i < \text{length } xs \wedge j < \text{length } ys \wedge xs ! i \neq \varepsilon \wedge$
 $xs ! i = ys ! j \wedge$
 $(\forall n < \text{length } xs. i < n \longrightarrow xs ! n = \varepsilon) \wedge$
 $(\forall n < \text{length } ys. j < n \longrightarrow ys ! n = \varepsilon))$
 $\langle \text{proof} \rangle$

lemma *f-shrink-0[simp]*: $xs \div_f 0 = []$

$\langle \text{proof} \rangle$

lemma *f-shrink-1[simp]*: $xs \div_f \text{Suc } 0 = xs$

$\langle \text{proof} \rangle$

lemma *f-shrink-Nil[simp]*: $[] \div_f k = []$

$\langle \text{proof} \rangle$

lemma *f-shrink-length*: $\text{length } (xs \div_f k) = \text{length } xs \text{ div } k$

$\langle \text{proof} \rangle$

lemma *f-shrink-empty-conv*: $0 < k \implies (xs \div_f k = []) = (\text{length } xs < k)$

$\langle \text{proof} \rangle$

lemma *f-shrink-Cons*:

$\llbracket 0 < k; \text{length } xs = k \rrbracket \implies (xs @ ys) \div_f k = \text{last-message } xs \# (ys \div_f k)$
 $\langle \text{proof} \rangle$

lemma *f-shrink-one*:

$\llbracket 0 < k; \text{length } xs = k \rrbracket \implies xs \div_f k = [\text{last-message } xs]$
 $\langle \text{proof} \rangle$

lemma *f-shrink-eq-f-shrink-take*:

$xs \downarrow (\text{length } xs \text{ div } k * k) \div_f k = xs \div_f k$
 $\langle \text{proof} \rangle$

lemma *f-shrink-nth*:

$n < \text{length } xs \text{ div } k \implies$
 $(xs \div_f k) ! n = \text{last-message } (xs \uparrow (n * k) \downarrow k)$

$\langle proof \rangle$

lemma *f-shrink-nth-eq-sublist-list*:

$n < \text{length } xs \text{ div } k \implies$
 $(xs \div_f k) ! n = \text{last-message } (\text{sublist-list } xs [n * k .. n * k + k])$
 $\langle proof \rangle$

lemma *f-shrink-take-nth*:

$\llbracket 0 < \text{length } xs \text{ div } k; n < m \text{ div } k \rrbracket \implies (xs \downarrow m) \div_f k ! n = xs \div_f k ! n$
 $\langle proof \rangle$

lemma *f-shrink-hd*:

$\llbracket 0 < k; k \leq \text{length } xs \rrbracket \implies \text{hd } (xs \div_f k) = \text{last-message } (xs \downarrow k)$
 $\langle proof \rangle$

lemma *f-shrink-append-mod*:

$\text{length } xs \bmod k = 0 \implies (xs @ ys) \div_f k = xs \div_f k @ (ys \div_f k)$
 $\langle proof \rangle$

lemma *f-shrink-append-mult*:

$\text{length } xs = m * k \implies (xs @ ys) \div_f k = xs \div_f k @ (ys \div_f k)$
 $\langle proof \rangle$

lemma *f-shrink-snoc*:

$\llbracket 0 < k; \text{length } ys = k; \text{length } xs \bmod k = 0 \rrbracket \implies$
 $(xs @ ys) \div_f k = xs \div_f k @ [\text{last-message } ys]$
 $\langle proof \rangle$

lemma *f-shrink-last-message[rule-format]*:

$\text{length } xs \bmod k = 0 \longrightarrow \text{last-message } (xs \div_f k) = \text{last-message } xs$
 $\langle proof \rangle$

lemma *f-shrink-replicate*: $m^n \div_f k = m^n \text{ div } k$

$\langle proof \rangle$

lemma *f-shrink-f-expand-id*: $0 < k \implies xs \odot_f k \div_f k = xs$

$\langle proof \rangle$

lemma *f-expand-f-shrink-id-take[rule-format]*:

$\llbracket \forall i < \text{length } xs. 0 < i \bmod k \longrightarrow xs ! i = \varepsilon \rrbracket \implies$
 $xs \div_f k \odot_f k = xs \downarrow (\text{length } xs \text{ div } k * k)$
 $\langle proof \rangle$

corollary *f-expand-f-shrink-id-mod-0*:

$\llbracket \text{length } xs \bmod k = 0; \bigwedge i. \llbracket i < \text{length } xs; 0 < i \bmod k \rrbracket \implies xs ! i = \varepsilon \rrbracket \implies$
 $xs \div_f k \odot_f k = xs$
 $\langle proof \rangle$

lemma *f-shrink-take*:

$$xs \downarrow n \div_f k = xs \div_f k \downarrow (n \text{ div } k)$$

<proof>

lemma *f-shrink-take-mult*: $xs \downarrow (n * k) \div_f k = xs \div_f k \downarrow n$

<proof>

lemma *f-shrink-drop-mult*: $xs \uparrow (n * k) \div_f k = xs \div_f k \uparrow n$

<proof>

lemma *f-shrink-drop-mod*:

$$n \bmod k = 0 \implies xs \uparrow n \div_f k = xs \div_f k \uparrow (n \text{ div } k)$$

<proof>

lemma *f-shrink-eq-conv*:

$$\begin{aligned} & (xs \div_f k1 = ys \div_f k2) = \\ & (\text{length } xs \text{ div } k1 = \text{length } ys \text{ div } k2 \wedge \\ & (\forall i < \text{length } xs \text{ div } k1. \\ & \quad \text{last-message } (xs \uparrow (i * k1) \downarrow k1) = \text{last-message } (ys \uparrow (i * k2) \downarrow k2))) \end{aligned}$$

<proof>

lemma *f-shrink-eq-conv'*:

$$\begin{aligned} & (xs' \div_f k = xs) = \\ & (\text{length } xs' \text{ div } k = \text{length } xs \wedge \\ & (\forall i < \text{length } xs. \\ & \quad \text{if } xs ! i = \varepsilon \text{ then } (\forall j < k. xs' ! (i * k + j) = \varepsilon) \\ & \quad \text{else } (\exists n < k. xs' ! (i * k + n) = xs ! i \wedge \\ & \quad \quad (\forall j < k. n < j \longrightarrow xs' ! (i * k + j) = \varepsilon)))) \end{aligned}$$

<proof>

lemma *f-shrink-assoc*: $xs \div_f a \div_f b = xs \div_f (a * b)$

<proof>

lemma *f-shrink-commute*: $xs \div_f a \div_f b = xs \div_f b \div_f a$

<proof>

lemma *i-shrink-0[simp]*: $f \div_i 0 = (\lambda n. \varepsilon)$

<proof>

lemma *i-shrink-1[simp]*: $f \div_i \text{Suc } 0 = f$

<proof>

lemma *i-shrink-nth*: $(f \div_i k) n = \text{last-message } (f \uparrow (n * k) \downarrow k)$

<proof>

lemma *i-shrink-nth-eq-map*: $(f \div_i k) n = \text{last-message } (\text{map } f [n * k..n * k + k])$

<proof>

lemma *i-shrink-hd*: $(f \div_i k) 0 = \text{last-message } (f \downarrow k)$

<proof>

lemma *i-shrink-i-append-mod*:

$length\ xs\ mod\ k = 0 \implies (xs \smallfrown f) \div_i k = xs \div_f k \smallfrown (f \div_i k)$
 $\langle proof \rangle$

lemma *i-shrink-i-append-mult*:

$length\ xs = m * k \implies (xs \smallfrown f) \div_i k = xs \div_f k \smallfrown (f \div_i k)$
 $\langle proof \rangle$

lemma *i-shrink-Cons*:

$\llbracket 0 < k; length\ xs = k \rrbracket \implies (xs \smallfrown f) \div_i k = [last-message\ xs] \smallfrown (f \div_i k)$
 $\langle proof \rangle$

lemma *i-shrink-take-nth*:

$n < m \div k \implies (f \Downarrow m) \div_f k ! n = (f \div_i k) n$
 $\langle proof \rangle$

lemma *i-shrink-const[simp]*: $0 < k \implies (\lambda x. m) \div_i k = (\lambda x. m)$
 $\langle proof \rangle$

lemma *i-shrink-const-NoMsg[simp]*: $(\lambda x. \varepsilon) \div_i k = (\lambda x. \varepsilon)$
 $\langle proof \rangle$

lemma *i-shrink-i-expand-id*: $0 < k \implies f \odot_i k \div_i k = f$
 $\langle proof \rangle$

lemma *i-shrink-i-take-mult*: $0 < k \implies f \Downarrow (n * k) \div_f k = f \div_i k \Downarrow n$
 $\langle proof \rangle$

lemma *i-shrink-i-take*:

$f \Downarrow n \div_f k = f \div_i k \Downarrow (n \div k)$
 $\langle proof \rangle$

lemma *i-shrink-i-drop-mult*: $f \Uparrow (n * k) \div_i k = f \div_i k \Uparrow n$
 $\langle proof \rangle$

lemma *i-shrink-i-drop-mod*:

$n \mod k = 0 \implies f \Uparrow n \div_i k = f \div_i k \Uparrow (n \div k)$
 $\langle proof \rangle$

lemma *i-shrink-eq-conv*:

$(f \div_i k1 = g \div_i k2) =$
 $(\forall i. last-message\ (f \Uparrow (i * k1) \Downarrow k1) =$
 $last-message\ (g \Uparrow (i * k2) \Downarrow k2))$
 $\langle proof \rangle$

lemma *i-shrink-eq-conv'*:

$(f' \div_i k = f) =$
 $(\forall i. \text{if } f\ i = \varepsilon \text{ then } \forall j < k. f'\ (i * k + j) = \varepsilon$
 $\text{else } \exists n < k. f'\ (i * k + n) = f\ i \wedge$
 $(\forall j < k. n < j \implies f'\ (i * k + j) = \varepsilon))$
 $\langle proof \rangle$

lemma *i-shrink-assoc*: $f \div_i a \div_i b = f \div_i (a * b)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-commute*: $f \div_i a \div_i b = f \div_i b \div_i a$
 $\langle \text{proof} \rangle$

2.2.4 Holding last messages in everly cycle of a stream

primrec *last-message-hold-init* :: $'a \text{ fstream-af} \Rightarrow 'a \text{ message-af} \Rightarrow 'a \text{ fstream-af}$
where

$\text{last-message-hold-init } [] \ m = []$
 $| \text{last-message-hold-init } (x \# xs) \ m =$
 $\quad (\text{if } x = \varepsilon \text{ then } m \text{ else } x) \#$
 $\quad (\text{last-message-hold-init } xs \ (\text{if } x = \varepsilon \text{ then } m \text{ else } x))$

definition *last-message-hold* :: $'a \text{ fstream-af} \Rightarrow 'a \text{ fstream-af}$
where $\text{last-message-hold } xs \equiv \text{last-message-hold-init } xs \ \varepsilon$

lemma *last-message-hold-init-length[simp]*:
 $\bigwedge m. \text{length } (\text{last-message-hold-init } xs \ m) = \text{length } xs$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-init-nth*:
 $\bigwedge i \ m. i < \text{length } xs \implies$
 $(\text{last-message-hold-init } xs \ m) ! i = \text{last-message } (m \# xs \downarrow \text{Suc } i)$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-init-snoc*:
 $\text{last-message-hold-init } (xs @ [x]) \ m =$
 $\text{last-message-hold-init } xs \ m @$
 $\quad [\text{if } x = \varepsilon \text{ then } \text{last-message } (m \# xs) \text{ else } x]$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-init-append[rule-format]*:
 $\bigwedge xs \ m. \text{last-message-hold-init } (xs @ ys) \ m =$
 $\text{last-message-hold-init } xs \ m @ \text{last-message-hold-init } ys \ (\text{last-message } (m \# xs))$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-length[simp]*: $\text{length } (\text{last-message-hold } xs) = \text{length } xs$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-Nil[simp]*: $\text{last-message-hold } [] = []$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-one[simp]*: $\text{last-message-hold } [x] = [x]$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-nth*:

$i < \text{length } xs \implies \text{last-message-hold } xs ! i = \text{last-message } (xs \downarrow \text{Suc } i)$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-last*:
 $xs \neq [] \implies \text{last } (\text{last-message-hold } xs) = \text{last-message } xs$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-take*:
 $\text{last-message-hold } xs \downarrow n = \text{last-message-hold } (xs \downarrow n)$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-snoc*:
 $\text{last-message-hold } (xs @ [x]) =$
 $\text{last-message-hold } xs @ [\text{if } x = \varepsilon \text{ then last-message } xs \text{ else } x]$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-append*:
 $\text{last-message-hold } (xs @ ys) =$
 $\text{last-message-hold } xs @ \text{last-message-hold-init } ys (\text{last-message } xs)$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-append'*:
 $\text{last-message-hold } (xs @ ys) =$
 $\text{last-message-hold } xs @ \text{tl } (\text{last-message-hold } (\text{last-message } xs \# ys))$
 $\langle \text{proof} \rangle$

lemma *last-message-last-message-hold[simp]*:
 $\text{last-message } (\text{last-message-hold } xs) = \text{last-message } xs$
 $\langle \text{proof} \rangle$

lemma *last-message-hold-idem[simp]*:
 $\text{last-message-hold } (\text{last-message-hold } xs) = \text{last-message-hold } xs$
 $\langle \text{proof} \rangle$

Returns for each point in time the currently last non-empty message of the current stream cycle of length k .

definition *f-last-message-hold* :: $'a \text{ fstream-af} \Rightarrow \text{nat} \Rightarrow 'a \text{ fstream-af}$ (**infixl** $\langle \mapsto_f \rangle$ 100)
where $f\text{-last-message-hold } xs \ k \equiv \text{concat } (\text{map } \text{last-message-hold } (\text{list-slice2 } xs \ k))$

definition *i-last-message-hold* :: $'a \text{ istream-af} \Rightarrow \text{nat} \Rightarrow 'a \text{ istream-af}$ (**infixl** $\langle \mapsto_i \rangle$ 100)
where $i\text{-last-message-hold } f \ k \equiv \lambda n. \text{last-message } (f \uparrow (n - n \bmod k) \downarrow \text{Suc } (n \bmod k))$

notation
 $f\text{-last-message-hold}$ (**infixl** $\langle \mapsto_f \rangle$ 100) **and**
 $i\text{-last-message-hold}$ (**infixl** $\langle \mapsto_i \rangle$ 100)

lemma *f-last-message-hold-0[simp]*: $xs \mapsto_f 0 = \text{last-message-hold } xs$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-1[simp]*: $xs \mapsto_f (\text{Suc } 0) = xs$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-Nil[simp]*: $[] \mapsto_f k = []$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-length[simp]*: $\text{length } (xs \mapsto_f k) = \text{length } xs$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-le*: $\text{length } xs \leq k \implies xs \mapsto_f k = \text{last-message-hold } xs$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-append-mult*:
 $\text{length } xs = m * k \implies (xs @ ys) \mapsto_f k = xs \mapsto_f k @ (ys \mapsto_f k)$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-append-mod*:
 $\text{length } xs \bmod k = 0 \implies (xs @ ys) \mapsto_f k = xs \mapsto_f k @ (ys \mapsto_f k)$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-nth[rule-format]*:
 $\forall n. n < \text{length } xs \implies xs \mapsto_f k ! n = \text{last-message } (xs \uparrow (n \text{ div } k * k) \downarrow \text{Suc } (n \bmod k))$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-take*: $xs \downarrow n \mapsto_f k = xs \mapsto_f k \downarrow n$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-drop-mult*:
 $xs \uparrow (n * k) \mapsto_f k = xs \mapsto_f k \uparrow (n * k)$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-drop-mod*:
 $n \bmod k = 0 \implies xs \uparrow n \mapsto_f k = xs \mapsto_f k \uparrow n$
 $\langle \text{proof} \rangle$

lemma *f-last-message-hold-idem*: $xs \mapsto_f k \mapsto_f k = xs \mapsto_f k$
 $\langle \text{proof} \rangle$

lemma *f-shrink-nth-eq-f-last-message-hold-last*:
 $n < \text{length } xs \text{ div } k \implies xs \div_f k ! n = \text{last } (xs \mapsto_f k \uparrow (n * k) \downarrow k)$
 $\langle \text{proof} \rangle$

lemma *f-shrink-nth-eq-f-last-message-hold-nth*:
 $n < \text{length } xs \text{ div } k \implies xs \div_f k ! n = xs \mapsto_f k ! (n * k + k - \text{Suc } 0)$

$\langle \text{proof} \rangle$

lemma *last-message-f-last-message-hold*:

$$\text{last-message } (xs \mapsto_f k) = \text{last-message } xs$$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-0[simp]*: $f \mapsto_i 0 = (\lambda n. \text{last-message } (f \Downarrow \text{Suc } n))$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-1[simp]*: $f \mapsto_i \text{Suc } 0 = f$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-nth*:

$$(f \mapsto_i k) \ n = \text{last-message } (f \Uparrow (n - n \bmod k) \Downarrow \text{Suc } (n \bmod k))$$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-i-append-mult*:

$$\text{length } xs = m * k \implies (xs \frown f) \mapsto_i k = (xs \mapsto_f k) \frown (f \mapsto_i k)$$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-i-append-mod*:

$$\text{length } xs \bmod k = 0 \implies (xs \frown f) \mapsto_i k = (xs \mapsto_f k) \frown (f \mapsto_i k)$$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-i-take*: $f \Downarrow n \mapsto_f k = (f \mapsto_i k) \Downarrow n$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-i-drop-mult*:

$$f \Uparrow (n * k) \mapsto_i k = f \mapsto_i k \Uparrow (n * k)$$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-i-drop-mod*:

$$n \bmod k = 0 \implies f \Uparrow n \mapsto_i k = f \mapsto_i k \Uparrow n$$

$\langle \text{proof} \rangle$

lemma *i-last-message-hold-idem*: $f \mapsto_i k \mapsto_i k = f \mapsto_i k$

$\langle \text{proof} \rangle$

lemma *i-shrink-nth-eq-i-last-message-hold-nth*:

$$0 < k \implies (f \div_i k) \ n = (f \mapsto_i k) \ (n * k + k - \text{Suc } 0)$$

$\langle \text{proof} \rangle$

lemma *i-shrink-nth-eq-i-last-message-hold-last*:

$$0 < k \implies (f \div_i k) \ n = \text{last } (f \mapsto_i k \Uparrow (n * k) \Downarrow k)$$

$\langle \text{proof} \rangle$

2.2.5 Compressing lists

Lists/Non-message streams do not have to permit the empty message ε to be element. Thus, they are compressed by factor k by just aggregating every

sequence of length k to its last element.

definition $f\text{-shrink-last} :: 'a \text{ list} \Rightarrow \text{nat} \Rightarrow 'a \text{ list}$ (**infixl** $\div_f$ 100)
where $f\text{-shrink-last } xs \ k \equiv f\text{-aggregate } xs \ k \text{ last}$

definition $i\text{-shrink-last} :: 'a \text{ ilist} \Rightarrow \text{nat} \Rightarrow 'a \text{ ilist}$ (**infixl** $\div_i$ 100)
where $i\text{-shrink-last } f \ k \equiv i\text{-aggregate } f \ k \text{ last}$

notation

$f\text{-shrink-last}$ (**infixl** $\div_l$ 100) **and**
 $i\text{-shrink-last}$ (**infixl** $\div_i$ 100)

lemma $f\text{-shrink-last-0}[simp]$: $xs \div_f 0 = []$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-1}[simp]$: $xs \div_f \text{Suc } 0 = xs$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-Nil}[simp]$: $[] \div_f k = []$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-length}$: $\text{length } (xs \div_f k) = \text{length } xs \text{ div } k$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-empty-conv}$:
 $0 < k \implies (xs \div_f k = []) = (\text{length } xs < k)$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-Cons}$:
 $\llbracket 0 < k; \text{length } xs = k \rrbracket \implies (xs @ ys) \div_f k = \text{last } xs \# (ys \div_f k)$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-one}$:
 $\llbracket 0 < k; \text{length } xs = k \rrbracket \implies xs \div_f k = [\text{last } xs]$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-eq-f-shrink-last-take}$:
 $xs \downarrow (\text{length } xs \text{ div } k * k) \div_f k = xs \div_f k$
 $\langle proof \rangle$

lemma $f\text{-shrink-last-nth}$:
 $n < \text{length } xs \text{ div } k \implies (xs \div_f k) ! n = xs ! (n * k + k - \text{Suc } 0)$
 $\langle proof \rangle$

corollary $f\text{-shrink-last-nth'}$:
 $n < \text{length } xs \text{ div } k \implies (xs \div_f k) ! n = xs ! (\text{Suc } n * k - \text{Suc } 0)$
 $\langle proof \rangle$

lemma *f-shrink-last-hd*:

$\llbracket 0 < k; k \leq \text{length } xs \rrbracket \implies \text{hd } (xs \div_{\text{fl}} k) = xs ! (k - \text{Suc } 0)$
 $\langle \text{proof} \rangle$

lemma *f-shrink-last-map*: $(\text{map } f \text{ } xs) \div_{\text{fl}} k = \text{map } f \text{ } (xs \div_{\text{fl}} k)$

$\langle \text{proof} \rangle$

lemma *f-shrink-last-append-mod*:

$\text{length } xs \bmod k = 0 \implies (xs @ ys) \div_{\text{fl}} k = xs \div_{\text{fl}} k @ (ys \div_{\text{fl}} k)$
 $\langle \text{proof} \rangle$

lemma *f-shrink-last-append-mult*:

$\text{length } xs = m * k \implies (xs @ ys) \div_{\text{fl}} k = xs \div_{\text{fl}} k @ (ys \div_{\text{fl}} k)$
 $\langle \text{proof} \rangle$

lemma *f-shrink-last-snoc*:

$\llbracket 0 < k; \text{length } ys = k; \text{length } xs \bmod k = 0 \rrbracket \implies$
 $(xs @ ys) \div_{\text{fl}} k = xs \div_{\text{fl}} k @ [\text{last } ys]$
 $\langle \text{proof} \rangle$

lemma *f-shrink-last-last*:

$\text{length } xs \bmod k = 0 \implies \text{last } (xs \div_{\text{fl}} k) = \text{last } xs$
 $\langle \text{proof} \rangle$

lemma *f-shrink-last-replicate*: $m^n \div_{\text{fl}} k = m^{n \text{ div } k}$

$\langle \text{proof} \rangle$

lemma *f-shrink-last-take*:

$xs \downarrow n \div_{\text{fl}} k = xs \div_{\text{fl}} k \downarrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *f-shrink-last-take-mult*: $xs \downarrow (n * k) \div_{\text{fl}} k = xs \div_{\text{fl}} k \downarrow n$

$\langle \text{proof} \rangle$

lemma *f-shrink-last-drop-mult*: $xs \uparrow (n * k) \div_{\text{fl}} k = xs \div_{\text{fl}} k \uparrow n$

$\langle \text{proof} \rangle$

lemma *f-shrink-last-drop-mod*:

$n \bmod k = 0 \implies xs \uparrow n \div_{\text{fl}} k = xs \div_{\text{fl}} k \uparrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *f-shrink-last-assoc*: $xs \div_{\text{fl}} a \div_{\text{fl}} b = xs \div_{\text{fl}} (a * b)$

$\langle \text{proof} \rangle$

lemma *f-shrink-last-commute*: $xs \div_{\text{fl}} a \div_{\text{fl}} b = xs \div_{\text{fl}} b \div_{\text{fl}} a$

$\langle \text{proof} \rangle$

lemma *i-shrink-last-1* [simp]: $f \div_{il} \text{Suc } 0 = f$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-nth*: $0 < k \implies (f \div_{il} k) \ n = f \ (n * k + k - \text{Suc } 0)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-nth'*: $0 < k \implies (f \div_{il} k) \ n = f \ (\text{Suc } n * k - \text{Suc } 0)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-hd*: $(f \div_{il} k) \ 0 = \text{last } (f \Downarrow k)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-o*: $0 < k \implies (f \circ g) \div_{il} k = f \circ (g \div_{il} k)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-i-append-mod*:
 $\text{length } xs \bmod k = 0 \implies (xs \frown f) \div_{il} k = xs \div_{fl} k \frown (f \div_{il} k)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-i-append-mult*:
 $\text{length } xs = m * k \implies (xs \frown f) \div_{il} k = xs \div_{fl} k \frown (f \div_{il} k)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-Cons*:
 $\llbracket 0 < k; \text{length } xs = k \rrbracket \implies (xs \frown f) \div_{il} k = [\text{last } xs] \frown (f \div_{il} k)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-const*: $0 < k \implies (\lambda x. m) \div_{il} k = (\lambda x. m)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-i-take-mult*:
 $0 < k \implies f \Downarrow (n * k) \div_{fl} k = f \div_{il} k \Downarrow n$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-i-take*:
 $f \Downarrow n \div_{fl} k = f \div_{il} k \Downarrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-i-drop-mult*: $f \Uparrow (n * k) \div_{il} k = f \div_{il} k \Uparrow n$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-i-drop-mod*:
 $n \bmod k = 0 \implies f \Uparrow n \div_{il} k = f \div_{il} k \Uparrow (n \text{ div } k)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-assoc*: $f \div_{il} a \div_{il} b = f \div_{il} (a * b)$
 $\langle \text{proof} \rangle$

lemma *i-shrink-last-commute*: $f \div_{il} a \div_{il} b = f \div_{il} b \div_{il} a$
 $\langle proof \rangle$

Shrinking a message stream with *last-message* as aggregation function corresponds to shrinking the stream holding last message in each cycle with *last* as aggregation function.

lemma *f-shrink-eq-f-last-message-hold-shrink-last*:
 $xs \div_f k = xs \mapsto_f k \div_{fl} k$
 $\langle proof \rangle$

lemma *i-shrink-eq-i-last-message-hold-shrink-last*:
 $0 < k \implies f \div_i k = f \mapsto_i k \div_{il} k$
 $\langle proof \rangle$

end

3 Processing of message streams

theory *AF-Stream-Exec*
imports *AF-Stream List-Infinite.ListInf-Prefix List-Infinite.SetIntervalStep*
begin

3.1 Executing components with state transition functions

3.1.1 Basic definitions

Function type for functions converting an input value to an input port message for a component

type-synonym (*'a*, *'in*) *Port-Input-Value* = *'a* $\Rightarrow$ *'in message-af*

Function type for functions extracting the output value of a single output port from a component value

type-synonym (*'comp*, *'out*) *Port-Output-Value* = *'comp* $\Rightarrow$ *'out message-af*

Function type for functions extracting the local state of a component from a component value

type-synonym (*'comp*, *'state*) *Comp-Local-State* = *'comp* $\Rightarrow$ *'state*

Function type for transition functions computing the component's value after processing an input for a single time unit

type-synonym (*'comp*, *'input*) *Comp-Trans-Fun* = *'input* $\Rightarrow$ *'comp* $\Rightarrow$ *'comp*

— Execute a component for all inputs in the input stream *'input list*

primrec *f-Exec-Comp* :: (*'comp*, *'input*) *Comp-Trans-Fun* $\Rightarrow$ *'input list* $\Rightarrow$ *'comp* $\Rightarrow$ *'comp*

where

f-Exec-Nil: $f\text{-Exec-Comp trans-fun } [] \ c = c$
 $|$ *f-Exec-Cons*: $f\text{-Exec-Comp trans-fun } (x \# xs) \ c = f\text{-Exec-Comp trans-fun } xs \ (trans\text{-fun } x \ c)$

— Execute the component for at most n steps

definition *f-Exec-Comp-N* :: $('comp, 'input) \text{ Comp-Trans-Fun} \Rightarrow nat \Rightarrow 'input \text{ list} \Rightarrow 'comp \Rightarrow 'comp$
where $f\text{-Exec-Comp-N trans-fun } n \ xs \ c \equiv f\text{-Exec-Comp trans-fun } (xs \downarrow n) \ c$

— Produce the component stream for all inputs in the input stream

primrec *f-Exec-Comp-Stream* :: $('comp, 'input) \text{ Comp-Trans-Fun} \Rightarrow 'input \text{ list} \Rightarrow 'comp \Rightarrow 'comp \text{ list}$
where

f-Exec-Stream-Nil: $f\text{-Exec-Comp-Stream trans-fun } [] \ c = []$
 $|$ *f-Exec-Stream-Cons*: $f\text{-Exec-Comp-Stream trans-fun } (x \# xs) \ c = (trans\text{-fun } x \ c) \# (f\text{-Exec-Comp-Stream trans-fun } xs \ (trans\text{-fun } x \ c))$

primrec *f-Exec-Comp-Stream-Init* ::

$('comp, 'input) \text{ Comp-Trans-Fun} \Rightarrow 'input \text{ list} \Rightarrow 'comp \Rightarrow 'comp \text{ list}$
where

f-Exec-Stream-Init-Nil: $f\text{-Exec-Comp-Stream-Init trans-fun } [] \ c = [c]$
 $|$ *f-Exec-Stream-Init-Cons*: $f\text{-Exec-Comp-Stream-Init trans-fun } (x \# xs) \ c = c \# (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ (trans\text{-fun } x \ c))$

definition *i-Exec-Comp-Stream* ::

$('comp, 'input) \text{ Comp-Trans-Fun} \Rightarrow 'input \text{ ilist} \Rightarrow 'comp \Rightarrow 'comp \text{ ilist}$
where $i\text{-Exec-Comp-Stream} \equiv \lambda trans\text{-fun input } c \ n. f\text{-Exec-Comp trans-fun } (input \downarrow Suc \ n) \ c$

definition *i-Exec-Comp-Stream-Init* ::

$('comp, 'input) \text{ Comp-Trans-Fun} \Rightarrow 'input \text{ ilist} \Rightarrow 'comp \Rightarrow 'comp \text{ ilist}$
where $i\text{-Exec-Comp-Stream-Init} \equiv \lambda trans\text{-fun input } c \ n. f\text{-Exec-Comp trans-fun } (input \downarrow n) \ c$

3.1.2 Basic results

lemma *f-Exec-one*: $f\text{-Exec-Comp trans-fun } [m] \ c = trans\text{-fun } m \ c$
 $\langle proof \rangle$

lemma *f-Exec-Stream-length*[*rule-format*, *simp*]:

$\forall c. \text{length } (f\text{-Exec-Comp-Stream trans-fun } xs \ c) = \text{length } xs$
 $\langle proof \rangle$

lemma *f-Exec-Stream-empty-conv*:

$(f\text{-Exec-Comp-Stream trans-fun } xs \ c = []) = (xs = [])$
 $\langle proof \rangle$

lemma *f-Exec-Stream-not-empty-conv*:

$(f\text{-Exec-Comp-Stream trans-fun } xs \ c \neq []) = (xs \neq [])$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-eq-f-Exec-Stream-last}$ [rule-format]:
 $\forall c. f\text{-Exec-Comp trans-fun } xs \ c = \text{last } (c \# (f\text{-Exec-Comp-Stream trans-fun } xs \ c))$
 $\langle \text{proof} \rangle$

corollary $f\text{-Exec-eq-f-Exec-Stream-last2}$ [rule-format]:
 $xs \neq [] \implies$
 $f\text{-Exec-Comp trans-fun } xs \ c = \text{last } (f\text{-Exec-Comp-Stream trans-fun } xs \ c)$
 $\langle \text{proof} \rangle$

corollary $f\text{-Exec-eq-f-Exec-Stream-last-if}$:
 $f\text{-Exec-Comp trans-fun } xs \ c = (\text{if } xs = [] \text{ then } c \text{ else } \text{last } (f\text{-Exec-Comp-Stream trans-fun } xs \ c))$
 $\langle \text{proof} \rangle$

corollary $f\text{-Exec-take-eq-last-f-Exec-Stream-take}$:
 $\llbracket xs \neq []; 0 < n \rrbracket \implies$
 $f\text{-Exec-Comp trans-fun } (xs \downarrow n) \ c =$
 $\text{last } (f\text{-Exec-Comp-Stream trans-fun } (xs \downarrow n) \ c)$
 $\langle \text{proof} \rangle$

corollary $f\text{-Exec-N-eq-last-f-Exec-Stream-take}$:
 $\llbracket xs \neq []; 0 < n \rrbracket \implies$
 $f\text{-Exec-Comp-N trans-fun } n \ xs \ c =$
 $\text{last } (f\text{-Exec-Comp-Stream trans-fun } (xs \downarrow n) \ c)$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-nth}$:
 $\bigwedge n \ c. n < \text{length } xs \implies$
 $f\text{-Exec-Comp-Stream trans-fun } xs \ c \ ! \ n = f\text{-Exec-Comp trans-fun } (xs \downarrow \text{Suc } n) \ c$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-nth2}$:
 $n \leq \text{length } xs \implies$
 $(c \# f\text{-Exec-Comp-Stream trans-fun } xs \ c) \ ! \ n = f\text{-Exec-Comp trans-fun } (xs \downarrow n) \ c$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-N-all}$:
 $\text{length } xs \leq n \implies$
 $f\text{-Exec-Comp-N trans-fun } n \ xs \ c = f\text{-Exec-Comp trans-fun } xs \ c$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-append}$ [rule-format]: $\forall c.$
 $f\text{-Exec-Comp-Stream trans-fun } (xs @ ys) \ c =$
 $(f\text{-Exec-Comp-Stream trans-fun } xs \ c) @$

(*f-Exec-Comp-Stream trans-fun ys (f-Exec-Comp trans-fun xs c)*)
 ⟨proof⟩

corollary *f-Exec-Stream-append-last-Cons*[rule-format]:

f-Exec-Comp-Stream trans-fun (xs @ ys) c =
(f-Exec-Comp-Stream trans-fun xs c) @
(f-Exec-Comp-Stream trans-fun ys (last (c # (f-Exec-Comp-Stream trans-fun
xs c))))
 ⟨proof⟩

corollary *f-Exec-Stream-append-last*[rule-format]:

xs ≠ [] ⇒
f-Exec-Comp-Stream trans-fun (xs @ ys) c =
(f-Exec-Comp-Stream trans-fun xs c) @
(f-Exec-Comp-Stream trans-fun ys (last (f-Exec-Comp-Stream trans-fun xs c)))
 ⟨proof⟩

corollary *f-Exec-Stream-append-if*:

f-Exec-Comp-Stream trans-fun (xs @ ys) c =
(f-Exec-Comp-Stream trans-fun xs c) @
(f-Exec-Comp-Stream trans-fun ys (
if xs = [] then c else last (f-Exec-Comp-Stream trans-fun xs c)))
 ⟨proof⟩

corollary *f-Exec-append*:

f-Exec-Comp trans-fun (xs @ ys) c =
f-Exec-Comp trans-fun ys (f-Exec-Comp trans-fun xs c)
 ⟨proof⟩

corollary *f-Exec-Stream-Cons-rev*:

xs ≠ [] ⇒
(trans-fun (hd xs) c) #
f-Exec-Comp-Stream trans-fun (tl xs) (trans-fun (hd xs) c) =
f-Exec-Comp-Stream trans-fun xs c
 ⟨proof⟩

lemma *f-Exec-Stream-snoc*:

f-Exec-Comp-Stream trans-fun (xs @ [x]) c =
f-Exec-Comp-Stream trans-fun xs c @
[trans-fun x (f-Exec-Comp trans-fun xs c)]
 ⟨proof⟩

lemma *f-Exec-snoc*:

f-Exec-Comp trans-fun (xs @ [x]) c =
trans-fun x (f-Exec-Comp trans-fun xs c)
 ⟨proof⟩

lemma *f-Exec-N-append*[rule-format]:

f-Exec-Comp-N trans-fun (a + b) xs c =

$f\text{-Exec-Comp-}N \text{ trans-fun } b \ (xs \uparrow a) \ (f\text{-Exec-Comp-}N \text{ trans-fun } a \ xs \ c)$
 $\langle \text{proof} \rangle$

corollary $f\text{-Exec-}N\text{-Suc}$ [rule-format]:

$f\text{-Exec-Comp-}N \text{ trans-fun } (Suc \ n) \ xs \ c =$
 $f\text{-Exec-Comp-}N \text{ trans-fun } (Suc \ 0) \ (xs \uparrow n) \ (f\text{-Exec-Comp-}N \text{ trans-fun } n \ xs \ c)$
 $\langle \text{proof} \rangle$

corollary $f\text{-Exec-}N\text{-Suc2}$ [rule-format]:

$n < \text{length } xs \implies$
 $f\text{-Exec-Comp-}N \text{ trans-fun } (Suc \ n) \ xs \ c =$
 $\text{trans-fun } (xs \ ! \ n) \ (f\text{-Exec-Comp-}N \text{ trans-fun } n \ xs \ c)$
 $\langle \text{proof} \rangle$

theorem $f\text{-Exec-Stream-take}$:

$(f\text{-Exec-Comp-Stream} \text{ trans-fun } xs \ c) \downarrow n =$
 $f\text{-Exec-Comp-Stream} \text{ trans-fun } (xs \downarrow n) \ c$
 $\langle \text{proof} \rangle$

theorem $f\text{-Exec-Stream-drop}$:

$(f\text{-Exec-Comp-Stream} \text{ trans-fun } xs \ c) \uparrow n =$
 $f\text{-Exec-Comp-Stream} \text{ trans-fun } (xs \uparrow n)$
 $(f\text{-Exec-Comp} \text{ trans-fun } (xs \downarrow n) \ c)$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-nth}$:

$i\text{-Exec-Comp-Stream} \text{ trans-fun } \text{input } c \ n = f\text{-Exec-Comp} \text{ trans-fun } (\text{input} \Downarrow \text{Suc}$
 $n) \ c$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-nth-Suc}$:

$i\text{-Exec-Comp-Stream} \text{ trans-fun } \text{input } c \ (Suc \ n) =$
 $\text{trans-fun } (\text{input } (Suc \ n)) \ (i\text{-Exec-Comp-Stream} \text{ trans-fun } \text{input } c \ n)$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-nth-Suc-first}$:

$i\text{-Exec-Comp-Stream} \text{ trans-fun } \text{input } c \ (Suc \ n) =$
 $(i\text{-Exec-Comp-Stream} \text{ trans-fun } (\text{input} \uparrow \text{Suc } 0) \ (\text{trans-fun } (\text{input } 0) \ c) \ n)$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-nth-eq-}i\text{-Exec-Stream-nth}$:

$n < n' \implies$
 $f\text{-Exec-Comp-Stream} \text{ trans-fun } (\text{input} \Downarrow \ n') \ c \ ! \ n =$
 $i\text{-Exec-Comp-Stream} \text{ trans-fun } \text{input } c \ n$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-append}$:

$i\text{-Exec-Comp-Stream} \text{ trans-fun } (xs \frown \text{input}) \ c =$

$f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c \frown$
 $i\text{-Exec-Comp-Stream trans-fun input } (f\text{-Exec-Comp trans-fun } xs \text{ } c)$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-append-last-Cons}$:
 $i\text{-Exec-Comp-Stream trans-fun } (xs \frown \text{input}) \text{ } c =$
 $f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c \frown$
 $i\text{-Exec-Comp-Stream trans-fun input } ($
 $\quad \text{last } (c \# f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c))$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-append-last}$:
 $xs \neq [] \implies$
 $i\text{-Exec-Comp-Stream trans-fun } (xs \frown \text{input}) \text{ } c =$
 $f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c \frown$
 $i\text{-Exec-Comp-Stream trans-fun input } ($
 $\quad \text{last } (f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c))$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-append-if}$:
 $i\text{-Exec-Comp-Stream trans-fun } (xs \frown \text{input}) \text{ } c =$
 $f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c \frown$
 $i\text{-Exec-Comp-Stream trans-fun input } ($
 $\quad \text{if } xs = [] \text{ then } c$
 $\quad \text{else last } (f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c))$
 $\langle \text{proof} \rangle$

corollary $i\text{-Exec-Stream-Cons}$:
 $i\text{-Exec-Comp-Stream trans-fun } ([x] \frown \text{input}) \text{ } c =$
 $[trans\text{-fun } x \text{ } c] \frown i\text{-Exec-Comp-Stream trans-fun input } (trans\text{-fun } x \text{ } c)$
 $\langle \text{proof} \rangle$

corollary $i\text{-Exec-Stream-Cons-rev}$:
 $[trans\text{-fun } (\text{input } 0) \text{ } c] \frown$
 $i\text{-Exec-Comp-Stream trans-fun } (\text{input } \uparrow \text{Suc } 0) (trans\text{-fun } (\text{input } 0) \text{ } c) =$
 $i\text{-Exec-Comp-Stream trans-fun input } c$
 $\langle \text{proof} \rangle$

theorem $i\text{-Exec-Stream-take}$:
 $(i\text{-Exec-Comp-Stream trans-fun input } c) \Downarrow n =$
 $f\text{-Exec-Comp-Stream trans-fun } (\text{input } \Downarrow n) \text{ } c$
 $\langle \text{proof} \rangle$

theorem $i\text{-Exec-Stream-drop}$:
 $(i\text{-Exec-Comp-Stream trans-fun input } c) \Uparrow n =$
 $i\text{-Exec-Comp-Stream trans-fun } (\text{input } \Uparrow n) (f\text{-Exec-Comp trans-fun } (\text{input } \Downarrow n)$
 $\text{ } c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-expand-aggregate-map-take:*

$$\begin{aligned} & f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun } (xs \odot_f k) \text{ c)}) \text{ k ag } \downarrow n = \\ & f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun } ((xs \downarrow n) \odot_f k) \text{ c)}) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

corollary *f-Exec-Stream-expand-aggregate-take:*

$$\begin{aligned} & f\text{-aggregate } (\text{f-Exec-Comp-Stream trans-fun } (xs \odot_f k) \text{ c}) \text{ k ag } \downarrow n = \\ & f\text{-aggregate } (\text{f-Exec-Comp-Stream trans-fun } ((xs \downarrow n) \odot_f k) \text{ c}) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Exec-Stream-expand-aggregate-map-take:*

$$\begin{aligned} & 0 < k \implies \\ & i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } (\text{input} \odot_i k) \text{ c})) \text{ k ag } \Downarrow n = \\ & f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun } ((\text{input} \Downarrow n) \odot_f k) \text{ c)}) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

corollary *i-Exec-Stream-expand-aggregate-take:*

$$\begin{aligned} & 0 < k \implies \\ & i\text{-aggregate } (i\text{-Exec-Comp-Stream trans-fun } (\text{input} \odot_i k) \text{ c}) \text{ k ag } \Downarrow n = \\ & f\text{-aggregate } (\text{f-Exec-Comp-Stream trans-fun } ((\text{input} \Downarrow n) \odot_f k) \text{ c}) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-expand-aggregate-map-drop:*

$$\begin{aligned} & f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun } (xs \odot_f k) \text{ c)}) \text{ k ag } \uparrow n = \\ & f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun } ((xs \uparrow n) \odot_f k) \text{ (} \\ & \quad \text{f-Exec-Comp trans-fun } ((xs \downarrow n) \odot_f k) \text{ c)})) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

corollary *f-Exec-Stream-expand-aggregate-drop:*

$$\begin{aligned} & f\text{-aggregate } (\text{f-Exec-Comp-Stream trans-fun } (xs \odot_f k) \text{ c}) \text{ k ag } \uparrow n = \\ & f\text{-aggregate } (\text{f-Exec-Comp-Stream trans-fun } ((xs \uparrow n) \odot_f k) \text{ (} \\ & \quad \text{f-Exec-Comp trans-fun } ((xs \downarrow n) \odot_f k) \text{ c)}) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Exec-Stream-expand-aggregate-map-drop:*

$$\begin{aligned} & 0 < k \implies \\ & i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } (\text{input} \odot_i k) \text{ c})) \text{ k ag } \Uparrow n = \\ & i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } ((\text{input} \Uparrow n) \odot_i k) \text{ (} \\ & \quad \text{f-Exec-Comp trans-fun } ((\text{input} \Downarrow n) \odot_f k) \text{ c)})) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

corollary *i-Exec-Stream-expand-aggregate-drop:*

$$\begin{aligned} & 0 < k \implies \\ & i\text{-aggregate } (i\text{-Exec-Comp-Stream trans-fun } (\text{input} \odot_i k) \text{ c}) \text{ k ag } \Uparrow n = \\ & i\text{-aggregate } (i\text{-Exec-Comp-Stream trans-fun } ((\text{input} \Uparrow n) \odot_i k) \text{ (} \\ & \quad \text{f-Exec-Comp trans-fun } ((\text{input} \Downarrow n) \odot_f k) \text{ c)}) \text{ k ag} \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-expand-aggregate-map-nth-eq-i-nth:*

$\llbracket 0 < k; n < n' \rrbracket \implies$
 $f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun (input } \Downarrow n' \odot_f k) \text{ c)}) \text{ k ag !}$
 $n =$
 $i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c)}) \text{ k ag n}$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-expand-aggregate-map-nth-eq-i-nth':*

$0 < k \implies$
 $f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun (input } \Downarrow \text{Suc } n \odot_f k) \text{ c)}) \text{ k ag !}$
 $n =$
 $i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c)}) \text{ k ag n}$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-expand-aggregate-nth-eq-i-nth:*

$\llbracket 0 < k; n < n' \rrbracket \implies$
 $f\text{-aggregate } (f\text{-Exec-Comp-Stream trans-fun (input } \Downarrow n' \odot_f k) \text{ c}) \text{ k ag !}$
 $n =$
 $i\text{-aggregate } (i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c}) \text{ k ag n}$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-expand-aggregate-nth-eq-i-nth':*

$0 < k \implies$
 $f\text{-aggregate } (f\text{-Exec-Comp-Stream trans-fun (input } \Downarrow \text{Suc } n \odot_f k) \text{ c}) \text{ k ag !}$
 $n =$
 $i\text{-aggregate } (i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c}) \text{ k ag n}$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-expand-shrink-last-map-nth-eq-f-Exec-Comp:*

$\llbracket 0 < k; n < \text{length } xs \rrbracket \implies$
 $\text{map } f \text{ (f-Exec-Comp-Stream trans-fun (xs } \odot_f k) \text{ c}) } \div_{\text{fl}} k \text{ ! } n =$
 $f \text{ (f-Exec-Comp trans-fun ((xs } \downarrow \text{Suc } n) \odot_f k) \text{ c})}$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-expand-shrink-last-nth-eq-f-Exec-Comp:*

$\llbracket 0 < k; n < \text{length } xs \rrbracket \implies$
 $f\text{-Exec-Comp-Stream trans-fun (xs } \odot_f k) \text{ c } \div_{\text{fl}} k \text{ ! } n =$
 $f\text{-Exec-Comp trans-fun ((xs } \downarrow \text{Suc } n) \odot_f k) \text{ c}$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-expand-aggregate-map-nth:*

$\llbracket 0 < k; n < \text{length } xs \rrbracket \implies$
 $f\text{-aggregate } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun (xs } \odot_f k) \text{ c)}) \text{ k ag !}$
 $n =$
 $\text{ag } (\text{map } f \text{ (f-Exec-Comp-Stream trans-fun (xs ! } n \# \varepsilon^k - \text{Suc } 0)$
 $\text{ (f-Exec-Comp trans-fun (xs } \downarrow n \odot_f k) \text{ c)}))$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-expand-aggregate-nth:*

$\llbracket 0 < k; n < \text{length } xs \rrbracket \implies$
 $f\text{-aggregate } (f\text{-Exec-Comp-Stream trans-fun (xs } \odot_f k) \text{ c}) \text{ k ag !}$
 $n =$

$ag (f\text{-Exec-Comp-Stream trans-fun } (xs ! n \# \varepsilon^k - Suc\ 0)$
 $(f\text{-Exec-Comp trans-fun } (xs \downarrow n \odot_f k) c))$
 $\langle proof \rangle$

corollary *f-Exec-Stream-expand-shrink-map-nth*:

$\llbracket 0 < k; n < length\ xs \rrbracket \implies$
 $(map\ f\ (f\text{-Exec-Comp-Stream trans-fun } (xs \odot_f k) c)) \div_f k ! n =$
 $last\text{-message } (map\ f\ (f\text{-Exec-Comp-Stream trans-fun } (xs ! n \# \varepsilon^k - Suc\ 0)$
 $(f\text{-Exec-Comp trans-fun } (xs \downarrow n \odot_f k) c)))$
 $\langle proof \rangle$

lemma *i-Exec-Stream-expand-aggregate-map-nth*:

$0 < k \implies$
 $i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } (input \odot_i k) c))\ k\ ag\ n =$
 $ag\ (map\ f\ (f\text{-Exec-Comp-Stream trans-fun } (input\ n \# \varepsilon^k - Suc\ 0)$
 $(f\text{-Exec-Comp trans-fun } ((input \downarrow n) \odot_f k) c)))$
 $\langle proof \rangle$

corollary *i-Exec-Stream-expand-aggregate-nth*:

$0 < k \implies$
 $i\text{-aggregate } (i\text{-Exec-Comp-Stream trans-fun } (input \odot_i k) c)\ k\ ag\ n =$
 $ag\ (f\text{-Exec-Comp-Stream trans-fun } (input\ n \# \varepsilon^k - Suc\ 0)$
 $(f\text{-Exec-Comp trans-fun } ((input \downarrow n) \odot_f k) c))$
 $\langle proof \rangle$

corollary *i-Exec-Stream-expand-shrink-map-nth*:

$0 < k \implies$
 $((f \circ (i\text{-Exec-Comp-Stream trans-fun } (input \odot_i k) c)) \div_i k)\ n =$
 $last\text{-message } (map\ f\ (f\text{-Exec-Comp-Stream trans-fun } (input\ n \# \varepsilon^k - Suc\ 0)$
 $(f\text{-Exec-Comp trans-fun } (input \downarrow n \odot_f k) c)))$
 $\langle proof \rangle$

lemma *f-Exec-Stream-expand-snoc*:

$\llbracket 0 < k; n < length\ xs \rrbracket \implies$
 $f\text{-Exec-Comp-Stream trans-fun } (xs \odot_f k) c \uparrow (n * k) \downarrow k =$
 $f\text{-Exec-Comp-Stream trans-fun } (xs ! n \# \varepsilon^k - Suc\ 0)$
 $(f\text{-Exec-Comp trans-fun } (xs \downarrow n \odot_f k) c)$
 $\langle proof \rangle$

lemma *f-Exec-Stream-expand-map-aggregate-append*:

$f\text{-aggregate } (map\ f\ (f\text{-Exec-Comp-Stream trans-fun } ((xs @ ys) \odot_f k) c))\ k\ ag =$
 $f\text{-aggregate } (map\ f\ (f\text{-Exec-Comp-Stream trans-fun } (xs \odot_f k) c))\ k\ ag @$
 $f\text{-aggregate } (map\ f\ (f\text{-Exec-Comp-Stream trans-fun } (ys \odot_f k) ($
 $f\text{-Exec-Comp trans-fun } (xs \odot_f k) c)))\ k\ ag$
 $\langle proof \rangle$

lemma *i-Exec-Stream-expand-map-aggregate-append*:

$i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } ((xs \frown input) \odot_i k) c))\ k\ ag =$
 $f\text{-aggregate } (map\ f\ (f\text{-Exec-Comp-Stream trans-fun } (xs \odot_f k) c))\ k\ ag \frown$

$i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } (input \odot_i k) (f\text{-Exec-Comp trans-fun } (xs \odot_f k) c))) k ag$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-expand-map-aggregate-Cons}$:

$0 < k \implies$
 $f\text{-aggregate } (map f (f\text{-Exec-Comp-Stream trans-fun } ((x \# xs) \odot_f k) c)) k ag =$
 $ag (map f (f\text{-Exec-Comp-Stream trans-fun } (x \# \varepsilon^k - Suc\ 0) c)) \#$
 $f\text{-aggregate } (map f (f\text{-Exec-Comp-Stream trans-fun } (xs \odot_f k) (f\text{-Exec-Comp trans-fun } (x \# \varepsilon^k - Suc\ 0) c))) k ag$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-expand-map-aggregate-snoc}$:

$0 < k \implies$
 $f\text{-aggregate } (map f (f\text{-Exec-Comp-Stream trans-fun } ((xs @ [x]) \odot_f k) c)) k ag =$
 $f\text{-aggregate } (map f (f\text{-Exec-Comp-Stream trans-fun } (xs \odot_f k) c)) k ag @$
 $[ag (map f (f\text{-Exec-Comp-Stream trans-fun } (x \# \varepsilon^k - Suc\ 0) (f\text{-Exec-Comp trans-fun } (xs \odot_f k) c)))]$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-expand-map-aggregate-Cons}$:

$0 < k \implies$
 $i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } (([x] \frown input) \odot_i k) c)) k ag =$
 $[ag (map f (f\text{-Exec-Comp-Stream trans-fun } (x \# \varepsilon^k - Suc\ 0) c))] \frown$
 $i\text{-aggregate } (f \circ (i\text{-Exec-Comp-Stream trans-fun } (input \odot_i k) (f\text{-Exec-Comp trans-fun } (x \# \varepsilon^k - Suc\ 0) c))) k ag$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-N-eq-f-Exec-Stream-nth}$:

$n \leq \text{length } xs \implies$
 $f\text{-Exec-Comp-N trans-fun } n\ xs\ c = (c \# f\text{-Exec-Comp-Stream trans-fun } xs\ c) ! n$
 $\langle \text{proof} \rangle$

theorem $f\text{-Exec-Stream-causal}$:

$xs \downarrow n = ys \downarrow n \implies$
 $(f\text{-Exec-Comp-Stream trans-fun } xs\ c) \downarrow n = (f\text{-Exec-Comp-Stream trans-fun } ys\ c)$
 $\downarrow n$
 $\langle \text{proof} \rangle$

theorem $i\text{-Exec-Stream-causal}$:

$input1 \Downarrow n = input2 \Downarrow n \implies$
 $(i\text{-Exec-Comp-Stream trans-fun } input1\ c) \Downarrow n = (i\text{-Exec-Comp-Stream trans-fun } input2\ c) \Downarrow n$
 $\langle \text{proof} \rangle$

Results for $f\text{-Exec-Comp-Stream-Init}$

$f\text{-Exec-Comp-Stream-Init}$ computes the execution stream of a component with the initial value of the component at the beginning of the result stream.

lemma $f\text{-Exec-Stream-Init-length}[\text{rule-format}, \text{simp}]$:

$\forall c. \text{length } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c) = \text{Suc } (\text{length } xs)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-not-empty*:
 $(f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \neq [])$
 $\langle \text{proof} \rangle$

lemma *f-Exec-eq-f-Exec-Stream-Init-last*[rule-format]:
 $\forall c. f\text{-Exec-Comp trans-fun } xs \ c = \text{last } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-eq-f-Exec-Stream-Cons*[rule-format]:
 $\forall c. f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c = c \# f\text{-Exec-Comp-Stream trans-fun } xs \ c$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-Init-eq-f-Exec-Stream-Cons-output*:
 $\text{output-fun } c = \varepsilon \implies$
 $\text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c) =$
 $\varepsilon \# \text{map output-fun } (f\text{-Exec-Comp-Stream trans-fun } xs \ c)$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-Init-tl-eq-f-Exec-Stream*:
 $\text{tl } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c) = f\text{-Exec-Comp-Stream trans-fun } xs \ c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-N-eq-last-f-Exec-Stream-Init-take*:
 $f\text{-Exec-Comp-N trans-fun } n \ xs \ c =$
 $\text{last } (f\text{-Exec-Comp-Stream-Init trans-fun } (xs \downarrow n) \ c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-nth*:
 $n \leq \text{length } xs \implies$
 $f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ n = f\text{-Exec-Comp trans-fun } (xs \downarrow n) \ c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-nth-0*: $f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ 0 = c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-hd*: $\text{hd } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c) = c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-nth-Suc-eq-f-Exec-Stream-nth*:
 $f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ (\text{Suc } n) = f\text{-Exec-Comp-Stream trans-fun } xs \ c \ ! \ n$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-append*:

$f\text{-Exec-Comp-Stream-Init trans-fun } (xs @ ys) c =$
 $(f\text{-Exec-Comp-Stream-Init trans-fun } xs c) @$
 $tl (f\text{-Exec-Comp-Stream-Init trans-fun } ys (f\text{-Exec-Comp trans-fun } xs c))$
 $\langle \text{proof} \rangle$

corollary $f\text{-Exec-Stream-Init-append-last}$:

$f\text{-Exec-Comp-Stream-Init trans-fun } (xs @ ys) c =$
 $(f\text{-Exec-Comp-Stream-Init trans-fun } xs c) @$
 $tl (f\text{-Exec-Comp-Stream-Init trans-fun } ys (last (f\text{-Exec-Comp-Stream-Init trans-fun } xs c)))$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Init-f-Exec-Stream-append}$:

$f\text{-Exec-Comp-Stream-Init trans-fun } (xs @ ys) c =$
 $(f\text{-Exec-Comp-Stream-Init trans-fun } xs c) @$
 $(f\text{-Exec-Comp-Stream trans-fun } ys (f\text{-Exec-Comp trans-fun } xs c))$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Init-take}$:

$(f\text{-Exec-Comp-Stream-Init trans-fun } xs c) \downarrow Suc n =$
 $f\text{-Exec-Comp-Stream-Init trans-fun } (xs \downarrow n) c$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Init-drop}$:

$n \leq length xs \implies$
 $(f\text{-Exec-Comp-Stream-Init trans-fun } xs c) \uparrow n =$
 $f\text{-Exec-Comp-Stream-Init trans-fun } (xs \uparrow n)$
 $(f\text{-Exec-Comp trans-fun } (xs \downarrow n) c)$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Init-drop-geq-not-valid}$:

$length xs \leq n \implies$
 $(f\text{-Exec-Comp-Stream-Init trans-fun } xs c) \uparrow Suc n \neq$
 $f\text{-Exec-Comp-Stream-Init trans-fun arbitrary-input arbitrary-comp}$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Init-nth}$:

$i\text{-Exec-Comp-Stream-Init trans-fun input } c n = f\text{-Exec-Comp trans-fun } (input \Downarrow$
 $n) c$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Init-nth-0}$:

$i\text{-Exec-Comp-Stream-Init trans-fun input } c 0 = c$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Init-nth-Suc-eq-i-Exec-Stream-nth}$:

$i\text{-Exec-Comp-Stream-Init trans-fun input } c (Suc n) = i\text{-Exec-Comp-Stream trans-fun}$
 $input c n$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Init-eq-i-Exec-Stream-Cons:*

i-Exec-Comp-Stream-Init trans-fun input c = [c] $\frown$ i-Exec-Comp-Stream trans-fun input c
 $\langle \text{proof} \rangle$

corollary *i-Exec-Stream-Init-eq-i-Exec-Stream-Cons-output:*

output-fun c = $\varepsilon \implies$
output-fun $\circ$ i-Exec-Comp-Stream-Init trans-fun input c =
[ε] $\frown$ (output-fun $\circ$ i-Exec-Comp-Stream trans-fun input c)
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Init-append:*

i-Exec-Comp-Stream-Init trans-fun (input1 $\frown$ input2) c =
(f-Exec-Comp-Stream-Init trans-fun input1 c) $\frown$
((i-Exec-Comp-Stream-Init trans-fun input2 (f-Exec-Comp trans-fun input1 c))
 $\uparrow \text{Suc } 0)$
 $\langle \text{proof} \rangle$

corollary *i-Exec-Stream-Init-append-last:*

i-Exec-Comp-Stream-Init trans-fun (input1 $\frown$ input2) c =
(f-Exec-Comp-Stream-Init trans-fun input1 c) $\frown$
((i-Exec-Comp-Stream-Init trans-fun input2 (last (f-Exec-Comp-Stream-Init
trans-fun input1 c))) $\uparrow \text{Suc } 0)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Init-i-Exec-Stream-append:*

i-Exec-Comp-Stream-Init trans-fun (input1 $\frown$ input2) c =
(f-Exec-Comp-Stream-Init trans-fun input1 c) $\frown$
(i-Exec-Comp-Stream trans-fun input2 (f-Exec-Comp trans-fun input1 c))
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Init-take:*

(i-Exec-Comp-Stream-Init trans-fun input c) $\downarrow \text{Suc } n =$
f-Exec-Comp-Stream-Init trans-fun (input $\downarrow n$) c
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Init-drop:*

(i-Exec-Comp-Stream-Init trans-fun input c) $\uparrow n =$
i-Exec-Comp-Stream-Init trans-fun (input $\uparrow n$)
(f-Exec-Comp trans-fun (input $\downarrow n$) c)
 $\langle \text{proof} \rangle$

theorem *f-Exec-Stream-Init-strictly-causal:*

xs $\downarrow n =$ ys $\downarrow n \implies$
(f-Exec-Comp-Stream-Init trans-fun xs c) $\downarrow \text{Suc } n =$ (f-Exec-Comp-Stream-Init
trans-fun ys c) $\downarrow \text{Suc } n$
 $\langle \text{proof} \rangle$

theorem *i-Exec-Stream-Init-strictly-causal:*

$input1 \Downarrow n = input2 \Downarrow n \implies$
 $(i-Exec-Comp-Stream-Init \text{ trans-fun } input1 \ c) \Downarrow Suc \ n = (i-Exec-Comp-Stream-Init$
 $\text{ trans-fun } input2 \ c) \Downarrow Suc \ n$
 $\langle proof \rangle$

theorem $f-Exec-N-eq-f-Exec-Stream-Init-nth$:

$n \leq \text{length } xs \implies$
 $f-Exec-Comp-N \text{ trans-fun } n \ xs \ c = f-Exec-Comp-Stream-Init \text{ trans-fun } xs \ c \ ! \ n$
 $\langle proof \rangle$

Basic results for previous element functions

The functions *list-Previous* and *ilist-Previous* return the previous element of the list relatively to the specified position n or the initial element if n is 0,

definition $list-Previous :: 'value \ list \Rightarrow 'value \Rightarrow nat \Rightarrow 'value$
where $list-Previous \ xs \ init \ n \equiv$
 $\text{case } n \text{ of}$
 $\quad 0 \Rightarrow init$
 $\quad | \ Suc \ n' \Rightarrow xs \ ! \ n'$

definition $ilist-Previous :: 'value \ ilist \Rightarrow 'value \Rightarrow nat \Rightarrow 'value$
where $ilist-Previous \ f \ init \ n \equiv$
 $\text{case } n \text{ of}$
 $\quad 0 \Rightarrow init$
 $\quad | \ Suc \ n' \Rightarrow f \ n'$

abbreviation $list-Previous' :: 'value \ list \Rightarrow 'value \Rightarrow nat \Rightarrow 'value$
 $(\ \leftarrow' \ - \rightarrow [1000, 10, 100] \ 100)$
where $xs \leftarrow' \ init \ n \equiv list-Previous \ xs \ init \ n$

abbreviation $ilist-Previous' :: 'value \ ilist \Rightarrow 'value \Rightarrow nat \Rightarrow 'value$
 $(\ \leftarrow' \ - \rightarrow [1000, 10, 100] \ 100)$
where $f \leftarrow' \ init \ n \equiv ilist-Previous \ f \ init \ n$

lemma $list-Previous-nth$: $xs \leftarrow' \ init \ n = (\text{case } n \text{ of } 0 \Rightarrow init \mid \ Suc \ n' \Rightarrow xs \ ! \ n')$
 $\langle proof \rangle$

lemma $ilist-Previous-nth$: $f \leftarrow' \ init \ n = (\text{case } n \text{ of } 0 \Rightarrow init \mid \ Suc \ n' \Rightarrow f \ n')$
 $\langle proof \rangle$

lemma $list-Previous-nth-if$: $xs \leftarrow' \ init \ n = (\text{if } n = 0 \text{ then } init \text{ else } xs \ ! \ (n - Suc \ 0))$
 $\langle proof \rangle$

lemma $ilist-Previous-nth-if$: $f \leftarrow' \ init \ n = (\text{if } n = 0 \text{ then } init \text{ else } f \ (n - Suc \ 0))$
 $\langle proof \rangle$

lemma $list-Previous-Cons$: $xs \leftarrow' \ init \ n = (init \ \# \ xs) \ ! \ n$

$\langle \text{proof} \rangle$

lemma *ilist-Previous-Cons*: $f^{\leftarrow} \text{init } n = ([\text{init}] \frown f) n$
 $\langle \text{proof} \rangle$

lemma *list-Previous-0*: $xs^{\leftarrow'} \text{init } 0 = \text{init}$
 $\langle \text{proof} \rangle$

lemma *ilist-Previous-0*: $f^{\leftarrow} \text{init } 0 = \text{init}$
 $\langle \text{proof} \rangle$

lemma *list-Previous-gr0*: $0 < n \implies xs^{\leftarrow'} \text{init } n = xs ! (n - \text{Suc } 0)$
 $\langle \text{proof} \rangle$

lemma *ilist-Previous-gr0*: $0 < n \implies f^{\leftarrow} \text{init } n = f (n - \text{Suc } 0)$
 $\langle \text{proof} \rangle$

lemma *list-Previous-Suc*: $xs^{\leftarrow'} \text{init } (\text{Suc } n) = xs ! n$
 $\langle \text{proof} \rangle$

lemma *ilist-Previous-Suc*: $f^{\leftarrow} \text{init } (\text{Suc } n) = f n$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Previous-f-Exec-Stream-Init*:
 $f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c ! n =$
 $(f\text{-Exec-Comp-Stream trans-fun } xs \ c)^{\leftarrow'} c \ n$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Previous-i-Exec-Stream-Init*:
 $i\text{-Exec-Comp-Stream-Init trans-fun input } c \ n =$
 $(i\text{-Exec-Comp-Stream trans-fun input } c)^{\leftarrow} c \ n$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-hd*:
 $0 < \text{length } xs \implies \text{hd } (f\text{-Exec-Comp-Stream trans-fun } xs \ c) = \text{trans-fun } (\text{hd } xs) \ c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-nth-0*:
 $0 < \text{length } xs \implies (f\text{-Exec-Comp-Stream trans-fun } xs \ c) ! 0 = \text{trans-fun } (xs ! 0) \ c$
 $\langle \text{proof} \rangle$

The calculation of the n-th result stream element from the previous result stream element and the current input stream element.

lemma *f-Exec-Stream-nth-gr0-calc*:
 $\llbracket n < \text{length } xs; 0 < n \rrbracket \implies$
 $f\text{-Exec-Comp-Stream trans-fun } xs \ c ! n =$
 $\text{trans-fun } (xs ! n) (f\text{-Exec-Comp-Stream trans-fun } xs \ c ! (n - 1))$

$\langle \text{proof} \rangle$

lemma *f-Exec-Stream-nth-calc-Previous:*

$$\begin{aligned} n < \text{length } xs &\implies \\ f\text{-Exec-Comp-Stream trans-fun } xs \ c \ ! \ n &= \\ \text{trans-fun } (xs \ ! \ n) \ ((f\text{-Exec-Comp-Stream trans-fun } xs \ c) \stackrel{\leftarrow}{\leftarrow} \ c \ n) & \\ \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Exec-Stream-nth-0:*

$$\begin{aligned} (i\text{-Exec-Comp-Stream trans-fun input } c) \ 0 &= \text{trans-fun } (\text{input } 0) \ c \\ \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Exec-Stream-nth-gr0-calc:*

$$\begin{aligned} 0 < n &\implies \\ (i\text{-Exec-Comp-Stream trans-fun input } c) \ n &= \\ \text{trans-fun } (\text{input } n) \ ((i\text{-Exec-Comp-Stream trans-fun input } c) \ (n - 1)) & \\ \langle \text{proof} \rangle \end{aligned}$$

The component state (and thus its output) at time point n is computed from the previous state (the state at time $n - 1$ for $0 < n$ or the initial state for $n = 0$) and the input at time n .

lemma *i-Exec-Stream-nth-calc-Previous:*

$$\begin{aligned} i\text{-Exec-Comp-Stream trans-fun input } c \ n &= \\ \text{trans-fun } (\text{input } n) \ ((i\text{-Exec-Comp-Stream trans-fun input } c) \stackrel{\leftarrow}{\leftarrow} \ c \ n) & \\ \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-Init-nth-Suc-calc:*

$$\begin{aligned} n < \text{length } xs &\implies \\ f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ \text{Suc } n &= \\ \text{trans-fun } (xs \ ! \ n) \ (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ n) & \\ \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-Init-nth-Plus1-calc:*

$$\begin{aligned} n < \text{length } xs &\implies \\ f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ (n + 1) &= \\ \text{trans-fun } (xs \ ! \ n) \ (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ n) & \\ \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-Init-nth-gr0-calc:*

$$\begin{aligned} \llbracket n \leq \text{length } xs; \ 0 < n \rrbracket &\implies \\ f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ n &= \\ \text{trans-fun } (xs \ ! \ (n - 1)) \ (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \ ! \ (n - 1)) & \\ \langle \text{proof} \rangle \end{aligned}$$

At the beginning, the component state (and thus its output) for the execution stream with initial state is represented by the initial state, contrary to the *i-Exec-Comp-Stream* that does not contain the initial state.

The component state (and thus its output) at time point $n + 1$ for the execution stream with initial state is computed from the previous state (the state at time n) and the previous input (input at time n), contrary to the *i-Exec-Comp-Stream*, where each state at time n represents the resulting state after processing the input at time n .

lemma *i-Exec-Stream-Init-nth-Suc-calc*:

$$\begin{aligned} & i\text{-Exec-Comp-Stream-Init trans-fun input } c \text{ (Suc } n) = \\ & \text{trans-fun (input } n) (i\text{-Exec-Comp-Stream-Init trans-fun input } c \text{ } n) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Exec-Stream-Init-nth-Plus1-calc*:

$$\begin{aligned} & i\text{-Exec-Comp-Stream-Init trans-fun input } c \text{ (} n + 1) = \\ & \text{trans-fun (input } n) (i\text{-Exec-Comp-Stream-Init trans-fun input } c \text{ } n) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Exec-Stream-Init-nth-gr0-calc*:

$$\begin{aligned} & 0 < n \implies \\ & i\text{-Exec-Comp-Stream-Init trans-fun input } c \text{ } n = \\ & \text{trans-fun (input (} n - 1)) (i\text{-Exec-Comp-Stream-Init trans-fun input } c \text{ (} n - 1)) \\ & \langle \text{proof} \rangle \end{aligned}$$

Correlation between Pre/Post-Conditions for *f-Exec-Comp-Stream* and *f-Exec-Comp-Stream-Init*

lemma *f-Exec-Stream-Pre-Post1*:

$$\begin{aligned} & \llbracket n < \text{length } xs; \\ & \quad c\text{-}n = (f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c)^{\leftarrow'} c \text{ } n; x\text{-}n = xs ! n \rrbracket \implies \\ & (P1 \text{ } x\text{-}n \wedge P2 \text{ } c\text{-}n \longrightarrow Q (f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c ! n)) = \\ & (P1 \text{ } x\text{-}n \wedge P2 \text{ } c\text{-}n \longrightarrow Q (\text{trans-fun } x\text{-}n \text{ } c\text{-}n)) \\ & \langle \text{proof} \rangle \end{aligned}$$

Direct relation between input and result after transition

lemma *f-Exec-Stream-Pre-Post2*:

$$\begin{aligned} & \llbracket n < \text{length } xs; \\ & \quad c\text{-}n = (f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c)^{\leftarrow'} c \text{ } n; x\text{-}n = xs ! n \rrbracket \implies \\ & (P \text{ } c\text{-}n \longrightarrow Q (xs ! n) (f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c ! n)) = \\ & (P \text{ } c\text{-}n \longrightarrow Q \text{ } x\text{-}n (\text{trans-fun } x\text{-}n \text{ } c\text{-}n)) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-Pre-Post2-Suc*:

$$\begin{aligned} & \llbracket \text{Suc } n < \text{length } xs; \\ & \quad c\text{-}n = f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c ! n; x\text{-}n1 = xs ! \text{Suc } n \rrbracket \implies \\ & (P \text{ } c\text{-}n \longrightarrow Q (xs ! \text{Suc } n) (f\text{-Exec-Comp-Stream trans-fun } xs \text{ } c ! \text{Suc } n)) = \\ & (P \text{ } c\text{-}n \longrightarrow Q \text{ } x\text{-}n1 (\text{trans-fun } x\text{-}n1 \text{ } c\text{-}n)) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-Init-Pre-Post1*:

$$\begin{aligned} & \llbracket n < \text{length } xs; \\ & \quad c\text{-}n = f\text{-Exec-Comp-Stream-Init trans-fun } xs \text{ } c ! n; x\text{-}n = xs ! n \rrbracket \implies \\ & (P1 \text{ } x\text{-}n \wedge P2 \text{ } c\text{-}n \longrightarrow Q (f\text{-Exec-Comp-Stream-Init trans-fun } xs \text{ } c ! \text{Suc } n)) = \end{aligned}$$

$(P1\ x\text{-}n \wedge P2\ c\text{-}n \longrightarrow Q\ (trans\text{-}fun\ x\text{-}n\ c\text{-}n))$
 $\langle proof \rangle$

Direct relation between input and state before transition

lemma *f-Exec-Stream-Init-Pre-Post2*:

$\llbracket n < length\ xs; \\ c\text{-}n = f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ xs\ c\ !\ n; x\text{-}n = xs\ !\ n \rrbracket \implies \\ (P\ (xs\ !\ n)\ (f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ xs\ c\ !\ n) \longrightarrow \\ Q\ (f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ xs\ c\ !\ Suc\ n)) = \\ (P\ x\text{-}n\ c\text{-}n \longrightarrow Q\ (trans\text{-}fun\ x\text{-}n\ c\text{-}n))$
 $\langle proof \rangle$

lemma *i-Exec-Stream-Pre-Post1*:

$\llbracket c\text{-}n = (i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c)^{\leftarrow c}\ n; x\text{-}n = input\ n \rrbracket \implies \\ (P1\ x\text{-}n \wedge P2\ c\text{-}n \longrightarrow Q\ (i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c\ n)) = \\ (P1\ x\text{-}n \wedge P2\ c\text{-}n \longrightarrow Q\ (trans\text{-}fun\ x\text{-}n\ c\text{-}n))$
 $\langle proof \rangle$

Direct relation between input and result after transition

lemma *i-Exec-Stream-Pre-Post2*:

$\llbracket c\text{-}n = (i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c)^{\leftarrow c}\ n; x\text{-}n = input\ n \rrbracket \implies \\ (P\ c\text{-}n \longrightarrow Q\ (input\ n)\ (i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c\ n)) = \\ (P\ c\text{-}n \longrightarrow Q\ x\text{-}n\ (trans\text{-}fun\ x\text{-}n\ c\text{-}n))$
 $\langle proof \rangle$

lemma *i-Exec-Stream-Pre-Post2-Suc*:

$\llbracket c\text{-}n = i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c\ n; x\text{-}n1 = input\ (Suc\ n) \rrbracket \implies \\ (P\ c\text{-}n \longrightarrow Q\ (input\ (Suc\ n))\ (i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c\ (Suc\ n))) = \\ = \\ (P\ c\text{-}n \longrightarrow Q\ x\text{-}n1\ (trans\text{-}fun\ x\text{-}n1\ c\text{-}n))$
 $\langle proof \rangle$

lemma *i-Exec-Stream-Init-Pre-Post1*:

$\llbracket c\text{-}n = i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ input\ c\ n; x\text{-}n = input\ n \rrbracket \implies \\ (P1\ x\text{-}n \wedge P2\ c\text{-}n \longrightarrow Q\ (i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ input\ c\ (Suc\ n))) = \\ (P1\ x\text{-}n \wedge P2\ c\text{-}n \longrightarrow Q\ (trans\text{-}fun\ x\text{-}n\ c\text{-}n))$
 $\langle proof \rangle$

Direct relation between input and state before transition

lemma *i-Exec-Stream-Init-Pre-Post2*:

$\llbracket c\text{-}n = i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ input\ c\ n; x\text{-}n = input\ n \rrbracket \implies \\ (P\ (input\ n)\ (i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ input\ c\ n) \longrightarrow \\ Q\ (i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Init\ trans\text{-}fun\ input\ c\ (Suc\ n))) = \\ (P\ x\text{-}n\ c\text{-}n \longrightarrow Q\ (trans\text{-}fun\ x\text{-}n\ c\text{-}n))$
 $\langle proof \rangle$

Basic results for stream prefixes

lemma *f-Exec-Stream-prefix*:

$\text{prefix } xs \ ys \implies$
 $\text{prefix } (f\text{-Exec-Comp-Stream trans-fun } xs \ c)$
 $(f\text{-Exec-Comp-Stream trans-fun } ys \ c)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-prefix*:

$xs \sqsubseteq \text{input} \implies$
 $f\text{-Exec-Comp-Stream trans-fun } xs \ c \sqsubseteq$
 $i\text{-Exec-Comp-Stream trans-fun input } c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-N-prefix*:

$\llbracket n \leq \text{length } xs; \text{prefix } xs \ ys \rrbracket \implies$
 $f\text{-Exec-Comp-N trans-fun } n \ xs \ c =$
 $f\text{-Exec-Comp-N trans-fun } n \ ys \ c$
 $\langle \text{proof} \rangle$

theorem *f-Exec-Stream-prefix-causal*[rule-format]:

$n \leq \text{length } (xs \sqcap ys) \implies$
 $f\text{-Exec-Comp-Stream trans-fun } xs \ c \downarrow n =$
 $f\text{-Exec-Comp-Stream trans-fun } ys \ c \downarrow n$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Init-prefix*:

$\text{prefix } xs \ ys \implies$
 $\text{prefix } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c)$
 $(f\text{-Exec-Comp-Stream-Init trans-fun } ys \ c)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Init-prefix*:

$xs \sqsubseteq \text{input} \implies$
 $f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \sqsubseteq$
 $i\text{-Exec-Comp-Stream-Init trans-fun input } c$
 $\langle \text{proof} \rangle$

theorem *f-Exec-Stream-Init-prefix-strictly-causal*[rule-format]:

$n \leq \text{length } (xs \sqcap ys) \implies$
 $f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c \downarrow \text{Suc } n =$
 $f\text{-Exec-Comp-Stream-Init trans-fun } ys \ c \downarrow \text{Suc } n$
 $\langle \text{proof} \rangle$

A predicate indicating whether a component is deterministically dependent on the local state extracted by the the given local state function.

definition *Deterministic-Trans-Fun* ::

$(\text{'comp}, \text{'input}) \text{ Comp-Trans-Fun} \Rightarrow (\text{'comp}, \text{'state}) \text{ Comp-Local-State} \Rightarrow \text{bool}$

where *Deterministic-Trans-Fun trans-fun localState* $\equiv$

$\forall c1 \ c2 \ x. \text{localState } c1 = \text{localState } c2 \longrightarrow \text{trans-fun } x \ c1 = \text{trans-fun } x \ c2$

lemma *Deterministic-f-Exec*:

$\llbracket \text{Deterministic-Trans-Fun trans-fun localState; localState } c1 = \text{localState } c2; xs \neq [] \rrbracket \implies$
 $f\text{-Exec-Comp trans-fun } xs \ c1 = f\text{-Exec-Comp trans-fun } xs \ c2$
 $\langle \text{proof} \rangle$

lemma *Deterministic-f-Exec-Stream:*

$\llbracket \text{Deterministic-Trans-Fun trans-fun localState; localState } c1 = \text{localState } c2 \rrbracket \implies$
 $f\text{-Exec-Comp-Stream trans-fun } xs \ c1 = f\text{-Exec-Comp-Stream trans-fun } xs \ c2$
 $\langle \text{proof} \rangle$

lemma *Deterministic-i-Exec-Stream:*

$\llbracket \text{Deterministic-Trans-Fun trans-fun localState; localState } c1 = \text{localState } c2 \rrbracket \implies$
 $i\text{-Exec-Comp-Stream trans-fun input } c1 = i\text{-Exec-Comp-Stream trans-fun input } c2$
 $\langle \text{proof} \rangle$

3.1.3 Connected streams

A predicate indicating for two message streams, that the ports, they correspond to, are connected. The predicate implies strict causality.

definition *f-Streams-Connected* :: 'a fstream-af $\Rightarrow$ 'a fstream-af $\Rightarrow$ bool
where *f-Streams-Connected* outS inS $\equiv$ inS = $\varepsilon \#$ outS

definition *i-Streams-Connected* :: 'a istream-af $\Rightarrow$ 'a istream-af $\Rightarrow$ bool
where *i-Streams-Connected* outS inS $\equiv$ inS = $[\varepsilon] \frown$ outS

lemmas *Streams-Connected-defs* =

f-Streams-Connected-def
i-Streams-Connected-def

lemma *f-Streams-Connected-imp-not-empty*: *f-Streams-Connected* outS inS $\implies$ inS $\neq []$
 $\langle \text{proof} \rangle$

lemma *f-Streams-Connected-nth-conv*:

f-Streams-Connected outS inS =
 $(\text{length inS} = \text{Suc } (\text{length outS})) \wedge$
 $(\forall i < \text{length inS}. \text{inS} ! i = (\text{case } i \text{ of } 0 \Rightarrow \varepsilon \mid \text{Suc } k \Rightarrow \text{outS} ! k)))$
 $\langle \text{proof} \rangle$

lemma *f-Streams-Connected-nth-conv-if*:

f-Streams-Connected outS inS =
 $(\text{length inS} = \text{Suc } (\text{length outS})) \wedge$
 $(\forall i < \text{length inS}. \text{inS} ! i = (\text{if } i = 0 \text{ then } \varepsilon \text{ else } \text{outS} ! (i - \text{Suc } 0)))$
 $\langle \text{proof} \rangle$

lemma *i-Streams-Connected-nth-conv*:

i-Streams-Connected outS inS =
 $(\forall i. \text{inS } i = (\text{case } i \text{ of } 0 \Rightarrow \varepsilon \mid \text{Suc } k \Rightarrow \text{outS } k))$
 <proof>

lemma *i-Streams-Connected-nth-conv-if:*
i-Streams-Connected outS inS =
 $(\forall i. \text{inS } i = (\text{if } i = 0 \text{ then } \varepsilon \text{ else } \text{outS } (i - \text{Suc } 0)))$
 <proof>

lemma *f-Exec-Stream-Init-eq-output-channel:*
 $\llbracket \text{output-fun } c = \varepsilon;$
f-Streams-Connected
 $(\text{map output-fun } (f\text{-Exec-Comp-Stream trans-fun } xs \ c))$
 $\text{channel} \rrbracket \implies$
 $\text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c) = \text{channel}$
 <proof>

lemma *i-Exec-Stream-Init-eq-output-channel:*
 $\llbracket \text{output-fun } c = \varepsilon;$
i-Streams-Connected
 $(\text{output-fun} \circ (i\text{-Exec-Comp-Stream trans-fun input } c))$
 $\text{channel} \rrbracket \implies$
 $\text{output-fun} \circ (i\text{-Exec-Comp-Stream-Init trans-fun input } c) = \text{channel}$
 <proof>

lemma *f-Exec-Stream-output-causal:*
 $\llbracket xs \downarrow n = ys \downarrow n;$
 $\text{output1} = \text{map output-fun } (f\text{-Exec-Comp-Stream trans-fun } xs \ c);$
 $\text{output2} = \text{map output-fun } (f\text{-Exec-Comp-Stream trans-fun } ys \ c) \rrbracket \implies$
 $\text{output1} \downarrow n = \text{output2} \downarrow n$
 <proof>

lemma *f-Exec-Stream-Init-output-strictly-causal:*
 $\llbracket xs \downarrow n = ys \downarrow n;$
 $\text{output1} = \text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c);$
 $\text{output2} = \text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } ys \ c) \rrbracket \implies$
 $\text{output1} \downarrow \text{Suc } n = \text{output2} \downarrow \text{Suc } n$
 <proof>

lemma *i-Exec-Stream-output-causal:*
 $\llbracket \text{input1} \Downarrow n = \text{input2} \Downarrow n;$
 $\text{output1} = \text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun input1 } c;$
 $\text{output2} = \text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun input2 } c \rrbracket \implies$
 $\text{output1} \Downarrow n = \text{output2} \Downarrow n$
 <proof>

lemma *i-Exec-Stream-Init-output-strictly-causal:*

$$\begin{aligned} & \llbracket \text{input1} \Downarrow n = \text{input2} \Downarrow n; \\ & \quad \text{output1} = \text{output-fun} \circ i\text{-Exec-Comp-Stream-Init trans-fun input1 } c; \\ & \quad \text{output2} = \text{output-fun} \circ i\text{-Exec-Comp-Stream-Init trans-fun input2 } c \rrbracket \implies \\ & \text{output1} \Downarrow \text{Suc } n = \text{output2} \Downarrow \text{Suc } n \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-Connected-strictly-causal*:

$$\begin{aligned} & \llbracket \text{xs} \Downarrow n = \text{ys} \Downarrow n; \\ & \quad f\text{-Streams-Connected} \\ & \quad (\text{map output-fun } (f\text{-Exec-Comp-Stream trans-fun xs } c)) \\ & \quad \text{channel1}; \\ & \quad f\text{-Streams-Connected} \\ & \quad (\text{map output-fun } (f\text{-Exec-Comp-Stream trans-fun ys } c)) \\ & \quad \text{channel2} \rrbracket \implies \\ & \text{channel1} \Downarrow \text{Suc } n = \text{channel2} \Downarrow \text{Suc } n \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Exec-Stream-Connected-strictly-causal*:

$$\begin{aligned} & \llbracket \text{input1} \Downarrow n = \text{input2} \Downarrow n; \\ & \quad i\text{-Streams-Connected} \\ & \quad (\text{portOutput} \circ (i\text{-Exec-Comp-Stream trans-fun input1 } c)) \\ & \quad \text{channel1}; \\ & \quad i\text{-Streams-Connected} \\ & \quad (\text{portOutput} \circ (i\text{-Exec-Comp-Stream trans-fun input2 } c)) \\ & \quad \text{channel2} \rrbracket \implies \\ & \text{channel1} \Downarrow \text{Suc } n = \text{channel2} \Downarrow \text{Suc } n \\ & \langle \text{proof} \rangle \end{aligned}$$

A predicate for the semantics with initial state in result stream indicating for two message streams that the ports, they correspond to, are connected.

definition *f-Streams-Connected-Init* :: 'a fstream-af $\Rightarrow$ 'a fstream-af $\Rightarrow$ bool
where *f-Streams-Connected-Init* outS inS $\equiv$ inS = outS

definition *i-Streams-Connected-Init* :: 'a istream-af $\Rightarrow$ 'a istream-af $\Rightarrow$ bool
where *i-Streams-Connected-Init* outS inS $\equiv$ inS = outS

lemmas *Streams-Connected-Init-defs* =

f-Streams-Connected-Init-def
i-Streams-Connected-Init-def

lemma *f-Streams-Connected-Init-nth-conv*:

$$\begin{aligned} & f\text{-Streams-Connected-Init outS inS} = \\ & (\text{length inS} = \text{length outS} \wedge (\forall i < \text{length inS}. \text{inS } ! i = \text{outS } ! i)) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *i-Streams-Connected-Init-nth-conv*:

$$\begin{aligned} & i\text{-Streams-Connected-Init outS inS} = \\ & (\forall i. \text{inS } i = \text{outS } i) \\ & \langle \text{proof} \rangle \end{aligned}$$

lemma *f-Exec-Stream-Init-eq-output-channel2*:

$\llbracket \text{output-fun } c = \varepsilon;$
 $\text{f-Streams-Connected-Init}$
 $(\text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c))$
 $\text{channel} \rrbracket \implies$
 $\text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c) = \text{channel}$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Init-eq-output-channel2*:

$\llbracket \text{output-fun } c = \varepsilon;$
 $\text{i-Streams-Connected-Init}$
 $(\text{output-fun} \circ (\text{i-Exec-Comp-Stream-Init trans-fun input } c))$
 $\text{channel} \rrbracket \implies$
 $\text{output-fun} \circ (\text{i-Exec-Comp-Stream-Init trans-fun input } c) = \text{channel}$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Connected-Init-strictly-causal*:

$\llbracket xs \downarrow n = ys \downarrow n;$
 $\text{f-Streams-Connected-Init}$
 $(\text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } xs \ c))$
 $\text{channel1};$
 $\text{f-Streams-Connected-Init}$
 $(\text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } ys \ c))$
 $\text{channel2} \rrbracket \implies$
 $\text{channel1} \downarrow \text{Suc } n = \text{channel2} \downarrow \text{Suc } n$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Connected-Init-strictly-causal*:

$\llbracket \text{input1} \Downarrow n = \text{input2} \Downarrow n;$
 $\text{i-Streams-Connected-Init}$
 $(\text{portOutput} \circ (\text{i-Exec-Comp-Stream-Init trans-fun input1 } c))$
 $\text{channel1};$
 $\text{i-Streams-Connected-Init}$
 $(\text{portOutput} \circ (\text{i-Exec-Comp-Stream-Init trans-fun input2 } c))$
 $\text{channel2} \rrbracket \implies$
 $\text{channel1} \Downarrow \text{Suc } n = \text{channel2} \Downarrow \text{Suc } n$
 $\langle \text{proof} \rangle$

3.1.4 Additional auxiliary results

The following lemma shows that, if the system state is different at some time points with respect to a certain predicate P , then there exists a defined time point between these two, where the state change has taken place

lemma *f-State-Change-exists-set*:

$\llbracket n1 \leq n2; n1 \in I; n2 \in I;$
 $\neg P (f\text{-Exec-Comp trans-fun } (\text{input} \downarrow n1) \ c);$
 $P (f\text{-Exec-Comp trans-fun } (\text{input} \downarrow n2) \ c) \rrbracket \implies$
 $\exists n \in I. n1 \leq n \wedge n < n2 \wedge$

$\neg P (f\text{-Exec-Comp trans-fun (input } \downarrow n) c) \wedge$
 $P (f\text{-Exec-Comp trans-fun (input } \downarrow (\text{inext } n I)) c)$
 $\langle \text{proof} \rangle$

lemma *f-State-Change-exists:*

$\llbracket n1 \leq n2;$
 $\neg P (f\text{-Exec-Comp trans-fun (input } \downarrow n1) c);$
 $P (f\text{-Exec-Comp trans-fun (input } \downarrow n2) c) \rrbracket \implies$
 $\exists n \geq n1. n < n2 \wedge$
 $\neg P (f\text{-Exec-Comp trans-fun (input } \downarrow n) c) \wedge$
 $P (f\text{-Exec-Comp trans-fun (input } \downarrow (\text{Suc } n)) c)$
 $\langle \text{proof} \rangle$

lemma *i-State-Change-exists-set:*

$\llbracket n1 \leq n2; n1 \in I; n2 \in I;$
 $\neg P (i\text{-Exec-Comp-Stream trans-fun input } c n1);$
 $P (i\text{-Exec-Comp-Stream trans-fun input } c n2) \rrbracket \implies$
 $\exists n \in I. n1 \leq n \wedge n < n2 \wedge$
 $\neg P (i\text{-Exec-Comp-Stream trans-fun input } c n) \wedge$
 $P (i\text{-Exec-Comp-Stream trans-fun input } c (\text{inext } n I))$
 $\langle \text{proof} \rangle$

lemma *i-State-Change-exists:*

$\llbracket n1 \leq n2;$
 $\neg P (i\text{-Exec-Comp-Stream trans-fun input } c n1);$
 $P (i\text{-Exec-Comp-Stream trans-fun input } c n2) \rrbracket \implies$
 $\exists n \geq n1. n < n2 \wedge$
 $\neg P (i\text{-Exec-Comp-Stream trans-fun input } c n) \wedge$
 $P (i\text{-Exec-Comp-Stream trans-fun input } c (\text{Suc } n))$
 $\langle \text{proof} \rangle$

lemma *i-State-Change-Init-exists-set:*

$\llbracket n1 \leq n2; n1 \in I; n2 \in I;$
 $\neg P (i\text{-Exec-Comp-Stream-Init trans-fun input } c n1);$
 $P (i\text{-Exec-Comp-Stream-Init trans-fun input } c n2) \rrbracket \implies$
 $\exists n \in I. n1 \leq n \wedge n < n2 \wedge$
 $\neg P (i\text{-Exec-Comp-Stream-Init trans-fun input } c n) \wedge$
 $P (i\text{-Exec-Comp-Stream-Init trans-fun input } c (\text{inext } n I))$
 $\langle \text{proof} \rangle$

lemma *i-State-Change-Init-exists:*

$\llbracket n1 \leq n2;$
 $\neg P (i\text{-Exec-Comp-Stream-Init trans-fun input } c n1);$
 $P (i\text{-Exec-Comp-Stream-Init trans-fun input } c n2) \rrbracket \implies$
 $\exists n \geq n1. n < n2 \wedge$
 $\neg P (i\text{-Exec-Comp-Stream-Init trans-fun input } c n) \wedge$
 $P (i\text{-Exec-Comp-Stream-Init trans-fun input } c (\text{Suc } n))$
 $\langle \text{proof} \rangle$

3.2 Components with accelerated execution

This section deals with variable execution speed components. A component accelerated by a (clocking) factor k processes streams expanded by factor k and its output streams are compressed by factor k .

3.2.1 Equivalence relation for executions

A predicate indicating for two components together with transition functions and a given equivalence predicate for their local states, that the components exhibit equivalent observable behaviour after expanding input streams and shrinking output streams by a constant factor, given that their local states are equivalent with respect to the specified equivalence relations.

definition

Equiv-Exec ::

$'input \Rightarrow$
 $('state1 \Rightarrow 'state2 \Rightarrow bool) \Rightarrow$ — Equivalence predicate for local states
 $('comp1, 'state1) \text{ Comp-Local-State} \Rightarrow$
 $('comp2, 'state2) \text{ Comp-Local-State} \Rightarrow$
 $('input, 'input1) \text{ Port-Input-Value} \Rightarrow$ — Input adaptor for first component
 $('input, 'input2) \text{ Port-Input-Value} \Rightarrow$ — Input adaptor for second component
 $('comp1, 'output) \text{ Port-Output-Value} \Rightarrow$
 $('comp2, 'output) \text{ Port-Output-Value} \Rightarrow$
 $('comp1, 'input1 \text{ message-af}) \text{ Comp-Trans-Fun} \Rightarrow$
 $('comp2, 'input2 \text{ message-af}) \text{ Comp-Trans-Fun} \Rightarrow$
 $nat \Rightarrow nat \Rightarrow 'comp1 \Rightarrow 'comp2 \Rightarrow bool$

where

Equiv-Exec

$m \text{ equiv-states}$

$localState1 \ localState2 \ input\text{-}fun1 \ input\text{-}fun2 \ output\text{-}fun1 \ output\text{-}fun2$
 $trans\text{-}fun1 \ trans\text{-}fun2 \ k1 \ k2 \ c1 \ c2 \equiv$
 $equiv\text{-}states \ (localState1 \ c1) \ (localState2 \ c2) \longrightarrow$ (
 $last\text{-}message \ (map \ output\text{-}fun1 \ ($
 $f\text{-}Exec\text{-}Comp\text{-}Stream \ trans\text{-}fun1 \ (input\text{-}fun1 \ m \ \# \ \varepsilon^{k1} - Suc \ 0) \ c1)) =$
 $last\text{-}message \ (map \ output\text{-}fun2 \ ($
 $f\text{-}Exec\text{-}Comp\text{-}Stream \ trans\text{-}fun2 \ (input\text{-}fun2 \ m \ \# \ \varepsilon^{k2} - Suc \ 0) \ c2)) \wedge$
 $equiv\text{-}states$
 $(localState1 \ (f\text{-}Exec\text{-}Comp \ trans\text{-}fun1 \ (input\text{-}fun1 \ m \ \# \ \varepsilon^{k1} - Suc \ 0) \ c1))$
 $(localState2 \ (f\text{-}Exec\text{-}Comp \ trans\text{-}fun2 \ (input\text{-}fun2 \ m \ \# \ \varepsilon^{k2} - Suc \ 0) \ c2)))$

Predicate indicating for two components together with transition functions and a given equivalence predicate for their local states, that the equivalence predicate is stable with respect to component execution, i.e., it determines the equivalence of components' local states both for the initial states and after the components have processed an arbitrary input. The restricting version *Equiv-Exec-stable-set* guarantees stability only for inputs from a given restriction set, the not-restricting version guarantees stability for all inputs.

definition

Equiv-Exec-stable-set ::

'input set $\Rightarrow$
 ('state1 $\Rightarrow$ 'state2 $\Rightarrow$ bool) $\Rightarrow$ — Equivalence predicate for local states
 ('comp1, 'state1) *Comp-Local-State* $\Rightarrow$
 ('comp2, 'state2) *Comp-Local-State* $\Rightarrow$
 ('input, 'input1) *Port-Input-Value* $\Rightarrow$ — Input adaptor for first component
 ('input, 'input2) *Port-Input-Value* $\Rightarrow$ — Input adaptor for second component
 ('comp1, 'output) *Port-Output-Value* $\Rightarrow$
 ('comp2, 'output) *Port-Output-Value* $\Rightarrow$
 ('comp1, 'input1 message-af) *Comp-Trans-Fun* $\Rightarrow$
 ('comp2, 'input2 message-af) *Comp-Trans-Fun* $\Rightarrow$
 nat $\Rightarrow$ nat $\Rightarrow$ 'comp1 $\Rightarrow$ 'comp2 $\Rightarrow$ bool

where

Equiv-Exec-stable-set A

equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
 trans-fun1 trans-fun2 k1 k2 c1 c2 $\equiv$
 $\forall$ input m. set input $\subseteq$ A $\wedge$ m $\in$ A $\longrightarrow$
Equiv-Exec m
 equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 out-
 put-fun2
 trans-fun1 trans-fun2 k1 k2
 (f-Exec-Comp trans-fun1 (map input-fun1 input $\odot_f$ k1) c1)
 (f-Exec-Comp trans-fun2 (map input-fun2 input $\odot_f$ k2) c2)

definition

Equiv-Exec-stable ::

('state1 $\Rightarrow$ 'state2 $\Rightarrow$ bool) $\Rightarrow$ — Equivalence predicate for local states
 ('comp1, 'state1) *Comp-Local-State* $\Rightarrow$
 ('comp2, 'state2) *Comp-Local-State* $\Rightarrow$
 ('input, 'input1) *Port-Input-Value* $\Rightarrow$ — Input adaptor for first component
 ('input, 'input2) *Port-Input-Value* $\Rightarrow$ — Input adaptor for second component
 ('comp1, 'output) *Port-Output-Value* $\Rightarrow$
 ('comp2, 'output) *Port-Output-Value* $\Rightarrow$
 ('comp1, 'input1 message-af) *Comp-Trans-Fun* $\Rightarrow$
 ('comp2, 'input2 message-af) *Comp-Trans-Fun* $\Rightarrow$
 nat $\Rightarrow$ nat $\Rightarrow$ 'comp1 $\Rightarrow$ 'comp2 $\Rightarrow$ bool

where

Equiv-Exec-stable

equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
 trans-fun1 trans-fun2 k1 k2 c1 c2 $\equiv$
 $\forall$ input m.
Equiv-Exec m
 equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 out-
 put-fun2
 trans-fun1 trans-fun2 k1 k2
 (f-Exec-Comp trans-fun1 (map input-fun1 input $\odot_f$ k1) c1)
 (f-Exec-Comp trans-fun2 (map input-fun2 input $\odot_f$ k2) c2)

lemma *Equiv-Exec-equiv-statesI*:

$\llbracket \text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
Equiv-Exec
 $m \text{ equiv-states}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 } k1 \ k2 \ c1 \ c2 \rrbracket \implies$
equiv-states
 $(\text{localState1 } (f\text{-Exec-Comp trans-fun1 } (\text{input-fun1 } m \ \# \ \varepsilon^{k1} - \text{Suc } 0) \ c1))$
 $(\text{localState2 } (f\text{-Exec-Comp trans-fun2 } (\text{input-fun2 } m \ \# \ \varepsilon^{k2} - \text{Suc } 0) \ c2))$
 <proof>

lemma *Equiv-Exec-output-eqI*:

$\llbracket \text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
Equiv-Exec
 $m \text{ equiv-states}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 } k1 \ k2 \ c1 \ c2 \rrbracket \implies$
 $\text{last-message } (\text{map output-fun1 } ($
 $\text{f-Exec-Comp-Stream trans-fun1 } (\text{input-fun1 } m \ \# \ \varepsilon^{k1} - \text{Suc } 0) \ c1)) =$
 $\text{last-message } (\text{map output-fun2 } ($
 $\text{f-Exec-Comp-Stream trans-fun2 } (\text{input-fun2 } m \ \# \ \varepsilon^{k2} - \text{Suc } 0) \ c2))$
 <proof>

lemma *Equiv-Exec-equiv-statesI'*:

$\llbracket \text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
Equiv-Exec
 $m \text{ equiv-states}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 } k1 \ k2 \ c1 \ c2 \rrbracket \implies$
equiv-states
 $(\text{localState1 } (f\text{-Exec-Comp trans-fun1 } \text{NoMsg}^{k1} - \text{Suc } 0 \ (\text{trans-fun1 } (\text{input-fun1 } m) \ c1)))$
 $(\text{localState2 } (f\text{-Exec-Comp trans-fun2 } \text{NoMsg}^{k2} - \text{Suc } 0 \ (\text{trans-fun2 } (\text{input-fun2 } m) \ c2)))$
 <proof>

lemma *Equiv-Exec-le1*:

$\llbracket k1 \leq \text{Suc } 0; k2 \leq \text{Suc } 0;$
equiv-states $(\text{localState1 } c1) (\text{localState2 } c2);$
Equiv-Exec m
 $\text{equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 out-}$
 put-fun2
 $\text{trans-fun1 trans-fun2 } k1 \ k2 \ c1 \ c2 \rrbracket \implies$
 $\text{output-fun1 } (\text{trans-fun1 } (\text{input-fun1 } m) \ c1) =$
 $\text{output-fun2 } (\text{trans-fun2 } (\text{input-fun2 } m) \ c2) \wedge$
equiv-states
 $(\text{localState1 } (\text{trans-fun1 } (\text{input-fun1 } m) \ c1))$
 $(\text{localState2 } (\text{trans-fun2 } (\text{input-fun2 } m) \ c2))$
 <proof>

lemma *Equiv-Exec-stable-set-UNIV*:

Equiv-Exec-stable-set
UNIV equiv-states
localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
trans-fun1 trans-fun2 k1 k2 c1 c2 =
Equiv-Exec-stable
equiv-states
localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
trans-fun1 trans-fun2 k1 k2 c1 c2
 ⟨proof⟩

lemma *Equiv-Exec-stable-setI*:

[[*Equiv-Exec-stable-set A*
equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
trans-fun1 trans-fun2 k1 k2 c1 c2;
set input $\subseteq$ *A*; *m* $\in$ *A*]] $\implies$
Equiv-Exec
m equiv-states
localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
trans-fun1 trans-fun2 k1 k2
(f-Exec-Comp trans-fun1 (map input-fun1 input $\odot_f$ k1) c1)
(f-Exec-Comp trans-fun2 (map input-fun2 input $\odot_f$ k2) c2)
 ⟨proof⟩

lemma *Equiv-Exec-stableI*:

Equiv-Exec-stable
equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
trans-fun1 trans-fun2 k1 k2 c1 c2 $\implies$
Equiv-Exec m
equiv-states localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2
trans-fun1 trans-fun2 k1 k2
(f-Exec-Comp trans-fun1 (map input-fun1 input $\odot_f$ k1) c1)
(f-Exec-Comp trans-fun2 (map input-fun2 input $\odot_f$ k2) c2)
 ⟨proof⟩

Reflexivity, symmetry and transitivity results for *Equiv-Exec*

lemma *Equiv-Exec-refl*:

[[$\bigwedge c.$ *equiv-states (localState c) (localState c)*]] $\implies$
Equiv-Exec
m equiv-states
localState localState input-fun input-fun output-fun output-fun
trans-fun trans-fun k k c c
 ⟨proof⟩

lemma *Equiv-Exec-sym[rule-format]*:

[[$\forall c1\ c2.$
equiv-states (localState1 c1) (localState2 c2) =

$\text{equiv-states } (\text{localState2 } c2) (\text{localState1 } c1) \parallel \implies$
Equiv-Exec
 $m \text{ equiv-states}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 k1 k2 c1 c2} =$
Equiv-Exec
 $m \text{ equiv-states}$
 $\text{localState2 localState1 input-fun2 input-fun1 output-fun2 output-fun1}$
 $\text{trans-fun2 trans-fun1 k2 k1 c2 c1}$
 $\langle \text{proof} \rangle$

lemma *Equiv-Exec-sym2*:

$\parallel \text{equiv-states-sym} = (\lambda s1 \ s2. \text{equiv-states } s2 \ s1) \parallel \implies$
Equiv-Exec
 $m \text{ equiv-states}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 k1 k2 c1 c2} =$
Equiv-Exec
 $m \text{ equiv-states-sym}$
 $\text{localState2 localState1 input-fun2 input-fun1 output-fun2 output-fun1}$
 $\text{trans-fun2 trans-fun1 k2 k1 c2 c1}$
 $\langle \text{proof} \rangle$

lemma *Equiv-Exec-sym2-ex*:

$\exists \text{equiv-states-sym.}$
Equiv-Exec
 $m \text{ equiv-states}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 k1 k2 c1 c2} =$
Equiv-Exec
 $m \text{ equiv-states-sym}$
 $\text{localState2 localState1 input-fun2 input-fun1 output-fun2 output-fun1}$
 $\text{trans-fun2 trans-fun1 k2 k1 c2 c1}$
 $\langle \text{proof} \rangle$

lemma *Equiv-Exec-trans*:

$\parallel \text{Equiv-Exec}$
 $m \text{ equiv-states12}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 k1 k2 c1 c2};$
Equiv-Exec
 $m \text{ equiv-states23}$
 $\text{localState2 localState3 input-fun2 input-fun3 output-fun2 output-fun3}$
 $\text{trans-fun2 trans-fun3 k2 k3 c2 c3};$
 $\text{equiv-states13} = (\lambda s1 \ s3. ($
 $\text{if } s1 = \text{localState1 } c1 \wedge s3 = \text{localState3 } c3 \text{ then}$
 $\text{equiv-states12 } s1 (\text{localState2 } c2) \wedge$
 $\text{equiv-states23 } (\text{localState2 } c2) \ s3$
 else

$$\begin{aligned}
& \text{equiv-states12 } s1 \ (\\
& \quad \text{localState2 } (f\text{-Exec-Comp trans-fun2 } (\text{input-fun2 } m \# \varepsilon^{k2} - \text{Suc } 0) \ c2))) \\
& \wedge \\
& \quad \text{equiv-states23 } (\\
& \quad \quad \text{localState2 } (f\text{-Exec-Comp trans-fun2 } (\text{input-fun2 } m \# \varepsilon^{k2} - \text{Suc } 0) \ c2)) \\
& s3) \] \implies \\
& \text{Equiv-Exec} \\
& \quad m \text{ equiv-states13} \\
& \quad \text{localState1 localState3 input-fun1 input-fun3 output-fun1 output-fun3} \\
& \quad \text{trans-fun1 trans-fun3 k1 k3 c1 c3} \\
& \langle \text{proof} \rangle
\end{aligned}$$

lemma *Equiv-Exec-trans-ex:*

$$\begin{aligned}
& \llbracket \text{Equiv-Exec} \\
& \quad m \text{ equiv-states12} \\
& \quad \text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2} \\
& \quad \text{trans-fun1 trans-fun2 k1 k2 c1 c2}; \\
& \text{Equiv-Exec} \\
& \quad m \text{ equiv-states23} \\
& \quad \text{localState2 localState3 input-fun2 input-fun3 output-fun2 output-fun3} \\
& \quad \text{trans-fun2 trans-fun3 k2 k3 c2 c3} \rrbracket \implies \\
& \exists \text{equiv-states13. } \text{Equiv-Exec} \\
& \quad m \text{ equiv-states13} \\
& \quad \text{localState1 localState3 input-fun1 input-fun3 output-fun1 output-fun3} \\
& \quad \text{trans-fun1 trans-fun3 k1 k3 c1 c3} \\
& \langle \text{proof} \rangle
\end{aligned}$$

A predicate indicating for a given local state extraction function and a given transition function, that components, whose states are equal with regard to the local state extraction function, are transformed into equal components, when the transition function is applied with the same input.

definition *Exec-Equal-State* ::

$$('comp, 'state) \text{ Comp-Local-State} \Rightarrow ('comp, 'input \text{ message-af}) \text{ Comp-Trans-Fun} \Rightarrow \text{bool}$$

where *Exec-Equal-State* *localState* *trans-fun* $\equiv$

$$\forall c1 \ c2 \ m. \text{localState } c1 = \text{localState } c2 \longrightarrow \text{trans-fun } m \ c1 = \text{trans-fun } m \ c2$$

lemma *Exec-Equal-StateD:*

$$\begin{aligned}
& \llbracket \text{Exec-Equal-State } \text{localState } \text{trans-fun}; \\
& \quad \text{localState } c1 = \text{localState } c2 \rrbracket \implies \\
& \quad \text{trans-fun } m \ c1 = \text{trans-fun } m \ c2 \\
& \langle \text{proof} \rangle
\end{aligned}$$

lemma *Exec-Equal-StateD':*

$$\begin{aligned}
& \text{Exec-Equal-State } \text{localState } \text{trans-fun} \implies \\
& \quad \forall c1 \ c2 \ m. \text{localState } c1 = \text{localState } c2 \longrightarrow \text{trans-fun } m \ c1 = \text{trans-fun } m \ c2 \\
& \langle \text{proof} \rangle
\end{aligned}$$

lemma *Exec-Equal-StateI:*

$(\bigwedge c1\ c2\ m.\ localState\ c1 = localState\ c2 \implies trans\text{-}fun\ m\ c1 = trans\text{-}fun\ m\ c2)$
 $\implies Exec\text{-}Equal\text{-}State\ localState\ trans\text{-}fun$
 $\langle proof \rangle$

lemma *f-Exec-Equal-State*: $\bigwedge c1\ c2.$
 $\llbracket Exec\text{-}Equal\text{-}State\ localState\ trans\text{-}fun;$
 $localState\ c1 = localState\ c2; xs \neq [] \rrbracket \implies$
 $f\text{-}Exec\text{-}Comp\ trans\text{-}fun\ xs\ c1 = f\text{-}Exec\text{-}Comp\ trans\text{-}fun\ xs\ c2$
 $\langle proof \rangle$

lemma *f-Exec-Stream-Equal-State*:
 $\llbracket Exec\text{-}Equal\text{-}State\ localState\ trans\text{-}fun;$
 $localState\ c1 = localState\ c2 \rrbracket \implies$
 $f\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ xs\ c1 =$
 $f\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ xs\ c2$
 $\langle proof \rangle$

lemma *i-Exec-Stream-Equal-State*:
 $\llbracket Exec\text{-}Equal\text{-}State\ localState\ trans\text{-}fun;$
 $localState\ c1 = localState\ c2 \rrbracket \implies$
 $i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c1 =$
 $i\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun\ input\ c2$
 $\langle proof \rangle$

3.2.2 Idle states

definition *State-Idle* ::
 $(\text{'comp}, \text{'state})\ Comp\text{-}Local\text{-}State \Rightarrow (\text{'comp} \Rightarrow \text{'output message-af}) \Rightarrow$
 $(\text{'comp}, \text{'input message-af})\ Comp\text{-}Trans\text{-}Fun \Rightarrow \text{'state} \Rightarrow bool$
where *State-Idle* $localState\ output\text{-}fun\ trans\text{-}fun\ state \equiv$
 $\forall c.\ localState\ c = state \longrightarrow$
 $localState\ (trans\text{-}fun\ \varepsilon\ c) = state \wedge$
 $output\text{-}fun\ (trans\text{-}fun\ \varepsilon\ c) = \varepsilon$

lemma *State-IdleD*:
 $\llbracket State\text{-}Idle\ localState\ output\text{-}fun\ trans\text{-}fun\ state;$
 $localState\ c = state \rrbracket \implies$
 $localState\ (trans\text{-}fun\ \varepsilon\ c) = state \wedge$
 $output\text{-}fun\ (trans\text{-}fun\ \varepsilon\ c) = \varepsilon$
 $\langle proof \rangle$

lemma *State-IdleD'*:
 $State\text{-}Idle\ localState\ output\text{-}fun\ trans\text{-}fun\ state \implies$
 $\forall c.\ localState\ c = state \longrightarrow$
 $localState\ (trans\text{-}fun\ \varepsilon\ c) = state \wedge$
 $output\text{-}fun\ (trans\text{-}fun\ \varepsilon\ c) = \varepsilon$
 $\langle proof \rangle$

lemma *State-IdleI*:

$$\llbracket \bigwedge c. \text{localState } c = \text{state} \implies$$

$$\text{localState } (\text{trans-fun } \varepsilon \ c) = \text{state} \wedge$$

$$\text{output-fun } (\text{trans-fun } \varepsilon \ c) = \varepsilon \rrbracket \implies$$

$$\text{State-Idle localState output-fun trans-fun state}$$

$$\langle \text{proof} \rangle$$

lemma *State-Idle-step*[rule-format]:

$$\llbracket \text{State-Idle localState output-fun trans-fun } (\text{localState } c) \rrbracket \implies$$

$$\text{State-Idle localState output-fun trans-fun } (\text{localState } (\text{trans-fun } \varepsilon \ c))$$

$$\langle \text{proof} \rangle$$

lemma *f-Exec-State-Idle-replicate-NoMsg-state*[rule-format]:

$$\bigwedge c. \text{State-Idle localState output-fun trans-fun } (\text{localState } c) \implies$$

$$\text{localState } (f\text{-Exec-Comp trans-fun } \varepsilon^n \ c) = \text{localState } c$$

$$\langle \text{proof} \rangle$$

lemma *f-Exec-State-Idle-replicate-NoMsg-gr0-output*[rule-format]: $\bigwedge c.$

$$\llbracket \text{State-Idle localState output-fun trans-fun } (\text{localState } c); 0 < n \rrbracket \implies$$

$$\text{output-fun } (f\text{-Exec-Comp trans-fun } \varepsilon^n \ c) = \varepsilon$$

$$\langle \text{proof} \rangle$$

lemma *f-Exec-State-Idle-replicate-NoMsg-output*[rule-format]:

$$\llbracket \text{State-Idle localState output-fun trans-fun } (\text{localState } c);$$

$$\text{output-fun } c = \varepsilon \rrbracket \implies$$

$$\text{output-fun } (f\text{-Exec-Comp trans-fun } \varepsilon^n \ c) = \varepsilon$$

$$\langle \text{proof} \rangle$$

lemma *f-Exec-Stream-State-Idle-replicate-NoMsg-output*[rule-format]:

$$\llbracket \text{State-Idle localState output-fun trans-fun } (\text{localState } c) \rrbracket \implies$$

$$\text{map output-fun } (f\text{-Exec-Comp-Stream trans-fun } \varepsilon^n \ c) = \varepsilon^n$$

$$\langle \text{proof} \rangle$$

corollary *f-Exec-State-Idle-append-replicate-NoMsg-state*:

$$\llbracket \text{State-Idle localState output-fun trans-fun } ($$

$$\text{localState } (f\text{-Exec-Comp trans-fun } xs \ c)) \rrbracket \implies$$

$$\text{localState } (f\text{-Exec-Comp trans-fun } (xs @ \varepsilon^n) \ c) =$$

$$\text{localState } (f\text{-Exec-Comp trans-fun } xs \ c)$$

$$\langle \text{proof} \rangle$$

corollary *f-Exec-State-Idle-append-replicate-NoMsg-ge-state*:

$$\llbracket \text{State-Idle localState output-fun trans-fun } ($$

$$\text{localState } (f\text{-Exec-Comp trans-fun } (xs @ \varepsilon^m) \ c));$$

$$m \leq n \rrbracket \implies$$

$$\text{localState } (f\text{-Exec-Comp trans-fun } (xs @ \varepsilon^n) \ c) =$$

$$\text{localState } (f\text{-Exec-Comp trans-fun } (xs @ \varepsilon^m) \ c)$$

$$\langle \text{proof} \rangle$$

corollary *f-Exec-State-Idle-replicate-NoMsg-ge-state*:

$$\llbracket \text{State-Idle localState output-fun trans-fun (}$$

$$\quad \text{localState (f-Exec-Comp trans-fun } \varepsilon^m \text{ c));}$$

$$m \leq n \rrbracket \implies$$

$$\text{localState (f-Exec-Comp trans-fun } \varepsilon^n \text{ c) =}$$

$$\text{localState (f-Exec-Comp trans-fun } \varepsilon^m \text{ c)}$$

 <proof>

corollary *f-Exec-State-Idle-append-replicate-NoMsg-gr0-output:*

$$\llbracket \text{State-Idle localState output-fun trans-fun (}$$

$$\quad \text{localState (f-Exec-Comp trans-fun xs c));}$$

$$0 < n \rrbracket \implies$$

$$\text{output-fun (f-Exec-Comp trans-fun (xs @ } \varepsilon^n \text{) c) = } \varepsilon$$

 <proof>

corollary *f-Exec-Stream-State-Idle-append-replicate-NoMsg-gr0-output:*

$$\llbracket \text{State-Idle localState output-fun trans-fun (}$$

$$\quad \text{localState (f-Exec-Comp trans-fun xs c)) \rrbracket \implies$$

$$\text{map output-fun (f-Exec-Comp-Stream trans-fun (xs @ } \varepsilon^n \text{) c) =}$$

$$\text{map output-fun (f-Exec-Comp-Stream trans-fun xs c) @ } \varepsilon^n$$

 <proof>

corollary *f-Exec-State-Idle-append-replicate-NoMsg-gr-output:*

$$\llbracket \text{State-Idle localState output-fun trans-fun (}$$

$$\quad \text{localState (f-Exec-Comp trans-fun (xs @ } \varepsilon^m \text{) c));}$$

$$m < n \rrbracket \implies$$

$$\text{output-fun (f-Exec-Comp trans-fun (xs @ } \varepsilon^n \text{) c) = } \varepsilon$$

 <proof>

corollary *f-Exec-State-Idle-append-replicate-NoMsg-ge-output:*

$$\llbracket \text{State-Idle localState output-fun trans-fun (}$$

$$\quad \text{localState (f-Exec-Comp trans-fun (xs @ } \varepsilon^m \text{) c));}$$

$$\text{output-fun (f-Exec-Comp trans-fun (xs @ } \varepsilon^m \text{) c) = } \varepsilon; m \leq n \rrbracket \implies$$

$$\text{output-fun (f-Exec-Comp trans-fun (xs @ } \varepsilon^n \text{) c) = } \varepsilon$$

 <proof>

corollary *f-Exec-State-Idle-replicate-NoMsg-gr-output:*

$$\llbracket \text{State-Idle localState output-fun trans-fun (}$$

$$\quad \text{localState (f-Exec-Comp trans-fun } \varepsilon^m \text{ c));}$$

$$m < n \rrbracket \implies$$

$$\text{output-fun (f-Exec-Comp trans-fun } \varepsilon^n \text{ c) = } \varepsilon$$

 <proof>

corollary *f-Exec-State-Idle-replicate-NoMsg-ge-output:*

$$\llbracket \text{State-Idle localState output-fun trans-fun (}$$

$$\quad \text{localState (f-Exec-Comp trans-fun } \varepsilon^m \text{ c));}$$

$$\text{output-fun (f-Exec-Comp trans-fun } \varepsilon^m \text{ c) = } \varepsilon; m \leq n \rrbracket \implies$$

$$\text{output-fun (f-Exec-Comp trans-fun } \varepsilon^n \text{ c) = } \varepsilon$$

 <proof>

lemma *State-Idle-append-replicate-NoMsg-output-last-message:*

$\llbracket \text{State-Idle localState output-fun trans-fun (}$
 $\quad \text{localState (f-Exec-Comp trans-fun xs c))} \rrbracket \implies$
 $\text{last-message (map output-fun (f-Exec-Comp-Stream trans-fun (xs @ } \varepsilon^n) \text{ c))} =$
 $\text{last-message (map output-fun (f-Exec-Comp-Stream trans-fun xs c))}$
 $\langle \text{proof} \rangle$

lemma *State-Idle-append-replicate-NoMsg-output-Msg-eq-last-message:*

$\llbracket \text{State-Idle localState output-fun trans-fun (}$
 $\quad \text{localState (f-Exec-Comp trans-fun xs c));}$
 $\quad \text{output-fun (f-Exec-Comp trans-fun xs c)} \neq \varepsilon;$
 $\quad \text{xs} \neq [] \rrbracket \implies$
 $\text{last-message (map output-fun (f-Exec-Comp-Stream trans-fun (xs @ } \varepsilon^n) \text{ c))} =$
 $\text{output-fun (f-Exec-Comp trans-fun xs c)}$
 $\langle \text{proof} \rangle$

corollary *State-Idle-output-Msg-eq-last-message:*

$\llbracket \text{State-Idle localState output-fun trans-fun (}$
 $\quad \text{localState (f-Exec-Comp trans-fun xs c));}$
 $\quad \text{output-fun (f-Exec-Comp trans-fun xs c)} \neq \varepsilon;$
 $\quad \text{xs} \neq [] \rrbracket \implies$
 $\text{last-message (map output-fun (f-Exec-Comp-Stream trans-fun xs c))} =$
 $\text{output-fun (f-Exec-Comp trans-fun xs c)}$
 $\langle \text{proof} \rangle$

lemma *State-Idle-imp-exists-state-change:*

$\llbracket \neg \text{State-Idle localState output-fun trans-fun (localState c);}$
 $\quad \text{State-Idle localState output-fun trans-fun (localState (f-Exec-Comp trans-fun } \varepsilon^n$
 $\text{c))} \rrbracket \implies$
 $\exists i < n. ($
 $\quad \neg \text{State-Idle localState output-fun trans-fun (localState (f-Exec-Comp trans-fun}$
 $\varepsilon^i \text{ c))} \wedge ($
 $\quad \forall j \leq n. i < j \longrightarrow \text{State-Idle localState output-fun trans-fun (localState (f-Exec-Comp}$
 $\text{trans-fun } \varepsilon^j \text{ c))}))$
 $\langle \text{proof} \rangle$

lemma *State-Idle-imp-exists-state-change2:*

$\llbracket \neg \text{State-Idle localState output-fun trans-fun (localState c);}$
 $\quad \text{State-Idle localState output-fun trans-fun (localState (f-Exec-Comp trans-fun } \varepsilon^n$
 $\text{c))} \rrbracket \implies$
 $\exists i < n. ($
 $\quad (\forall j \leq i. \neg \text{State-Idle localState output-fun trans-fun (localState (f-Exec-Comp}$
 $\text{trans-fun } \varepsilon^i \text{ c))}) \wedge$
 $\quad (\forall j \leq n. i < j \longrightarrow \text{State-Idle localState output-fun trans-fun (localState (f-Exec-Comp}$
 $\text{trans-fun } \varepsilon^j \text{ c))}))$
 $\langle \text{proof} \rangle$

3.2.3 Basic definitions for accelerated execution

Stream processing with accelerated components

definition *f-Exec-Comp-Stream-Acc-Output* ::

nat $\Rightarrow$ — Acceleration factor
 ('comp $\Rightarrow$ 'output message-af) $\Rightarrow$ — Output extraction function
 ('comp, 'input message-af) *Comp-Trans-Fun* $\Rightarrow$
 'input fstream-af $\Rightarrow$ 'comp $\Rightarrow$
 'output fstream-af
where *f-Exec-Comp-Stream-Acc-Output* *k* *output-fun* *trans-fun* *xs* *c* $\equiv$
 (map *output-fun* (*f-Exec-Comp-Stream* *trans-fun* (*xs* $\odot_f$ *k*) *c*)) $\div_f$ *k*

definition *f-Exec-Comp-Stream-Acc-LocalState* ::

nat $\Rightarrow$ — Acceleration factor
 ('comp $\Rightarrow$ 'state) $\Rightarrow$ — Local state extraction function
 ('comp, 'input message-af) *Comp-Trans-Fun* $\Rightarrow$
 'input fstream-af $\Rightarrow$ 'comp $\Rightarrow$
 'state list
where *f-Exec-Comp-Stream-Acc-LocalState* *k* *localState* *trans-fun* *xs* *c* $\equiv$
 (map *localState* (*f-Exec-Comp-Stream* *trans-fun* (*xs* $\odot_f$ *k*) *c*)) $\div_f$ *k*

definition *i-Exec-Comp-Stream-Acc-Output* ::

nat $\Rightarrow$ — Acceleration factor
 ('comp $\Rightarrow$ 'output message-af) $\Rightarrow$ — Output extraction function
 ('comp, 'input message-af) *Comp-Trans-Fun* $\Rightarrow$
 'input istream-af $\Rightarrow$ 'comp $\Rightarrow$
 'output istream-af
where *i-Exec-Comp-Stream-Acc-Output* *k* *output-fun* *trans-fun* *input* *c* $\equiv$
 (*output-fun* $\circ$ (*i-Exec-Comp-Stream* *trans-fun* (*input* $\odot_i$ *k*) *c*)) $\div_i$ *k*

definition *i-Exec-Comp-Stream-Acc-LocalState* ::

nat $\Rightarrow$ — Acceleration factor
 ('comp $\Rightarrow$ 'state) $\Rightarrow$ — Local state extraction function
 ('comp, 'input message-af) *Comp-Trans-Fun* $\Rightarrow$
 'input istream-af $\Rightarrow$ 'comp $\Rightarrow$
 'state ilist
where *i-Exec-Comp-Stream-Acc-LocalState* *k* *localState* *trans-fun* *input* *c* $\equiv$
 (*localState* $\circ$ (*i-Exec-Comp-Stream* *trans-fun* (*input* $\odot_i$ *k*) *c*)) $\div_{il}$ *k*

definition *f-Exec-Comp-Stream-Acc-Output-Init* ::

nat $\Rightarrow$ — Acceleration factor
 ('comp $\Rightarrow$ 'output message-af) $\Rightarrow$ — Output extraction function
 ('comp, 'input message-af) *Comp-Trans-Fun* $\Rightarrow$
 'input fstream-af $\Rightarrow$ 'comp $\Rightarrow$
 'output fstream-af
where *f-Exec-Comp-Stream-Acc-Output-Init* *k* *output-fun* *trans-fun* *xs* *c* $\equiv$
 (*output-fun* *c*) $\#$ *f-Exec-Comp-Stream-Acc-Output* *k* *output-fun* *trans-fun* *xs* *c*

definition *f-Exec-Comp-Stream-Acc-LocalState-Init* ::

$nat \Rightarrow$ — Acceleration factor
 $('comp \Rightarrow 'state) \Rightarrow$ — Local state extraction function
 $('comp, 'input\ message\text{-}af) \text{ } Comp\text{-}Trans\text{-}Fun \Rightarrow 'input\ fstream\text{-}af \Rightarrow 'comp \Rightarrow 'state\ list$
where $f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}LocalState\text{-}Init\ k\ localState\ trans\text{-}fun\ xs\ c \equiv (localState\ c) \# f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}LocalState\ k\ localState\ trans\text{-}fun\ xs\ c$

definition $i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}Output\text{-}Init ::$

$nat \Rightarrow$ — Acceleration factor
 $('comp \Rightarrow 'output\ message\text{-}af) \Rightarrow$ — Output extraction function
 $('comp, 'input\ message\text{-}af) \text{ } Comp\text{-}Trans\text{-}Fun \Rightarrow 'input\ istream\text{-}af \Rightarrow 'comp \Rightarrow 'output\ istream\text{-}af$
where $i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}Output\text{-}Init\ k\ output\text{-}fun\ trans\text{-}fun\ input\ c \equiv [output\text{-}fun\ c] \frown (i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}Output\ k\ output\text{-}fun\ trans\text{-}fun\ input\ c)$

definition $i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}LocalState\text{-}Init ::$

$nat \Rightarrow$ — Acceleration factor
 $('comp \Rightarrow 'state) \Rightarrow$ — Local state extraction function
 $('comp, 'input\ message\text{-}af) \text{ } Comp\text{-}Trans\text{-}Fun \Rightarrow 'input\ istream\text{-}af \Rightarrow 'comp \Rightarrow 'state\ ilist$
where $i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}LocalState\text{-}Init\ k\ localState\ trans\text{-}fun\ input\ c \equiv [localState\ c] \frown (i\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}LocalState\ k\ localState\ trans\text{-}fun\ input\ c)$

lemma $f\text{-}Exec\text{-}Stream\text{-}Acc\text{-}Output\text{-}length[simp]:$

$0 < k \implies$
 $length\ (f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}Output\ k\ output\text{-}fun\ trans\text{-}fun\ xs\ c) = length\ xs$
 $\langle proof \rangle$

lemma $f\text{-}Exec\text{-}Stream\text{-}Acc\text{-}LocalState\text{-}length[simp]:$

$0 < k \implies$
 $length\ (f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}LocalState\ k\ localState\ trans\text{-}fun\ xs\ c) = length\ xs$
 $\langle proof \rangle$

lemmas $f\text{-}Exec\text{-}Stream\text{-}Acc\text{-}length =$
 $f\text{-}Exec\text{-}Stream\text{-}Acc\text{-}LocalState\text{-}length$
 $f\text{-}Exec\text{-}Stream\text{-}Acc\text{-}Output\text{-}length$

3.2.4 Basic results for accelerated execution

lemma $f\text{-}Exec\text{-}Stream\text{-}Acc\text{-}Output\text{-}Nil[simp]:$

$f\text{-}Exec\text{-}Comp\text{-}Stream\text{-}Acc\text{-}Output\ k\ output\text{-}fun\ trans\text{-}fun\ []\ c = []$
 $\langle proof \rangle$

lemma $f\text{-}Exec\text{-}Stream\text{-}Acc\text{-}LocalState\text{-}Nil[simp]:$

f-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* $\square$ $c = \square$
 $\langle \text{proof} \rangle$

lemmas *f-Exec-Stream-Acc-Nil* =
f-Exec-Stream-Acc-LocalState-Nil
f-Exec-Stream-Acc-Output-Nil

lemma *f-Exec-Stream-Acc-Output-0*[*simp*]:
f-Exec-Comp-Stream-Acc-Output 0 *output-fun* *trans-fun* *xs* $c = \square$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-LocalState-0*[*simp*]:
f-Exec-Comp-Stream-Acc-LocalState 0 *localState* *trans-fun* *xs* $c = \square$
 $\langle \text{proof} \rangle$

lemmas *f-Exec-Stream-Acc-0* =
f-Exec-Stream-Acc-LocalState-0
f-Exec-Stream-Acc-Output-0

lemma *f-Exec-Stream-Acc-Output-1*[*simp*]:
f-Exec-Comp-Stream-Acc-Output (*Suc* 0) *output-fun* *trans-fun* *xs* $c =$
 $\text{map } \text{output-fun } (f\text{-Exec-Comp-Stream } \text{trans-fun } \text{xs } c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-LocalState-1*[*simp*]:
f-Exec-Comp-Stream-Acc-LocalState (*Suc* 0) *localState* *trans-fun* *xs* $c =$
 $\text{map } \text{localState } (f\text{-Exec-Comp-Stream } \text{trans-fun } \text{xs } c)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-Output-1*[*simp*]:
i-Exec-Comp-Stream-Acc-Output (*Suc* 0) *output-fun* *trans-fun* *input* $c =$
 $\text{output-fun} \circ (i\text{-Exec-Comp-Stream } \text{trans-fun } \text{input } c)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-LocalState-1*[*simp*]:
i-Exec-Comp-Stream-Acc-LocalState (*Suc* 0) *localState* *trans-fun* *input* $c =$
 $\text{localState} \circ (i\text{-Exec-Comp-Stream } \text{trans-fun } \text{input } c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-eq-last-message-hold*:
f-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* *xs* $c =$
 $(\text{map } \text{output-fun } (f\text{-Exec-Comp-Stream } \text{trans-fun } (\text{xs} \odot_f k) c)) \mapsto_f k \div_f k$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-Output-eq-last-message-hold*: $0 < k \implies$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* *input* $c =$
 $(\text{output-fun} \circ (i\text{-Exec-Comp-Stream } \text{trans-fun } (\text{input} \odot_i k) c)) \mapsto_i k \div_{il} k$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-take*:

f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *xs* *c* $\downarrow$ *n* =
f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* (*xs* $\downarrow$ *n*) *c*
 ⟨proof⟩

lemma *f-Exec-Stream-Acc-Output-drop*:

f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *xs* *c* $\uparrow$ *n* =
f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* (*xs* $\uparrow$ *n*) (
f-Exec-Comp *trans-fun* (*xs* $\downarrow$ *n* $\odot_f$ *k*) *c*)
 ⟨proof⟩

lemma *i-Exec-Stream-Acc-Output-take*:

$0 < k \implies$
i-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *input* *c* $\Downarrow$ *n* =
f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* (*input* $\Downarrow$ *n*) *c*
 ⟨proof⟩

lemma *i-Exec-Stream-Acc-Output-drop*:

$0 < k \implies$
i-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *input* *c* $\Uparrow$ *n* =
i-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* (*input* $\Uparrow$ *n*) (
f-Exec-Comp *trans-fun* (*input* $\Downarrow$ *n* $\odot_f$ *k*) *c*)
 ⟨proof⟩

lemma *i-Exec-Stream-Acc-LocalState-take*:

$0 < k \implies$
i-Exec-Comp-Stream-Acc-LocalState *k* *localState* *trans-fun* *input* *c* $\Downarrow$ *n* =
f-Exec-Comp-Stream-Acc-LocalState *k* *localState* *trans-fun* (*input* $\Downarrow$ *n*) *c*
 ⟨proof⟩

lemma *i-Exec-Stream-Acc-LocalState-drop*:

$0 < k \implies$
i-Exec-Comp-Stream-Acc-LocalState *k* *localState* *trans-fun* *input* *c* $\Uparrow$ *n* =
i-Exec-Comp-Stream-Acc-LocalState *k* *localState* *trans-fun* (*input* $\Uparrow$ *n*) (
f-Exec-Comp *trans-fun* (*input* $\Downarrow$ *n* $\odot_f$ *k*) *c*)
 ⟨proof⟩

lemma *f-Exec-Stream-Acc-Output-append*:

f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* (*xs* @ *ys*) *c* =
f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *xs* *c* @
f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *ys* (
f-Exec-Comp *trans-fun* (*xs* $\odot_f$ *k*) *c*)
 ⟨proof⟩

lemma *f-Exec-Stream-Acc-Output-Cons*:

$0 < k \implies$
f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* (*x* # *xs*) *c* =
last-message (*map* *output-fun* (*f-Exec-Comp-Stream* *trans-fun* (*x* # $\varepsilon^k - \text{Suc } 0$)
c)) #

f-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* xs (
f-Exec-Comp *trans-fun* $(x \# \varepsilon^k - \text{Suc } 0)$ c)
 ⟨proof⟩

lemma *f-Exec-Stream-Acc-Output-one*:

$0 < k \implies$
f-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* $[x]$ $c =$
 $[\text{last-message } (\text{map } \text{output-fun } (\text{f-Exec-Comp-Stream } \text{trans-fun } (x \# \varepsilon^k - \text{Suc } 0)$
 $c))]$
 ⟨proof⟩

lemma *f-Exec-Stream-Acc-Output-snoc*:

$0 < k \implies$
f-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* $(xs @ [x])$ $c =$
f-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* xs $c @$
 $[\text{last-message } (\text{map } \text{output-fun } (\text{f-Exec-Comp-Stream } \text{trans-fun } (x \# \varepsilon^k - \text{Suc } 0)$
 $($
 $\text{f-Exec-Comp } \text{trans-fun } (xs \odot_f k) \text{ c})))]$
 ⟨proof⟩

lemma *i-Exec-Stream-Acc-Output-append*:

i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* $(xs \frown \text{input})$ $c =$
f-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* xs $c \frown$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* input (
f-Exec-Comp *trans-fun* $(xs \odot_f k)$ c)
 ⟨proof⟩

lemma *i-Exec-Stream-Acc-Output-Cons*:

$0 < k \implies$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* $([x] \frown \text{input})$ $c =$
 $[\text{last-message } (\text{map } \text{output-fun } (\text{f-Exec-Comp-Stream } \text{trans-fun } (x \# \varepsilon^k - \text{Suc } 0)$
 $c))]$ $\frown$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* input (
f-Exec-Comp *trans-fun* $(x \# \varepsilon^k - \text{Suc } 0)$ c)
 ⟨proof⟩

lemma *f-Exec-Stream-Acc-LocalState-append*:

f-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* $(xs @ ys)$ $c =$
f-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* xs $c @$
f-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* ys (
f-Exec-Comp *trans-fun* $(xs \odot_f k)$ c)
 ⟨proof⟩

lemma *f-Exec-Stream-Acc-LocalState-Cons*:

$0 < k \implies$
f-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* $(x \# xs)$ $c =$
 $\text{localState } (\text{f-Exec-Comp } \text{trans-fun } (x \# \varepsilon^k - \text{Suc } 0) \text{ c}) \#$
f-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* xs (
f-Exec-Comp *trans-fun* $(x \# \varepsilon^k - \text{Suc } 0)$ c)

$\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-LocalState-one*:

$0 < k \implies$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } [x] \text{ } c =$
 $[localState (f\text{-Exec-Comp trans-fun } (x \# \varepsilon^k - Suc \ 0) \ c)]$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-LocalState-snoc*:

$0 < k \implies$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } (xs @ [x]) \text{ } c =$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } xs \text{ } c @$
 $[localState (f\text{-Exec-Comp trans-fun } ((xs @ [x]) \odot_f k) \ c)]$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-LocalState-append*:

$i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } (xs \smallfrown input) \text{ } c =$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } xs \text{ } c \smallfrown$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } input \text{ } ($
 $f\text{-Exec-Comp trans-fun } (xs \odot_f k) \ c)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-LocalState-Cons*:

$0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } ([x] \smallfrown input) \text{ } c =$
 $[localState (f\text{-Exec-Comp trans-fun } (x \# \varepsilon^k - Suc \ 0) \ c)] \smallfrown$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } input \text{ } ($
 $f\text{-Exec-Comp trans-fun } (x \# \varepsilon^k - Suc \ 0) \ c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-nth*:

$\llbracket 0 < k; n < \text{length } xs \rrbracket \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \text{ } c ! n =$
 $\text{last-message } (\text{map output-fun } ($
 $f\text{-Exec-Comp-Stream trans-fun } (xs ! n \# \varepsilon^k - Suc \ 0) \ ($
 $f\text{-Exec-Comp trans-fun } (xs \downarrow n \odot_f k) \ c)))$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-nth-eq-i-nth*:

$\llbracket 0 < k; n < n' \rrbracket \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } (input \downarrow n') \text{ } c ! n =$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } input \text{ } c \text{ } n$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-Output-nth*:

$0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } input \text{ } c \text{ } n =$
 $\text{last-message } (\text{map output-fun } ($
 $f\text{-Exec-Comp-Stream trans-fun } (input \text{ } n \# \varepsilon^k - Suc \ 0) \ ($

$f\text{-Exec-Comp trans-fun (input } \Downarrow n \odot_f k) c))$
 $\langle \text{proof} \rangle$

corollary $i\text{-Exec-Stream-Acc-Output-nth-f-nth}$:

$0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } n =$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun (input } \Downarrow \text{Suc } n) \text{ } c \text{ } ! \text{ } n$
 $\langle \text{proof} \rangle$

corollary $i\text{-Exec-Stream-Acc-Output-nth-f-last}$:

$0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } n =$
 $\text{last (} f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun (input } \Downarrow \text{Suc } n) \text{ } c \text{)}$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Acc-LocalState-nth}$:

$\llbracket 0 < k; n < \text{length } xs \rrbracket \implies$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } xs \text{ } c \text{ } ! \text{ } n =$
 $\text{localState (} f\text{-Exec-Comp trans-fun (} xs \downarrow \text{Suc } n \odot_f k) \text{ } c \text{)}$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Acc-LocalState-nth-eq-i-nth}$:

$\llbracket 0 < k; n < n' \rrbracket \implies$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun (input } \Downarrow n') \text{ } c \text{ } ! \text{ } n =$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } n$
 $\langle \text{proof} \rangle$

corollary $i\text{-Exec-Stream-Acc-LocalState-nth-f-nth}$:

$0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ output-fun trans-fun input } c \text{ } n =$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ output-fun trans-fun (input } \Downarrow \text{Suc } n) \text{ } c \text{ } ! \text{ } n$
 $\langle \text{proof} \rangle$

corollary $i\text{-Exec-Stream-Acc-LocalState-nth-f-last}$:

$0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } n =$
 $\text{last (} f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun (input } \Downarrow \text{Suc } n) \text{ } c \text{)}$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Acc-LocalState-nth}$:

$0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } n =$
 $\text{localState (} f\text{-Exec-Comp trans-fun (input } \Downarrow \text{Suc } n \odot_f k) \text{ } c \text{)}$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Acc-Output-causal}$:

$xs \downarrow n = ys \downarrow n \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \text{ } c \downarrow n =$

f-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* ys $c \downarrow n$
 <proof>

lemma *i-Exec-Stream-Acc-Output-causal*:

$input1 \Downarrow n = input2 \Downarrow n \implies$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* $input1$ $c \Downarrow n =$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* $input2$ $c \Downarrow n$
 <proof>

lemma *f-Exec-Stream-Acc-Output-Connected-strictly-causal*:

$\llbracket xs \downarrow n = ys \downarrow n;$
f-Streams-Connected
 (*f-Exec-Comp-Stream-Acc-Output* k *output-fun* *trans-fun* xs c)
channel1;
f-Streams-Connected
 (*f-Exec-Comp-Stream-Acc-Output* k *output-fun* *trans-fun* ys c)
channel2 $\rrbracket \implies$
channel1 $\downarrow \text{Suc } n = \text{channel2} \downarrow \text{Suc } n$
 <proof>

lemma *i-Exec-Stream-Acc-Output-Connected-strictly-causal*:

$\llbracket input1 \Downarrow n = input2 \Downarrow n;$
i-Streams-Connected
 (*i-Exec-Comp-Stream-Acc-Output* k *output-fun* *trans-fun* $input1$ c)
channel1;
i-Streams-Connected
 (*i-Exec-Comp-Stream-Acc-Output* k *output-fun* *trans-fun* $input2$ c)
channel2 $\rrbracket \implies$
channel1 $\Downarrow \text{Suc } n = \text{channel2} \Downarrow \text{Suc } n$
 <proof>

Complete execution cycles/steps of accelerated execution

definition *Acc-Trans-Fun-Step* ::

$nat \Rightarrow \text{--- Acceleration factor}$
 (*'comp*, *'input message-af*) *Comp-Trans-Fun* $\Rightarrow$
 (*'comp list* $\Rightarrow$ *'comp*) $\Rightarrow$ --- Pointwise output shrink function
'input message-af $\Rightarrow$ *'comp* $\Rightarrow$
'comp

where *Acc-Trans-Fun-Step* k *trans-fun* *pointwise-shrink* x $c \equiv$
pointwise-shrink (*f-Exec-Comp-Stream* *trans-fun* ($x \# \varepsilon^k - \text{Suc } 0$) c)

definition *is-Pointwise-Output-Shrink* ::

(*'comp list* $\Rightarrow$ *'comp*) $\Rightarrow$ --- Pointwise output shrink function
 (*'comp* $\Rightarrow$ *'output message-af*) $\Rightarrow$ --- Output extraction function for consideration
 bool

where *is-Pointwise-Output-Shrink* *pointwise-shrink* *output-fun* $\equiv$
 $\forall cs. \text{output-fun} (\text{pointwise-shrink } cs) = \text{last-message} (\text{map } \text{output-fun } cs)$

primrec *is-Pointwise-Output-Shrink-list* ::

$(\text{'comp } list \Rightarrow \text{'comp}) \Rightarrow \text{--- Pointwise output shrink function}$
 $(\text{'comp } \Rightarrow \text{'output message-af}) \text{ list } \Rightarrow \text{--- List of output extraction functions for consideration}$
 $bool$
where
 $is\text{-Pointwise-Output-Shrink-list } pointwise\text{-shrink } [] = True$
 $| is\text{-Pointwise-Output-Shrink-list } pointwise\text{-shrink } (f \# fs) =$
 $(is\text{-Pointwise-Output-Shrink } pointwise\text{-shrink } f \wedge$
 $is\text{-Pointwise-Output-Shrink-list } pointwise\text{-shrink } fs)$

definition $is\text{-correct-localState-Pointwise-Output-Shrink} ::$
 $(\text{'comp } list \Rightarrow \text{'comp}) \Rightarrow \text{--- Pointwise output shrink function}$
 $(\text{'comp } \Rightarrow \text{'state}) \Rightarrow \text{--- Local state extraction function}$
 $bool$
where $is\text{-correct-localState-Pointwise-Output-Shrink } pointwise\text{-shrink } localState$
 $\equiv$
 $\forall cs. cs \neq [] \longrightarrow localState (pointwise\text{-shrink } cs) = localState (last\ cs)$

lemma $Deterministic\text{-trans-fun-imp-acc-trans-fun}:$
 $Deterministic\text{-Trans-Fun } trans\text{-fun } localState \implies$
 $Deterministic\text{-Trans-Fun } (Acc\text{-Trans-Fun-Step } k \text{ trans-fun } pointwise\text{-shrink}) \text{ localState}$
 $\langle proof \rangle$

lemma $is\text{-Pointwise-Output-Shrink-list-imp-is-Pointwise-Output-Shrink}:$
 $\llbracket is\text{-Pointwise-Output-Shrink-list } pointwise\text{-shrink } fs; output\text{-fun} \in set\ fs \rrbracket \implies$
 $is\text{-Pointwise-Output-Shrink } pointwise\text{-shrink } output\text{-fun}$
 $\langle proof \rangle$

lemma $is\text{-Pointwise-Output-Shrink-list-eq-is-Pointwise-Output-Shrink-all}:$
 $(is\text{-Pointwise-Output-Shrink-list } pointwise\text{-shrink } fs) =$
 $(\forall output\text{-fun} \in set\ fs. is\text{-Pointwise-Output-Shrink } pointwise\text{-shrink } output\text{-fun})$
 $\langle proof \rangle$

lemma $is\text{-Pointwise-Output-Shrink-subset}:$
 $\llbracket is\text{-Pointwise-Output-Shrink-list } pointwise\text{-shrink } fs; set\ fs' \subseteq set\ fs \rrbracket \implies$
 $is\text{-Pointwise-Output-Shrink-list } pointwise\text{-shrink } fs'$
 $\langle proof \rangle$

lemma $f\text{-Exec-Stream-Acc-LocalState-eq-Acc-Trans-Fun-Step-LocalState}: \bigwedge c.$
 $\llbracket 0 < k;$
 $Deterministic\text{-Trans-Fun } trans\text{-fun } localState;$
 $is\text{-correct-localState-Pointwise-Output-Shrink } pointwise\text{-shrink } localState \rrbracket \implies$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState } trans\text{-fun } xs\ c =$
 $map\ localState (f\text{-Exec-Comp-Stream } (Acc\text{-Trans-Fun-Step } k \text{ trans-fun } pointwise\text{-shrink})$
 $xs\ c)$
 $\langle proof \rangle$

lemma $f\text{-Exec-Stream-Acc-Output-eq-Acc-Trans-Fun-Step-Output}: \bigwedge c.$

$\llbracket 0 < k;$
Deterministic-Trans-Fun *trans-fun* *localState*;
is-correct-localState-Pointwise-Output-Shrink *pointwise-shrink* *localState*;
is-Pointwise-Output-Shrink *pointwise-shrink* *output-fun* $\rrbracket \implies$
f-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *xs* *c* =
map *output-fun* (*f-Exec-Comp-Stream* (*Acc-Trans-Fun-Step* *k* *trans-fun* *pointwise-shrink*) *xs* *c*)
 <proof>

lemma *i-Exec-Stream-Acc-LocalState-eq-Acc-Trans-Fun-Step-LocalState*: $\bigwedge c.$
 $\llbracket 0 < k;$
Deterministic-Trans-Fun *trans-fun* *localState*;
is-correct-localState-Pointwise-Output-Shrink *pointwise-shrink* *localState* $\rrbracket \implies$
i-Exec-Comp-Stream-Acc-LocalState *k* *localState* *trans-fun* *input* *c* =
localState $\circ$ (*i-Exec-Comp-Stream* (*Acc-Trans-Fun-Step* *k* *trans-fun* *pointwise-shrink*)
input *c*)
 <proof>

lemma *i-Exec-Stream-Acc-Output-eq-Acc-Trans-Fun-Step-Output*: $\bigwedge c.$
 $\llbracket 0 < k;$
Deterministic-Trans-Fun *trans-fun* *localState*;
is-correct-localState-Pointwise-Output-Shrink *pointwise-shrink* *localState*;
is-Pointwise-Output-Shrink *pointwise-shrink* *output-fun* $\rrbracket \implies$
i-Exec-Comp-Stream-Acc-Output *k* *output-fun* *trans-fun* *input* *c* =
output-fun $\circ$ (*i-Exec-Comp-Stream* (*Acc-Trans-Fun-Step* *k* *trans-fun* *pointwise-shrink*)
input *c*)
 <proof>

3.2.5 Basic results for accelerated execution with initial state in the resulting stream

lemma *f-Exec-Stream-Acc-Output-Init-length*:
 $0 < k \implies$
length (*f-Exec-Comp-Stream-Acc-Output-Init* *k* *output-fun* *trans-fun* *xs* *c*) = *Suc*
 (*length* *xs*)
 <proof>

lemma *f-Exec-Stream-Acc-LocalState-Init-length*:
 $0 < k \implies$
length (*f-Exec-Comp-Stream-Acc-LocalState-Init* *k* *localState* *trans-fun* *xs* *c*) = *Suc*
 (*length* *xs*)
 <proof>

lemma *f-Exec-Stream-Acc-Output-Init-Nil*:
f-Exec-Comp-Stream-Acc-Output-Init *k* *output-fun* *trans-fun* [] *c* = [*output-fun* *c*]
 <proof>

lemma *f-Exec-Stream-Acc-LocalState-Init-Nil*:
f-Exec-Comp-Stream-Acc-LocalState-Init *k* *localState* *trans-fun* [] *c* = [*localState*

$c]$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-Init-1*:
 $f\text{-Exec-Comp-Stream-Acc-Output-Init } (Suc\ 0) \text{ output-fun trans-fun } xs\ c =$
 $\text{map output-fun } (f\text{-Exec-Comp-Stream-Init trans-fun } xs\ c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-LocalState-Init-1*:
 $f\text{-Exec-Comp-Stream-Acc-LocalState-Init } (Suc\ 0) \text{ localState trans-fun } xs\ c =$
 $\text{map localState } (f\text{-Exec-Comp-Stream-Init trans-fun } xs\ c)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-Output-Init-1*:
 $i\text{-Exec-Comp-Stream-Acc-Output-Init } (Suc\ 0) \text{ output-fun trans-fun input } c =$
 $\text{output-fun } \circ (i\text{-Exec-Comp-Stream-Init trans-fun input } c)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-LocalState-Init-1*:
 $i\text{-Exec-Comp-Stream-Acc-LocalState-Init } (Suc\ 0) \text{ localState trans-fun input } c =$
 $\text{localState } \circ (i\text{-Exec-Comp-Stream-Init trans-fun input } c)$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-Init-take*:
 $f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs\ c \downarrow (Suc\ n) =$
 $f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } (xs \downarrow n) \ c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-Init-drop'*:
 $\llbracket 0 < k; n < \text{length } xs \rrbracket \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs\ c \uparrow Suc\ n =$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs\ c \uparrow n$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-Output-Init-take*:
 $0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun input } c \downarrow (Suc\ n) =$
 $i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } (input \downarrow n) \ c$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-Output-Init-drop'*:
 $0 < k \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs\ c \uparrow Suc\ n =$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs\ c \uparrow n$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output-Init-strictly-causal*:
 $xs \downarrow n = ys \downarrow n \implies$

$f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs \ c \downarrow \text{Suc } n =$
 $f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } ys \ c \downarrow \text{Suc } n$
 <proof>

lemma *i-Exec-Stream-Acc-Output-Init-strictly-causal:*

$input1 \downarrow n = input2 \downarrow n \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } input1 \ c \downarrow \text{Suc } n =$
 $i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } input2 \ c \downarrow \text{Suc } n$
 <proof>

lemma *f-Exec-Stream-Acc-Output-Init-eq-f-Exec-Stream-Acc-Output-Cons:*

$f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs \ c =$
 $output\text{-fun } c \ \# \ f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \ c$
 <proof>

lemma *f-Exec-Stream-Acc-Output-Init-eq-f-Exec-Stream-Acc-Output-Cons-output:*

$output\text{-fun } c = \varepsilon \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs \ c =$
 $\varepsilon \ \# \ f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \ c$
 <proof>

lemma *f-Exec-Stream--Acc-OutputInit-tl-eq-f-Exec-Stream-Acc-Output:*

$tl \ (f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs \ c) =$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \ c$
 <proof>

lemma *f-Exec-Stream-Previous-f-Exec-Stream-Acc-Output-Init:*

$f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs \ c \ ! \ n =$
 $(f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \ c)^{\leftarrow n} \text{ output-fun } c \ n$
 <proof>

lemma *f-Exec-Stream-Acc-Output-Init-eq-output-channel:*

$\llbracket output\text{-fun } c = \varepsilon;$
 $f\text{-Streams-Connected}$
 $(f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \ c)$
 $channel \rrbracket \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } xs \ c = channel$
 <proof>

lemma *i-Exec-Stream-Acc-Output-Init-eq-i-Exec-Stream-Acc-Output-Cons:*

$i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun } input \ c =$
 $[output\text{-fun } c] \ \frown \ i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } input \ c$
 <proof>

lemma *i-Exec-Stream-Acc-Output-Init-eq-i-Exec-Stream-Acc-Output-Cons-output:*

$output\text{-fun } c = \varepsilon \implies$

$i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun input } c =$
 $[\varepsilon] \frown i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Previous-}i\text{-Exec-Stream-Acc-Output-Init}$:

$i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun input } c \ n =$
 $(i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c)^{\leftarrow \text{output-fun } c \ n}$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Acc-Output-Init-eq-output-channel}$:

$\llbracket \text{output-fun } c = \varepsilon;$
 $i\text{-Streams-Connected}$
 $(i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c)$
 $\text{channel} \rrbracket \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output-Init } k \text{ output-fun trans-fun input } c = \text{channel}$
 $\langle \text{proof} \rangle$

3.2.6 Rules for proving execution equivalence

A required precondition is that the *equiv-states* relation, which indicates whether the local states of $c1$ and $c2$ are equivalent with respect to observable behaviour, is preserved also after executing an input stream, because the *equiv-states* relation should deliver valid results not only at the time point 0 but at every time point.

lemma $f\text{-Equiv-Exec-Stream-expand-shrink-equiv-state-set}[\text{rule-format}]$:

$\bigwedge c1 \ c2 \ i. \llbracket$
 $0 < k1; 0 < k2;$
 $\text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
 $\forall \text{input0}. \text{set input0} \subseteq A \longrightarrow (\forall m \in A.$
 $\text{Equiv-Exec } m \text{ equiv-states}$
 $\text{localState1 localState2 input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 } k1 \ k2$
 $(f\text{-Exec-Comp trans-fun1 } (\text{map input-fun1 input0} \odot_f k1) \ c1)$
 $(f\text{-Exec-Comp trans-fun2 } (\text{map input-fun2 input0} \odot_f k2) \ c2));$
 $\text{— equiv-states relation implies equivalent executions}$
 $\text{— not only at the beginning but also after processing an input}$
 $\text{set input} \subseteq A; i < \text{length input} \rrbracket \implies$
 equiv-states
 $(\text{localState1 } ((f\text{-Exec-Comp-Stream trans-fun1 } (\text{map input-fun1 input} \odot_f k1)$
 $c1) \div_f k1 \ ! \ i))$
 $(\text{localState2 } ((f\text{-Exec-Comp-Stream trans-fun2 } (\text{map input-fun2 input} \odot_f k2)$
 $c2) \div_f k2 \ ! \ i))$
 $\langle \text{proof} \rangle$

corollary $f\text{-Equiv-Exec-Stream-expand-shrink-equiv-state}$:

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
 $\bigwedge \text{input0 } m. \text{Equiv-Exec } m$

$equiv\text{-}states\ localState1\ localState2\ input\text{-}fun1\ input\text{-}fun2\ output\text{-}fun1\ out\text{-}put\text{-}fun2$
 $trans\text{-}fun1\ trans\text{-}fun2\ k1\ k2$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun1\ (\map\ input\text{-}fun1\ input0\ \odot_f\ k1)\ c1)$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun2\ (\map\ input\text{-}fun2\ input0\ \odot_f\ k2)\ c2);$
 $i < length\ input\] \implies$
 $equiv\text{-}states$
 $(localState1\ ((f\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun1\ (\map\ input\text{-}fun1\ input\ \odot_f\ k1)$
 $c1) \div_{\#} k1\ !\ i))$
 $(localState2\ ((f\text{-}Exec\text{-}Comp\text{-}Stream\ trans\text{-}fun2\ (\map\ input\text{-}fun2\ input\ \odot_f\ k2)$
 $c2) \div_{\#} k2\ !\ i))$
 $\langle proof \rangle$

lemma $f\text{-}Equiv\text{-}Exec\text{-}expand\text{-}shrink\text{-}equiv\text{-}state\text{-}set$:

$\llbracket 0 < k1; 0 < k2; equiv\text{-}states\ (localState1\ c1)\ (localState2\ c2);$
 $\bigwedge input0\ m. \llbracket set\ input0 \subseteq A; m \in A \rrbracket \implies$
 $Equiv\text{-}Exec$
 $m\ equiv\text{-}states\ localState1\ localState2$
 $input\text{-}fun1\ input\text{-}fun2\ output\text{-}fun1\ output\text{-}fun2\ trans\text{-}fun1\ trans\text{-}fun2\ k1\ k2$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun1\ (\map\ input\text{-}fun1\ input0\ \odot_f\ k1)\ c1)$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun2\ (\map\ input\text{-}fun2\ input0\ \odot_f\ k2)\ c2);$
 $set\ input \subseteq A\] \implies$
 $equiv\text{-}states$
 $(localState1\ (f\text{-}Exec\text{-}Comp\ trans\text{-}fun1\ (\map\ input\text{-}fun1\ input\ \odot_f\ k1)\ c1))$
 $(localState2\ (f\text{-}Exec\text{-}Comp\ trans\text{-}fun2\ (\map\ input\text{-}fun2\ input\ \odot_f\ k2)\ c2))$
 $\langle proof \rangle$

lemma $f\text{-}Equiv\text{-}Exec\text{-}expand\text{-}shrink\text{-}equiv\text{-}state$:

$\llbracket 0 < k1; 0 < k2; equiv\text{-}states\ (localState1\ c1)\ (localState2\ c2);$
 $\bigwedge input0\ m.$
 $Equiv\text{-}Exec$
 $m\ equiv\text{-}states\ localState1\ localState2$
 $input\text{-}fun1\ input\text{-}fun2\ output\text{-}fun1\ output\text{-}fun2\ trans\text{-}fun1\ trans\text{-}fun2\ k1\ k2$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun1\ (\map\ input\text{-}fun1\ input0\ \odot_f\ k1)\ c1)$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun2\ (\map\ input\text{-}fun2\ input0\ \odot_f\ k2)\ c2)\] \implies$
 $equiv\text{-}states$
 $(localState1\ (f\text{-}Exec\text{-}Comp\ trans\text{-}fun1\ (\map\ input\text{-}fun1\ input\ \odot_f\ k1)\ c1))$
 $(localState2\ (f\text{-}Exec\text{-}Comp\ trans\text{-}fun2\ (\map\ input\text{-}fun2\ input\ \odot_f\ k2)\ c2))$
 $\langle proof \rangle$

lemma $i\text{-}Equiv\text{-}Exec\text{-}Stream\text{-}expand\text{-}shrink\text{-}equiv\text{-}state\text{-}set[rule\text{-}format]$:

$\llbracket 0 < k1; 0 < k2; equiv\text{-}states\ (localState1\ c1)\ (localState2\ c2);$
 $\bigwedge input0\ m. \llbracket set\ input0 \subseteq A; m \in A \rrbracket \implies$
 $Equiv\text{-}Exec$
 $m\ equiv\text{-}states\ localState1\ localState2$
 $input\text{-}fun1\ input\text{-}fun2\ output\text{-}fun1\ output\text{-}fun2\ trans\text{-}fun1\ trans\text{-}fun2\ k1\ k2$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun1\ (\map\ input\text{-}fun1\ input0\ \odot_f\ k1)\ c1)$
 $(f\text{-}Exec\text{-}Comp\ trans\text{-}fun2\ (\map\ input\text{-}fun2\ input0\ \odot_f\ k2)\ c2);$
 $range\ input \subseteq A\] \implies$

equiv-states
 (localState1 ((i-Exec-Comp-Stream trans-fun1 ((input-fun1 $\circ$ input) $\odot_i$ k1) c1
 $\div_{il}$ k1) i))
 (localState2 ((i-Exec-Comp-Stream trans-fun2 ((input-fun2 $\circ$ input) $\odot_i$ k2) c2
 $\div_{il}$ k2) i))
 <proof>

lemma *i-Equiv-Exec-Stream-expand-shrink-equiv-state:*

$\llbracket 0 < k1; 0 < k2; \text{equiv-states (localState1 c1) (localState2 c2);}$
 $\bigwedge \text{input0 } m.$
Equiv-Exec
 $m \text{ equiv-states localState1 localState2}$
 $\text{input-fun1 input-fun2 output-fun1 output-fun2 trans-fun1 trans-fun2 } k1 \ k2$
 $(f\text{-Exec-Comp trans-fun1 (map input-fun1 input0 } \odot_f \ k1) \ c1)$
 $(f\text{-Exec-Comp trans-fun2 (map input-fun2 input0 } \odot_f \ k2) \ c2) \rrbracket \implies$
equiv-states
 (localState1 ((i-Exec-Comp-Stream trans-fun1 ((input-fun1 $\circ$ input) $\odot_i$ k1) c1
 $\div_{il}$ k1) i))
 (localState2 ((i-Exec-Comp-Stream trans-fun2 ((input-fun2 $\circ$ input) $\odot_i$ k2) c2
 $\div_{il}$ k2) i))
 <proof>

lemma *f-Equiv-Exec-Stream-expand-shrink-output-set-eq:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states (localState1 c1) (localState2 c2);}$
 $\bigwedge \text{input0 } m. \llbracket \text{set input0} \subseteq A; m \in A \rrbracket \implies$
Equiv-Exec
 $m \text{ equiv-states localState1 localState2}$
 $\text{input-fun1 input-fun2 output-fun1 output-fun2 trans-fun1 trans-fun2 } k1 \ k2$
 $(f\text{-Exec-Comp trans-fun1 (map input-fun1 input0 } \odot_f \ k1) \ c1)$
 $(f\text{-Exec-Comp trans-fun2 (map input-fun2 input0 } \odot_f \ k2) \ c2);$
 $\text{set input} \subseteq A \rrbracket \implies$
 $(\text{map output-fun1 (}$
 $\text{f-Exec-Comp-Stream trans-fun1 (map input-fun1 input } \odot_f \ k1) \ c1)) \div_f \ k1 =$
 $(\text{map output-fun2 (}$
 $\text{f-Exec-Comp-Stream trans-fun2 (map input-fun2 input } \odot_f \ k2) \ c2)) \div_f \ k2$
 <proof>

lemma *f-Equiv-Exec-Stream-expand-shrink-output-eq:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states (localState1 c1) (localState2 c2);}$
 $\bigwedge \text{input0 } m.$
Equiv-Exec
 $m \text{ equiv-states localState1 localState2}$
 $\text{input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 } k1 \ k2$
 $(f\text{-Exec-Comp trans-fun1 (map input-fun1 input0 } \odot_f \ k1) \ c1)$
 $(f\text{-Exec-Comp trans-fun2 (map input-fun2 input0 } \odot_f \ k2) \ c2) \rrbracket \implies$
 $(\text{map output-fun1 (}$

$f\text{-Exec-Comp-Stream trans-fun1 (map input-fun1 input } \odot_f k1) c1) \div_f k1 =$
 $(\text{map output-fun2 (}$
 $f\text{-Exec-Comp-Stream trans-fun2 (map input-fun2 input } \odot_f k2) c2) \div_f k2$
 $\langle \text{proof} \rangle$

lemma *i-Equiv-Exec-Stream-expand-shrink-output-set-eq:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states (localState1 c1) (localState2 c2);}$
 $\bigwedge \text{input0 m. } \llbracket \text{set input0} \subseteq A; m \in A \rrbracket \implies$
 Equiv-Exec
 $m \text{ equiv-states localState1 localState2}$
 $\text{input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 k1 k2}$
 $(f\text{-Exec-Comp trans-fun1 (map input-fun1 input0 } \odot_f k1) c1)$
 $(f\text{-Exec-Comp trans-fun2 (map input-fun2 input0 } \odot_f k2) c2);$
 $\text{range input} \subseteq A \rrbracket \implies$
 $(\text{output-fun1 } \circ$
 $i\text{-Exec-Comp-Stream trans-fun1 ((input-fun1 } \circ \text{input}) \odot_i k1) c1) \div_i k1 =$
 $(\text{output-fun2 } \circ$
 $i\text{-Exec-Comp-Stream trans-fun2 ((input-fun2 } \circ \text{input}) \odot_i k2) c2) \div_i k2$
 $\langle \text{proof} \rangle$

lemma *i-Equiv-Exec-Stream-expand-shrink-output-eq:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states (localState1 c1) (localState2 c2);}$
 $\bigwedge \text{input0 m.}$
 Equiv-Exec
 $m \text{ equiv-states localState1 localState2}$
 $\text{input-fun1 input-fun2 output-fun1 output-fun2 trans-fun1 trans-fun2 k1 k2}$
 $(f\text{-Exec-Comp trans-fun1 (map input-fun1 input0 } \odot_f k1) c1)$
 $(f\text{-Exec-Comp trans-fun2 (map input-fun2 input0 } \odot_f k2) c2) \rrbracket \implies$
 $(\text{output-fun1 } \circ$
 $i\text{-Exec-Comp-Stream trans-fun1 ((input-fun1 } \circ \text{input}) \odot_i k1) c1) \div_i k1 =$
 $(\text{output-fun2 } \circ$
 $i\text{-Exec-Comp-Stream trans-fun2 ((input-fun2 } \circ \text{input}) \odot_i k2) c2) \div_i k2$
 $\langle \text{proof} \rangle$

lemma *f-Equiv-Exec-Stream-Acc-LocalState-set:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states (localState1 c1) (localState2 c2);}$
 $\text{Equiv-Exec-stable-set } A$
 $\text{equiv-states localState1 localState2}$
 $\text{input-fun1 input-fun2 output-fun1 output-fun2}$
 $\text{trans-fun1 trans-fun2 k1 k2 c1 c2;}$
 $\text{— equiv-states relation implies equivalent executions}$
 $\text{— not only at the beginning but also after processing an input}$
 $\text{set input} \subseteq A;$
 $i < \text{length input} \rrbracket \implies$

equiv-states
 (*f-Exec-Comp-Stream-Acc-LocalState* *k1 localState1 trans-fun1 (map input-fun1 input) c1 ! i*)
 (*f-Exec-Comp-Stream-Acc-LocalState* *k2 localState2 trans-fun2 (map input-fun2 input) c2 ! i*)
 <proof>

lemma *f-Equiv-Exec-Stream-Acc-LocalState*:

[$0 < k1; 0 < k2;$
equiv-states (localState1 c1) (localState2 c2);
Equiv-Exec-stable
equiv-states localState1 localState2
input-fun1 input-fun2 output-fun1 output-fun2
trans-fun1 trans-fun2 k1 k2 c1 c2;
 — *equiv-states* relation implies equivalent executions
 — not only at the beginning but also after processing an input
i < length input] $\implies$
equiv-states
 (*f-Exec-Comp-Stream-Acc-LocalState* *k1 localState1 trans-fun1 (map input-fun1 input) c1 ! i*)
 (*f-Exec-Comp-Stream-Acc-LocalState* *k2 localState2 trans-fun2 (map input-fun2 input) c2 ! i*)
 <proof>

lemma *f-Equiv-Exec-Stream-Acc-Output-set-eq*:

[$0 < k1; 0 < k2;$
equiv-states (localState1 c1) (localState2 c2);
Equiv-Exec-stable-set A
equiv-states localState1 localState2
input-fun1 input-fun2 output-fun1 output-fun2 trans-fun1 trans-fun2 k1 k2 c1
c2;
set input $\subseteq A$] $\implies$
f-Exec-Comp-Stream-Acc-Output *k1 output-fun1 trans-fun1 (map input-fun1 input) c1* =
f-Exec-Comp-Stream-Acc-Output *k2 output-fun2 trans-fun2 (map input-fun2 input) c2*
 <proof>

lemma *f-Equiv-Exec-Stream-Acc-Output-eq*:

[$0 < k1; 0 < k2;$
equiv-states (localState1 c1) (localState2 c2);
Equiv-Exec-stable
equiv-states localState1 localState2
input-fun1 input-fun2 output-fun1 output-fun2 trans-fun1 trans-fun2 k1 k2 c1
c2] $\implies$
f-Exec-Comp-Stream-Acc-Output *k1 output-fun1 trans-fun1 (map input-fun1 input) c1* =
f-Exec-Comp-Stream-Acc-Output *k2 output-fun2 trans-fun2 (map input-fun2 input) c2*

$\langle \text{proof} \rangle$

lemma *i-Equiv-Exec-Stream-Acc-LocalState-set:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
 $\text{Equiv-Exec-stable-set } A$
 $\text{equiv-states } \text{localState1 } \text{localState2 } \text{input-fun1 } \text{input-fun2 } \text{output-fun1 } \text{output-fun2}$
 $\text{trans-fun1 } \text{trans-fun2 } k1 \ k2 \ c1 \ c2;$
 $\text{range input} \subseteq A \rrbracket \implies$
 equiv-states
 $(i\text{-Exec-Comp-Stream-Acc-LocalState } k1 \ \text{localState1 } \text{trans-fun1 } (\text{input-fun1} \circ \text{input}) \ c1 \ i)$
 $(i\text{-Exec-Comp-Stream-Acc-LocalState } k2 \ \text{localState2 } \text{trans-fun2 } (\text{input-fun2} \circ \text{input}) \ c2 \ i)$
 $\langle \text{proof} \rangle$

lemma *i-Equiv-Exec-Stream-Acc-LocalState:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
 Equiv-Exec-stable
 $\text{equiv-states } \text{localState1 } \text{localState2}$
 $\text{input-fun1 } \text{input-fun2 } \text{output-fun1 } \text{output-fun2}$
 $\text{trans-fun1 } \text{trans-fun2 } k1 \ k2 \ c1 \ c2 \rrbracket \implies$
 equiv-states
 $(i\text{-Exec-Comp-Stream-Acc-LocalState } k1 \ \text{localState1 } \text{trans-fun1 } (\text{input-fun1} \circ \text{input}) \ c1 \ i)$
 $(i\text{-Exec-Comp-Stream-Acc-LocalState } k2 \ \text{localState2 } \text{trans-fun2 } (\text{input-fun2} \circ \text{input}) \ c2 \ i)$
 $\langle \text{proof} \rangle$

lemma *i-Equiv-Exec-Stream-Acc-Output-set-eq:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$
 $\text{Equiv-Exec-stable-set } A$
 $\text{equiv-states } \text{localState1 } \text{localState2}$
 $\text{input-fun1 } \text{input-fun2 } \text{output-fun1 } \text{output-fun2 } \text{trans-fun1 } \text{trans-fun2 } k1 \ k2 \ c1$
 $c2;$
 $\text{range input} \subseteq A \rrbracket \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k1 \ \text{output-fun1 } \text{trans-fun1 } (\text{input-fun1} \circ \text{input})$
 $c1 =$
 $i\text{-Exec-Comp-Stream-Acc-Output } k2 \ \text{output-fun2 } \text{trans-fun2 } (\text{input-fun2} \circ \text{input})$
 $c2$
 $\langle \text{proof} \rangle$

lemma *i-Equiv-Exec-Stream-Acc-Output-eq:*

$\llbracket 0 < k1; 0 < k2;$
 $\text{equiv-states } (\text{localState1 } c1) (\text{localState2 } c2);$

Equiv-Exec-stable
equiv-states localState1 localState2
input-fun1 input-fun2 output-fun1 output-fun2 trans-fun1 trans-fun2 k1 k2 c1
c2 $\mathbb{I} \implies$
i-Exec-Comp-Stream-Acc-Output k1 output-fun1 trans-fun1 (input-fun1 $\circ$ input)
c1 =
i-Exec-Comp-Stream-Acc-Output k2 output-fun2 trans-fun2 (input-fun2 $\circ$ input)
c2
 $\langle \text{proof} \rangle$

3.2.7 Idle states and accelerated execution

lemma *f-Exec-Stream-Acc-LocalState--State-Idle-nth*[rule-format]:

$\bigwedge^c i.$
 $\mathbb{I} \ 0 < l; l \leq k; \text{Exec-Equal-State } \text{localState } \text{trans-fun};$
 $\forall n \leq i. \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun} \ ($
 $\text{f-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } xs \ c \ ! \ n);$
 $i < \text{length } xs \mathbb{I} \implies$
 $\text{f-Exec-Comp-Stream-Acc-LocalState } k \text{ localState } \text{trans-fun } xs \ c \ ! \ i =$
 $\text{f-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } xs \ c \ ! \ i$
 $\langle \text{proof} \rangle$

corollary *f-Exec-Stream-Acc-LocalState--State-Idle-eq*[rule-format]:

$\mathbb{I} \ 0 < l; l \leq k; \text{Exec-Equal-State } \text{localState } \text{trans-fun};$
 $\forall n < \text{length } xs. \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun} \ ($
 $\text{f-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } xs \ c \ ! \ n) \mathbb{I} \implies$
 $\text{f-Exec-Comp-Stream-Acc-LocalState } k \text{ localState } \text{trans-fun } xs \ c =$
 $\text{f-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } xs \ c$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-Acc-LocalState--State-Idle-nth*[rule-format]:

$\mathbb{I} \ 0 < l; l \leq k; \text{Exec-Equal-State } \text{localState } \text{trans-fun};$
 $\forall n \leq i. \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun} \ ($
 $\text{i-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } \text{input } c \ n) \mathbb{I} \implies$
 $\text{i-Exec-Comp-Stream-Acc-LocalState } k \text{ localState } \text{trans-fun } \text{input } c \ i =$
 $\text{i-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } \text{input } c \ i$
 $\langle \text{proof} \rangle$

corollary *i-Exec-Stream-Acc-LocalState--State-Idle-eq*[rule-format]:

$\mathbb{I} \ 0 < l; l \leq k; \text{Exec-Equal-State } \text{localState } \text{trans-fun};$
 $\forall n. \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun} \ ($
 $\text{i-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } \text{input } c \ n) \mathbb{I} \implies$
 $\text{i-Exec-Comp-Stream-Acc-LocalState } k \text{ localState } \text{trans-fun } \text{input } c =$
 $\text{i-Exec-Comp-Stream-Acc-LocalState } l \text{ localState } \text{trans-fun } \text{input } c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-Acc-Output--State-Idle-nth*[rule-format]:

$\mathbb{I} \ 0 < l; l \leq k; \text{Exec-Equal-State } \text{localState } \text{trans-fun};$
 $\forall n \leq i. \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun} \ ($

$f\text{-Exec-Comp-Stream-Acc-LocalState } l \text{ localState trans-fun } xs \text{ } c ! n);$
 $i < \text{length } xs \parallel \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \text{ } c ! i =$
 $f\text{-Exec-Comp-Stream-Acc-Output } l \text{ output-fun trans-fun } xs \text{ } c ! i$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Acc-Output--State-Idle-eq}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k; \text{Exec-Equal-State localState trans-fun};$
 $\forall n < \text{length } xs. \text{State-Idle localState output-fun trans-fun } ($
 $f\text{-Exec-Comp-Stream-Acc-LocalState } l \text{ localState trans-fun } xs \text{ } c ! n) \parallel \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \text{ } c =$
 $f\text{-Exec-Comp-Stream-Acc-Output } l \text{ output-fun trans-fun } xs \text{ } c$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Acc-Output--State-Idle-nth}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k; \text{Exec-Equal-State localState trans-fun};$
 $\forall n \leq i. \text{State-Idle localState output-fun trans-fun } ($
 $i\text{-Exec-Comp-Stream-Acc-LocalState } l \text{ localState trans-fun input } c \text{ } n) \parallel \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } i =$
 $i\text{-Exec-Comp-Stream-Acc-Output } l \text{ output-fun trans-fun input } c \text{ } i$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Acc-Output--State-Idle-eq}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k; \text{Exec-Equal-State localState trans-fun};$
 $\forall n. \text{State-Idle localState output-fun trans-fun } ($
 $i\text{-Exec-Comp-Stream-Acc-LocalState } l \text{ localState trans-fun input } c \text{ } n) \parallel \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c =$
 $i\text{-Exec-Comp-Stream-Acc-Output } l \text{ output-fun trans-fun input } c$
 $\langle \text{proof} \rangle$

When a certain number l of steps suffices to reach an idle state from any other idle state, than for any acceleration factor $l \leq k$ the accelerated processing of every input message will be finished in an idle state.

lemma $f\text{-Exec-Stream-Acc-LocalState--State-Idle-all}[\text{rule-format}]$:
 $\bigwedge c \text{ } xs. \parallel 0 < l; l \leq k;$
 $\text{State-Idle localState output-fun trans-fun } (\text{localState } c);$
 $\forall c \text{ } m. \text{State-Idle localState output-fun trans-fun } (\text{localState } c) \longrightarrow$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\text{localState } (f\text{-Exec-Comp trans-fun } (m \# \varepsilon^l - \text{Suc } 0) \text{ } c));$
 $i < \text{length } xs \parallel \implies$
 $\text{State-Idle localState output-fun trans-fun } ($
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } xs \text{ } c ! i)$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Acc-LocalState--State-Idle-all}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k;$
 $\text{State-Idle localState output-fun trans-fun } (\text{localState } c);$
 $\forall c \text{ } m. \text{State-Idle localState output-fun trans-fun } (\text{localState } c) \longrightarrow$
 $\text{State-Idle localState output-fun trans-fun } ($

$\text{localState } (f\text{-Exec-Comp trans-fun } (m \# \varepsilon^l - \text{Suc } 0) \ c)) \parallel \implies$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\text{ } i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } xs \ c \ i)$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Acc-Output--State-Idle-all-imp-eq}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k; \text{Exec-Equal-State localState trans-fun};$
 $\text{State-Idle localState output-fun trans-fun } (localState \ c);$
 $\forall c \ m. \text{State-Idle localState output-fun trans-fun } (localState \ c) \longrightarrow$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\text{ } localState \ (f\text{-Exec-Comp trans-fun } (m \# \varepsilon^l - \text{Suc } 0) \ c)) \parallel \implies$
 $f\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun } xs \ c =$
 $f\text{-Exec-Comp-Stream-Acc-Output } l \text{ output-fun trans-fun } xs \ c$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Acc-Output--State-Idle-all-imp-eq}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k; \text{Exec-Equal-State localState trans-fun};$
 $\text{State-Idle localState output-fun trans-fun } (localState \ c);$
 $\forall c \ m. \text{State-Idle localState output-fun trans-fun } (localState \ c) \longrightarrow$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\text{ } localState \ (f\text{-Exec-Comp trans-fun } (m \# \varepsilon^l - \text{Suc } 0) \ c)) \parallel \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c =$
 $i\text{-Exec-Comp-Stream-Acc-Output } l \text{ output-fun trans-fun input } c$
 $\langle \text{proof} \rangle$

lemma $f\text{-Exec-Stream-Acc-LocalState--State-Idle-all-imp-eq}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k; \text{Exec-Equal-State localState trans-fun};$
 $\text{State-Idle localState output-fun trans-fun } (localState \ c);$
 $\forall c \ m. \text{State-Idle localState output-fun trans-fun } (localState \ c) \longrightarrow$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\text{ } localState \ (f\text{-Exec-Comp trans-fun } (m \# \varepsilon^l - \text{Suc } 0) \ c)) \parallel \implies$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } xs \ c =$
 $f\text{-Exec-Comp-Stream-Acc-LocalState } l \text{ localState trans-fun } xs \ c$
 $\langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Acc-LocalState--State-Idle-all-imp-eq}[\text{rule-format}]$:
 $\parallel 0 < l; l \leq k; \text{Exec-Equal-State localState trans-fun};$
 $\text{State-Idle localState output-fun trans-fun } (localState \ c);$
 $\forall c \ m. \text{State-Idle localState output-fun trans-fun } (localState \ c) \longrightarrow$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\text{ } localState \ (f\text{-Exec-Comp trans-fun } (m \# \varepsilon^l - \text{Suc } 0) \ c)) \parallel \implies$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun } xs \ c =$
 $i\text{-Exec-Comp-Stream-Acc-LocalState } l \text{ localState trans-fun } xs \ c$
 $\langle \text{proof} \rangle$

Converting inputs

lemma $f\text{-Exec-input-map}$: $\bigwedge c.$
 $f\text{-Exec-Comp trans-fun } (map \ f \ xs) \ c = f\text{-Exec-Comp } (trans\text{-fun } \circ \ f) \ xs \ c$
 $\langle \text{proof} \rangle$

lemma *f-Exec-Stream-input-map*:
 $f\text{-Exec-Comp-Stream } \text{trans-fun } (\text{map } f \text{ } xs) \text{ } c =$
 $f\text{-Exec-Comp-Stream } (\text{trans-fun } \circ f) \text{ } xs \text{ } c$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Stream-input-map*:
 $i\text{-Exec-Comp-Stream } \text{trans-fun } (f \circ \text{input}) \text{ } c =$
 $i\text{-Exec-Comp-Stream } (\text{trans-fun } \circ f) \text{ } \text{input } c$
 $\langle \text{proof} \rangle$

end

4 AutoFocus message streams and temporal logic on intervals

theory *IL-AF-Stream*

imports *Main Nat-Interval-Logic.IL-TemporalOperators AF-Stream*
begin

4.1 Stream views – joining streams and intervals

4.1.1 Basic definitions

primrec *f-join-aux* :: 'a list $\Rightarrow$ nat $\Rightarrow$ iT $\Rightarrow$ 'a list

where

$f\text{-join-aux } [] \text{ } n \text{ } I = []$
 $| f\text{-join-aux } (x \# xs) \text{ } n \text{ } I =$
 $(\text{if } n \in I \text{ then } [x] \text{ else } []) @ f\text{-join-aux } xs \text{ } (\text{Suc } n) \text{ } I$

The functions *f-join* and *i-join* deliver views of finite and infinite streams through intervals (more exactly: arbitrary natural sets). A stream view contains only the elements of the original stream at positions, which are contained in the interval. For instance, $f\text{-join } [0,10,20,30,40] \{1,4\} = [10,40]$

definition *f-join* :: 'a list $\Rightarrow$ iT $\Rightarrow$ 'a list (**infixl** $\langle \bowtie_f \rangle$ 100)
where $xs \bowtie_f I \equiv f\text{-join-aux } xs \text{ } 0 \text{ } I$

definition *i-join* :: 'a ilist $\Rightarrow$ iT $\Rightarrow$ 'a ilist (**infixl** $\langle \bowtie_i \rangle$ 100)
where $f \bowtie_i I \equiv \lambda n. (f \text{ } (I \rightarrow n))$

notation

f-join (**infixl** $\langle \bowtie \rangle$ 100) **and**
i-join (**infixl** $\langle \bowtie \rangle$ 100)

The function *i-f-join* can be used for the case, when an infinite stream is joined with a finite interval. The function *i-join* would then deliver an infinite stream, whose elements after position *card I* are equal to initial stream's element at position *Max I*. The function *i-f-join* in contrast cuts the resulting stream at this position and returns a finite stream.

definition $i\text{-}f\text{-}join :: 'a\ i\text{list} \Rightarrow iT \Rightarrow 'a\ list$ (**infixl** $\bowtie_{i-f}$ 100)

where $f \bowtie_{i-f} I \equiv f \Downarrow Suc (Max I) \bowtie_f I$

notation

$i\text{-}f\text{-}join$ (**infixl** $\bowtie$, 100)

The function $i\text{-}f\text{-}join$ should be used only for finite sets in order to deliver well-defined results. The function $i\text{-}join$ should be used for infinite sets, because joining an infinite stream s and a finite set I using $i\text{-}join$ would deliver an infinite stream, ending with an infinite sequence of elements equal to $s (Max I)$.

4.1.2 Basic results

lemma $f\text{-}join\text{-}aux\text{-}length$:

$\bigwedge n. length (f\text{-}join\text{-}aux\ xs\ n\ I) = card (I \cap \{n..<n + length\ xs\})$
 $\langle proof \rangle$

lemma $f\text{-}join\text{-}aux\text{-}nth[rule\text{-}format]$:

$\forall n\ i. i < card (I \cap \{n..<n + length\ xs\}) \longrightarrow$
 $(f\text{-}join\text{-}aux\ xs\ n\ I) ! i = xs ! ((I \cap \{n..<n + length\ xs\}) \rightarrow i) - n$
 $\langle proof \rangle$

Joining finite streams and intervals

lemma $f\text{-}join\text{-}length$: $length (xs \bowtie_f I) = card (I \downarrow < length\ xs)$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}nth$: $n < length (xs \bowtie_f I) \implies (xs \bowtie_f I) ! n = xs ! (I \rightarrow n)$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}nth2$: $n < card (I \downarrow < length\ xs) \implies (xs \bowtie_f I) ! n = xs ! (I \rightarrow n)$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}empty$: $xs \bowtie_f \{\} = []$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}Nil$: $[] \bowtie_f I = []$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}Nil\text{-}conv$: $(xs \bowtie_f I = []) = (I \downarrow < length\ xs = \{\})$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}Nil\text{-}conv'$: $(xs \bowtie_f I = []) = (\forall i < length\ xs. i \notin I)$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}all\text{-}conv$: $(xs \bowtie_f I = xs) = (\{..<length\ xs\} \subseteq I)$

$\langle proof \rangle$

lemma $f\text{-}join\text{-}all$: $\{..<length\ xs\} \subseteq I \implies xs \bowtie_f I = xs$

$\langle proof \rangle$

corollary *f-join-UNIV*: $xs \bowtie_f UNIV = xs$

$\langle proof \rangle$

lemma *f-join-union*:

$\llbracket \text{finite } A; \text{Max } A < iMin B \rrbracket \implies xs \bowtie_f (A \cup B) = xs \bowtie_f A @ (xs \bowtie_f B)$

$\langle proof \rangle$

lemma *f-join-singleton-if*:

$xs \bowtie_f \{n\} = (\text{if } n < \text{length } xs \text{ then } [xs ! n] \text{ else } [])$

$\langle proof \rangle$

lemma *f-join-insert*:

$n < \text{length } xs \implies$

$xs \bowtie_f \text{insert } n I = xs \bowtie_f (I \downarrow < n) @ (xs ! n) \# (xs \bowtie_f (I \downarrow > n))$

$\langle proof \rangle$

lemma *f-join-snoc*:

$(xs @ [x]) \bowtie_f I =$

$xs \bowtie_f I @ (\text{if } \text{length } xs \in I \text{ then } [x] \text{ else } [])$

$\langle proof \rangle$

lemma *f-join-append*:

$(xs @ ys) \bowtie_f I = xs \bowtie_f I @ ys \bowtie_f (I \oplus - (\text{length } xs))$

$\langle proof \rangle$

lemma *take-f-join-eq1*:

$n < \text{card } (I \downarrow < \text{length } xs) \implies$

$(xs \bowtie_f I) \downarrow n = xs \bowtie_f (I \downarrow < (I \rightarrow n))$

$\langle proof \rangle$

lemma *take-f-join-eq2*:

$\text{card } (I \downarrow < \text{length } xs) \leq n \implies (xs \bowtie_f I) \downarrow n = xs \bowtie_f I$

$\langle proof \rangle$

lemma *take-f-join-if*:

$(xs \bowtie_f I) \downarrow n =$

$(\text{if } n < \text{card } (I \downarrow < \text{length } xs) \text{ then } xs \bowtie_f (I \downarrow < (I \rightarrow n)) \text{ else } xs \bowtie_f I)$

$\langle proof \rangle$

lemma *drop-f-join-eq1*:

$n < \text{card } (I \downarrow < \text{length } xs) \implies$

$(xs \bowtie_f I) \uparrow n = xs \bowtie_f (I \downarrow \geq (I \rightarrow n))$

$\langle proof \rangle$

lemma *drop-f-join-eq2*:

$\text{card } (I \downarrow < \text{length } xs) \leq n \implies (xs \bowtie_f I) \uparrow n = []$

$\langle proof \rangle$

lemma *drop-f-join-if*:

$(xs \bowtie_f I) \uparrow n =$
 $(\text{if } n < \text{card } (I \downarrow < \text{length } xs) \text{ then } xs \bowtie_f (I \downarrow \geq (I \rightarrow n)) \text{ else } [])$
 $\langle \text{proof} \rangle$

lemma *f-join-take*: $xs \downarrow n \bowtie_f I = xs \bowtie_f (I \downarrow < n)$

$\langle \text{proof} \rangle$

lemma *f-join-drop*: $xs \uparrow n \bowtie_f I = xs \bowtie_f (I \oplus n)$

$\langle \text{proof} \rangle$

lemma *cut-less-eq-imp-f-join-eq*:

$A \downarrow < \text{length } xs = B \downarrow < \text{length } xs \implies xs \bowtie_f A = xs \bowtie_f B$
 $\langle \text{proof} \rangle$

corollary *f-join-cut-less-eq*:

$\text{length } xs \leq t \implies xs \bowtie_f (I \downarrow < t) = xs \bowtie_f I$
 $\langle \text{proof} \rangle$

lemma *take-Suc-Max-eq-imp-f-join-eq*:

$\llbracket \text{finite } I; xs \downarrow \text{Suc } (\text{Max } I) = ys \downarrow \text{Suc } (\text{Max } I) \rrbracket \implies$
 $xs \bowtie_f I = ys \bowtie_f I$
 $\langle \text{proof} \rangle$

corollary *f-join-take-Suc-Max-eq*:

$\text{finite } I \implies xs \downarrow \text{Suc } (\text{Max } I) \bowtie_f I = xs \bowtie_f I$
 $\langle \text{proof} \rangle$

Joining infinite streams and infinite intervals

lemma *i-join-nth*: $(f \bowtie_i I) n = f (I \rightarrow n)$

$\langle \text{proof} \rangle$

lemma *i-join-UNIV*: $f \bowtie_i \text{UNIV} = f$

$\langle \text{proof} \rangle$

lemma *i-join-union*:

$\llbracket \text{finite } A; \text{Max } A < i\text{Min } B; B \neq \{\} \rrbracket \implies$
 $f \bowtie_i (A \cup B) = (f \downarrow \text{Suc } (\text{Max } A) \bowtie_f A) \smallfrown (f \bowtie_i B)$
 $\langle \text{proof} \rangle$

lemma *i-join-singleton*: $f \bowtie_i \{a\} = (\lambda n. f a)$

$\langle \text{proof} \rangle$

lemma *i-join-insert*:

$f \bowtie_i (\text{insert } n I) =$
 $(f \downarrow n) \bowtie_f (I \downarrow < n) \smallfrown [f n] \smallfrown ($
 $\text{if } I \downarrow > n = \{\} \text{ then } (\lambda x. f n) \text{ else } f \bowtie_i (I \downarrow > n))$
 $\langle \text{proof} \rangle$

lemma *i-join-i-append:*

$\text{infinite } I \implies (xs \smallfrown f) \bowtie_i I = (xs \bowtie_f I) \smallfrown (f \bowtie_i (I \oplus - \text{length } xs))$
 $\langle \text{proof} \rangle$

lemma *i-take-i-join:* $\text{infinite } I \implies f \bowtie_i I \Downarrow n = f \Downarrow (I \rightarrow n) \bowtie_f I$
 $\langle \text{proof} \rangle$

lemma *i-drop-i-join:* $I \neq \{\} \implies f \bowtie_i I \Uparrow n = f \bowtie_i (I \Downarrow \geq (I \rightarrow n))$
 $\langle \text{proof} \rangle$

lemma *i-join-i-take:* $f \Downarrow n \bowtie_f I = f \bowtie_i I \Downarrow \text{card } (I \Downarrow < n)$
 $\langle \text{proof} \rangle$

lemma *i-join-i-drop:* $I \neq \{\} \implies f \Uparrow n \bowtie_i I = f \bowtie_i (I \oplus n)$
 $\langle \text{proof} \rangle$

lemma *i-join-finite-nth-ge-card-eq-nth-Max:*

$\llbracket \text{finite } I; I \neq \{\}; \text{card } I \leq \text{Suc } n \rrbracket \implies (f \bowtie_i I) n = f (\text{Max } I)$
 $\langle \text{proof} \rangle$

lemma *i-join-finite-i-drop-card-eq-const-nth-Max:*

$\llbracket \text{finite } I; I \neq \{\} \rrbracket \implies (f \bowtie_i I) \Uparrow (\text{card } I) = (\lambda n. f (\text{Max } I))$
 $\langle \text{proof} \rangle$

lemma *i-join-finite-i-append-nth-Max-conv:*

$\llbracket \text{finite } I; I \neq \{\} \rrbracket \implies (f \bowtie_i I) = f \Downarrow \text{Suc } (\text{Max } I) \bowtie_f I \smallfrown (\lambda n. f (\text{Max } I))$
 $\langle \text{proof} \rangle$

Joining infinite streams and finite intervals

lemma *i-f-join-length:* $\text{finite } I \implies \text{length } (f \bowtie_{i-f} I) = \text{card } I$
 $\langle \text{proof} \rangle$

lemma *i-f-join-nth:* $n < \text{card } I \implies f \bowtie_{i-f} I ! n = f (I \rightarrow n)$
 $\langle \text{proof} \rangle$

lemma *i-f-join-empty:* $f \bowtie_{i-f} \{\} = []$
 $\langle \text{proof} \rangle$

lemma *i-f-join-eq-i-join-i-take:*

$\text{finite } I \implies f \bowtie_{i-f} I = f \bowtie_i I \Downarrow (\text{card } I)$
 $\langle \text{proof} \rangle$

lemma *i-f-join-union:*

$\llbracket \text{finite } A; \text{finite } B; \text{Max } A < i\text{Min } B \rrbracket \implies$
 $f \bowtie_{i-f} (A \cup B) = f \bowtie_{i-f} A @ f \bowtie_{i-f} B$
 $\langle \text{proof} \rangle$

lemma *i-f-join-singleton:* $f \bowtie_{i-f} \{n\} = [f n]$

$\langle \text{proof} \rangle$

lemma *i-f-join-insert*:

$\text{finite } I \implies$
 $f \bowtie_{i-f} \text{insert } n \ I = f \bowtie_{i-f} (I \downarrow < n) @ f \ n \ \# \ f \bowtie_{i-f} (I \downarrow > n)$
 $\langle \text{proof} \rangle$

lemma *take-i-f-join-eq1*:

$n < \text{card } I \implies f \bowtie_{i-f} I \downarrow n = f \bowtie_{i-f} (I \downarrow < (I \rightarrow n))$
 $\langle \text{proof} \rangle$

lemma *take-i-f-join-eq2*:

$\llbracket \text{finite } I; \text{card } I \leq n \rrbracket \implies f \bowtie_{i-f} I \downarrow n = f \bowtie_{i-f} I$
 $\langle \text{proof} \rangle$

lemma *take-i-f-join-if*:

$\text{finite } I \implies$
 $f \bowtie_{i-f} I \downarrow n = (\text{if } n < \text{card } I \text{ then } f \bowtie_{i-f} (I \downarrow < (I \rightarrow n)) \text{ else } f \bowtie_{i-f} I)$
 $\langle \text{proof} \rangle$

lemma *drop-i-f-join-eq1*:

$n < \text{card } I \implies f \bowtie_{i-f} I \uparrow n = f \bowtie_{i-f} (I \downarrow \geq (I \rightarrow n))$
 $\langle \text{proof} \rangle$

lemma *drop-i-f-join-eq2*:

$\llbracket \text{finite } I; \text{card } I \leq n \rrbracket \implies f \bowtie_{i-f} I \uparrow n = []$
 $\langle \text{proof} \rangle$

lemma *drop-i-f-join-if*:

$\text{finite } I \implies$
 $f \bowtie_{i-f} I \uparrow n = (\text{if } n < \text{card } I \text{ then } f \bowtie_{i-f} (I \downarrow \geq (I \rightarrow n)) \text{ else } [])$
 $\langle \text{proof} \rangle$

lemma *i-f-join-i-drop*:

$\text{finite } I \implies f \uparrow n \bowtie_{i-f} I = f \bowtie_{i-f} (I \oplus n)$
 $\langle \text{proof} \rangle$

lemma *i-take-Suc-Max-eq-imp-i-f-join-eq*:

$f \downarrow \text{Suc } (\text{Max } I) = g \downarrow \text{Suc } (\text{Max } I) \implies f \bowtie_{i-f} I = g \bowtie_{i-f} I$
 $\langle \text{proof} \rangle$

lemma *i-take-i-join-eq-i-f-join*:

$\text{infinite } I \implies f \bowtie_i I \downarrow n = f \bowtie_{i-f} (I \downarrow < (I \rightarrow n))$
 $\langle \text{proof} \rangle$

4.1.3 Results for intervals from *IL-Interval*

lemma *f-join-iFROM*: $xs \bowtie_f [n..] = xs \uparrow n$

$\langle \text{proof} \rangle$

lemma *i-join-iFROM*: $f \bowtie_i [n..] = f \uparrow n$
 $\langle \text{proof} \rangle$

lemma *f-join-iIN*: $xs \bowtie_f [n.., d] = xs \uparrow n \downarrow \text{Suc } d$
 $\langle \text{proof} \rangle$

lemma *i-f-join-iIN*: $f \bowtie_{i-f} [n.., d] = f \uparrow n \downarrow \text{Suc } d$
 $\langle \text{proof} \rangle$

lemma *f-join-iTILL*: $xs \bowtie_f [\dots n] = xs \downarrow (\text{Suc } n)$
 $\langle \text{proof} \rangle$

lemma *i-f-join-iTILL*: $f \bowtie_{i-f} [\dots n] = f \downarrow \text{Suc } n$
 $\langle \text{proof} \rangle$

lemma *f-join-f-expand-iT-Mult*:
 $0 < k \implies xs \odot_f k \bowtie_f (I \otimes k) = xs \bowtie_f I$
 $\langle \text{proof} \rangle$

lemma *i-join-i-expand-iT-Mult*:
 $\llbracket 0 < k; I \neq \{\} \rrbracket \implies f \odot_i k \bowtie_i (I \otimes k) = f \bowtie_i I$
 $\langle \text{proof} \rangle$

lemma *i-f-join-i-expand-iT-Mult*:
 $\llbracket 0 < k; \text{finite } I \rrbracket \implies f \odot_i k \bowtie_{i-f} (I \otimes k) = f \bowtie_{i-f} I$
 $\langle \text{proof} \rangle$

lemma *f-join-f-shrink-iT-Plus-iT-Div-mod*:
 $\llbracket 0 < k; \forall x \in I. x \bmod k = 0 \rrbracket \implies$
 $(xs \mapsto_f k) \bowtie_f (I \oplus (k - 1)) = xs \div_f k \bowtie_f (I \oslash k)$
 $\langle \text{proof} \rangle$

lemma *i-join-i-shrink-iT-Plus-iT-Div-mod*:
 $\llbracket 0 < k; I \neq \{\}; \forall x \in I. x \bmod k = 0 \rrbracket \implies$
 $(f \mapsto_i k) \bowtie_i (I \oplus (k - 1)) = f \div_i k \bowtie_i (I \oslash k)$
 $\langle \text{proof} \rangle$

lemma *i-f-join-i-shrink-iT-Plus-iT-Div-mod*:
 $\llbracket 0 < k; \text{finite } I; \forall x \in I. x \bmod k = 0 \rrbracket \implies$
 $(f \mapsto_i k) \bowtie_{i-f} (I \oplus (k - 1)) = f \div_i k \bowtie_{i-f} (I \oslash k)$
 $\langle \text{proof} \rangle$

corollary *f-join-f-shrink-iT-Plus-iT-Div-mod-subst*:
 $\llbracket 0 < k; \forall x \in I. x \bmod k = 0; A = I \oplus (k - 1); B = I \oslash k \rrbracket \implies$
 $(xs \mapsto_f k) \bowtie_f A = xs \div_f k \bowtie_f B$
 $\langle \text{proof} \rangle$

corollary *i-join-i-shrink-iT-Plus-iT-Div-mod-subst:*

$$\begin{aligned} & \llbracket 0 < k; I \neq \{\}; \forall x \in I. x \bmod k = 0; \\ & A = I \oplus (k - 1); B = I \odot k \rrbracket \implies \\ & (f \mapsto_i k) \bowtie_i A = f \div_i k \bowtie_i B \end{aligned}$$

<proof>

corollary *i-f-join-i-shrink-iT-Plus-iT-Div-mod-subst:*

$$\begin{aligned} & \llbracket 0 < k; \text{finite } I; \forall x \in I. x \bmod k = 0; \\ & A = I \oplus (k - 1); B = I \odot k \rrbracket \implies \\ & (f \mapsto_i k) \bowtie_{i-f} A = f \div_i k \bowtie_{i-f} B \end{aligned}$$

<proof>

lemma *f-join-f-shrink-iT-Div-mod:*

$$\begin{aligned} & \llbracket 0 < k; \forall x \in I. x \bmod k = k - 1 \rrbracket \implies \\ & (xs \mapsto_f k) \bowtie_f I = xs \div_f k \bowtie_f (I \odot k) \end{aligned}$$

<proof>

lemma *i-join-i-shrink-iT-Div-mod:*

$$\begin{aligned} & \llbracket 0 < k; I \neq \{\}; \forall x \in I. x \bmod k = k - 1 \rrbracket \implies \\ & (f \mapsto_i k) \bowtie_i I = f \div_i k \bowtie_i (I \odot k) \end{aligned}$$

<proof>

lemma *i-f-join-i-shrink-iT-Div-mod:*

$$\begin{aligned} & \llbracket 0 < k; \text{finite } I; \forall x \in I. x \bmod k = k - 1 \rrbracket \implies \\ & (f \mapsto_i k) \bowtie_{i-f} I = f \div_i k \bowtie_{i-f} (I \odot k) \end{aligned}$$

<proof>

lemma *f-join-f-expand-iMOD:*

$$0 < k \implies xs \odot_f k \bowtie_f [n * k, \text{mod } k] = xs \bowtie_f [n \dots]$$

<proof>

corollary *f-join-f-expand-iMOD-0:*

$$0 < k \implies xs \odot_f k \bowtie_f [0, \text{mod } k] = xs$$

<proof>

lemma *f-join-f-expand-iMODb:*

$$0 < k \implies xs \odot_f k \bowtie_f [n * k, \text{mod } k, d] = xs \bowtie_f [n \dots, d]$$

<proof>

corollary *f-join-f-expand-iMODb-0:*

$$0 < k \implies xs \odot_f k \bowtie_f [0, \text{mod } k, n] = xs \bowtie_f [\dots n]$$

<proof>

lemma *i-join-i-expand-iMOD:*

$$0 < k \implies f \odot_i k \bowtie_i [n * k, \text{mod } k] = f \bowtie_i [n \dots]$$

<proof>

corollary *i-join-i-expand-iMOD-0:*

$$0 < k \implies f \odot_i k \bowtie_i [0, \text{mod } k] = f$$

$\langle proof \rangle$

lemma *i-join-i-expand-iMODb*:

$$0 < k \implies f \odot_i k \bowtie_i [n * k, \text{mod } k, d] = f \bowtie_i [n \dots, d]$$

$\langle proof \rangle$

corollary *i-join-i-expand-iMODb-0*:

$$0 < k \implies f \odot_i k \bowtie_i [0, \text{mod } k, n] = f \bowtie_i [\dots n]$$

$\langle proof \rangle$

lemma *i-f-join-i-expand-iMODb*:

$$0 < k \implies f \odot_i k \bowtie_{i-f} [n * k, \text{mod } k, d] = f \bowtie_{i-f} [n \dots, d]$$

$\langle proof \rangle$

corollary *i-f-join-i-expand-iMODb-0*:

$$0 < k \implies f \odot_i k \bowtie_{i-f} [0, \text{mod } k, n] = f \bowtie_{i-f} [\dots n]$$

$\langle proof \rangle$

lemma *f-join-f-shrink-iMOD*:

$$0 < k \implies (xs \mapsto_f k) \bowtie_f [n * k + (k - 1), \text{mod } k] = xs \div_f k \bowtie_f [n \dots]$$

$\langle proof \rangle$

corollary *f-join-f-shrink-iMOD-0*:

$$0 < k \implies (xs \mapsto_f k) \bowtie_f [k - 1, \text{mod } k] = xs \div_f k$$

$\langle proof \rangle$

lemma *f-join-f-shrink-iMODb*:

$$0 < k \implies (xs \mapsto_f k) \bowtie_f [n * k + (k - 1), \text{mod } k, d] = xs \div_f k \bowtie_f [n \dots, d]$$

$\langle proof \rangle$

corollary *f-join-f-shrink-iMODb-0*:

$$0 < k \implies (xs \mapsto_f k) \bowtie_f [k - 1, \text{mod } k, n] = xs \div_f k \bowtie_f [\dots n]$$

$\langle proof \rangle$

lemma *i-join-i-shrink-iMOD*:

$$0 < k \implies (f \mapsto_i k) \bowtie_i [n * k + (k - 1), \text{mod } k] = f \div_i k \bowtie_i [n \dots]$$

$\langle proof \rangle$

corollary *i-join-i-shrink-iMOD-0*:

$$0 < k \implies (f \mapsto_i k) \bowtie_i [k - 1, \text{mod } k] = f \div_i k$$

$\langle proof \rangle$

lemma *i-f-join-i-shrink-iMODb*:

$$0 < k \implies (f \mapsto_i k) \bowtie_{i-f} [n * k + (k - 1), \text{mod } k, d] = f \div_i k \bowtie_{i-f} [n \dots, d]$$

$\langle proof \rangle$

corollary *i-f-join-i-shrink-iMODb-0*:

$$0 < k \implies (f \mapsto_i k) \bowtie_{i-f} [k - 1, \text{mod } k, n] = f \div_i k \bowtie_{i-f} [\dots n]$$

$\langle \text{proof} \rangle$

4.2 Streams and temporal operators

lemma *i-shrink-eq-NoMsg-iAll-conv*:

$$0 < k \implies ((s \div_i k) \ t = \varepsilon) = (\Box \ t1 \ [t * k \dots, k - \text{Suc } 0]. \ s \ t1 = \varepsilon)$$

$\langle \text{proof} \rangle$

lemma *i-shrink-eq-NoMsg-iAll-conv2*:

$$0 < k \implies ((s \div_i k) \ t = \varepsilon) = (\Box \ t1 \ [\dots k - 1] \oplus (t * k). \ s \ t1 = \varepsilon)$$

$\langle \text{proof} \rangle$

lemma *i-shrink-eq-Msg-iEx-iAll-conv*:

$$\begin{aligned} & \llbracket 0 < k; m \neq \varepsilon \rrbracket \implies \\ & ((s \div_i k) \ t = m) = \\ & (\Diamond \ t1 \ [t * k \dots, k - \text{Suc } 0]. \ s \ t1 = m \wedge \\ & \quad (\Box \ t2 \ [\text{Suc } t1 \dots]. \ t2 \leq t * k + k - \text{Suc } 0 \longrightarrow s \ t2 = \varepsilon)) \end{aligned}$$

$\langle \text{proof} \rangle$

lemma *i-shrink-eq-Msg-iEx-iAll-conv2*:

$$\begin{aligned} & \llbracket 0 < k; m \neq \varepsilon \rrbracket \implies \\ & ((s \div_i k) \ t = m) = \\ & (\Diamond \ t1 \ [\dots k - 1] \oplus (t * k). \ s \ t1 = m \wedge \\ & \quad (\Box \ t2 \ [1 \dots] \oplus t1 . \ t2 \leq t * k + k - 1 \longrightarrow s \ t2 = \varepsilon)) \end{aligned}$$

$\langle \text{proof} \rangle$

lemma *i-shrink-eq-Msg-iEx-iAll-cut-greater-conv*:

$$\begin{aligned} & \llbracket 0 < k; m \neq \varepsilon \rrbracket \implies \\ & ((s \div_i k) \ t = m) = \\ & (\Diamond \ t1 \ [t * k \dots, k - \text{Suc } 0]. \ s \ t1 = m \wedge \\ & \quad (\Box \ t2 \ [t * k \dots, k - \text{Suc } 0] \downarrow > t1. \ s \ t2 = \varepsilon)) \end{aligned}$$

$\langle \text{proof} \rangle$

lemma *i-shrink-eq-Msg-iEx-iAll-cut-greater-conv2*:

$$\begin{aligned} & \llbracket 0 < k; m \neq \varepsilon \rrbracket \implies \\ & ((s \div_i k) \ t = m) = \\ & (\Diamond \ t1 \ [\dots k - 1] \oplus (t * k). \ s \ t1 = m \wedge \\ & \quad (\Box \ t2 \ ([\dots k - 1] \oplus (t * k)) \downarrow > t1. \ s \ t2 = \varepsilon)) \end{aligned}$$

$\langle \text{proof} \rangle$

lemma *i-shrink-eq-Msg-iSince-conv*:

$$\begin{aligned} & \llbracket 0 < k; m \neq \varepsilon \rrbracket \implies \\ & ((s \div_i k) \ t = m) = \\ & (s \ t2 = \varepsilon. \ t2 \ \mathcal{S} \ t1 \ [t * k \dots, k - \text{Suc } 0]. \ s \ t1 = m) \end{aligned}$$

$\langle \text{proof} \rangle$

lemma *i-shrink-eq-Msg-iSince-conv2*:

$$\begin{aligned} & \llbracket 0 < k; m \neq \varepsilon \rrbracket \implies \\ & ((s \div_i k) \ t = m) = \\ & (s \ t2 = \varepsilon. \ t2 \ \mathcal{S} \ t1 \ [\dots k - 1] \oplus (t * k). \ s \ t1 = m) \end{aligned}$$

$\langle proof \rangle$

lemma *iT-Mult-iAll-i-expand-nth-iff*:

$0 < k \implies (\Box t (I \otimes k). P ((f \odot_i k) t)) = (\Box t I. P (f t))$
 $\langle proof \rangle$

Streams and temporal operators cycle start/finish events

lemma *i-shrink-eq-NoMsg-iAll-start-event-conv*:

$\llbracket 0 < k; \bigwedge t. \text{event } t = (t \bmod k = 0); t0 = t * k \rrbracket \implies$
 $((s \div_i k) t = \varepsilon) =$
 $(s t0 = \varepsilon \wedge (\bigcirc t' t0 [0\dots]. (s t1 = \varepsilon. t1 \mathcal{U} t2 ([0\dots] \oplus t'). \text{event } t2)))$
 $\langle proof \rangle$

lemma *i-shrink-eq-Msg-iUntil-start-event-conv*:

$\llbracket 0 < k; m \neq \varepsilon; \bigwedge t. \text{event } t = (t \bmod k = 0); t0 = t * k \rrbracket \implies$
 $((s \div_i k) t = m) =$
 $(s t0 = m \wedge (\bigcirc t' t0 [0\dots]. (s t1 = \varepsilon. t1 \mathcal{U} t2 ([0\dots] \oplus t'). \text{event } t2))) \vee$
 $(\bigcirc t' t0 [0\dots]. (\neg \text{event } t1. t1 \mathcal{U} t2 ([0\dots] \oplus t'). ($
 $s t2 = m \wedge \neg \text{event } t2 \wedge (\bigcirc t'' t2 [0\dots].$
 $(s t3 = \varepsilon. t3 \mathcal{U} t4 ([0\dots] \oplus t''). \text{event } t4))))))$
 $\langle proof \rangle$

lemma *i-shrink-eq-NoMsg-iAll-finish-event-conv*:

$\llbracket 1 < k; \bigwedge t. \text{event } t = (t \bmod k = k - 1); t0 = t * k \rrbracket \implies$
 $((s \div_i k) t = \varepsilon) =$
 $(s t0 = \varepsilon \wedge (\bigcirc t' t0 [0\dots]. (s t1 = \varepsilon. t1 \mathcal{U} t2 ([0\dots] \oplus t'). (\text{event } t2 \wedge s t2 =$
 $\varepsilon))))$
 $\langle proof \rangle$

lemma *i-shrink-eq-Msg-iUntil-finish-event-conv*:

$\llbracket 1 < k; m \neq \varepsilon; \bigwedge t. \text{event } t = (t \bmod k = k - 1); t0 = t * k \rrbracket \implies$
 $((s \div_i k) t = m) =$
 $(\neg \text{event } t1. t1 \mathcal{U} t2 ([0\dots] \oplus t0). \text{event } t2 \wedge s t2 = m) \vee$
 $(\neg \text{event } t1. t1 \mathcal{U} t2 ([0\dots] \oplus t0). (\neg \text{event } t2 \wedge s t2 = m \wedge ($
 $\bigcirc t' t2 [0\dots]. (s t3 = \varepsilon. t3 \mathcal{U} t4 ([0\dots] \oplus t'). \text{event } t4 \wedge s t4 = \varepsilon))))$
 $\langle proof \rangle$

end

5 AutoFocus message stream processing and temporal logic on intervals

theory *IL-AF-Stream-Exec*

imports *Main IL-AF-Stream AF-Stream-Exec*

begin

5.1 Correlation between Pre/Post-Conditions for $f\text{-Exec-Comp-Stream}$ and $f\text{-Exec-Comp-Stream-Init}$

lemma $i\text{-Exec-Stream-Pre-Post1-iAll}$:

$\llbracket \text{result} = i\text{-Exec-Comp-Stream trans-fun input } c; \\ \forall x\text{-n } c\text{-n}. P1\ x\text{-n} \wedge P2\ c\text{-n} \longrightarrow Q\ (\text{trans-fun } x\text{-n } c\text{-n}) \rrbracket \implies \\ \square t\ I. (P1\ (\text{input } t) \wedge P2\ (\text{result} \stackrel{\leftarrow}{\leftarrow} c\ t) \longrightarrow Q\ (\text{result } t)) \\ \langle \text{proof} \rangle$

Direct relation between input and result after transition

lemma $i\text{-Exec-Stream-Pre-Post2-iAll}$:

$\llbracket \text{result} = i\text{-Exec-Comp-Stream trans-fun input } c; \\ \forall x\text{-n } c\text{-n}. P\ c\text{-n} \longrightarrow Q\ x\text{-n}\ (\text{trans-fun } x\text{-n } c\text{-n}) \rrbracket \implies \\ \square t\ I. P\ (\text{result} \stackrel{\leftarrow}{\leftarrow} c\ t) \longrightarrow Q\ (\text{input } t)\ (\text{result } t) \\ \langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Pre-Post3-iAll-iNext}$:

$\llbracket \text{result} = i\text{-Exec-Comp-Stream trans-fun input } c; \\ \forall x\text{-n } c\text{-n}. P\ c\text{-n} \longrightarrow Q\ x\text{-n}\ (\text{trans-fun } x\text{-n } c\text{-n}); \\ \forall t \in I. \text{inext } t\ I' = \text{Suc } t \rrbracket \implies \\ \square t\ I. P\ (\text{result } t) \longrightarrow (\bigcirc\ t1\ t\ I'. Q\ (\text{input } t1)\ (\text{result } t1)) \\ \langle \text{proof} \rangle$

lemma $i\text{-Exec-Stream-Init-Pre-Post1-iAll-iNext}$:

$\llbracket \text{result} = i\text{-Exec-Comp-Stream-Init trans-fun input } c; \\ \forall x\text{-n } c\text{-n}. P1\ x\text{-n} \wedge P2\ c\text{-n} \longrightarrow Q\ (\text{trans-fun } x\text{-n } c\text{-n}); \\ \forall t \in I. \text{inext } t\ I' = \text{Suc } t \rrbracket \implies \\ \square t\ I. (P1\ (\text{input } t) \wedge P2\ (\text{result } t) \longrightarrow (\bigcirc\ t1\ t\ I'. Q\ (\text{result } t1))) \\ \langle \text{proof} \rangle$

Direct relation between input and state before transition

lemma $i\text{-Exec-Stream-Init-Pre-Post2-iAll-iNext}$:

$\llbracket \text{result} = i\text{-Exec-Comp-Stream-Init trans-fun input } c; \\ \forall x\text{-n } c\text{-n}. P\ x\text{-n } c\text{-n} \longrightarrow Q\ (\text{trans-fun } x\text{-n } c\text{-n}); \\ \forall t \in I. \text{inext } t\ I' = \text{Suc } t \rrbracket \implies \\ \square t\ I. (P\ (\text{input } t)\ (\text{result } t) \longrightarrow (\bigcirc\ t1\ t\ I'. Q\ (\text{result } t1))) \\ \langle \text{proof} \rangle$

Relation between input and output

lemma $i\text{-Exec-Stream-Init-Pre-Post3-iAll-iNext}$:

$\llbracket \text{result} = i\text{-Exec-Comp-Stream-Init trans-fun input } c; \\ \forall x\text{-n } c\text{-n}. P\ c\text{-n} \longrightarrow Q\ x\text{-n}\ (\text{trans-fun } x\text{-n } c\text{-n}); \\ \forall t \in I. \text{inext } t\ I' = \text{Suc } t \rrbracket \implies \\ \square t\ I. (P\ (\text{result } t) \longrightarrow (\bigcirc\ t1\ t\ I'. Q\ (\text{input} \stackrel{\leftarrow}{\leftarrow} \varepsilon\ t1)\ (\text{result } t1))) \\ \langle \text{proof} \rangle$

5.2 *i-Exec-Comp-Stream-Acc-Output* and temporal operators with bounded intervals.

Temporal relation between uncompressed and compressed output of accelerated components.

lemma *i-Exec-Comp-Stream-Acc-Output--eq-NoMsg-iAll-conv:*

$$\begin{aligned}
 &0 < k \implies \\
 &((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = \varepsilon) = \\
 &(\Box t1 \ [t * k \dots, k - \text{Suc } 0]. \ (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun } (\text{input} \\
 &\odot_i k) \ c) \ t1 = \varepsilon) \\
 &\langle \text{proof} \rangle
 \end{aligned}$$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-NoMsg-iAll-conv2:*

$$\begin{aligned}
 &0 < k \implies \\
 &((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = \varepsilon) = \\
 &(\Box t1 \ [\dots k - \text{Suc } 0] \oplus (t * k). \ (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun} \\
 &(\text{input} \odot_i k) \ c) \ t1 = \varepsilon) \\
 &\langle \text{proof} \rangle
 \end{aligned}$$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-NoMsg-iAll-conv:*

$$\begin{aligned}
 &0 < k \implies \\
 &((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = \varepsilon) = \\
 &(\Box t1 \ [\text{Suc } (t * k) \dots, k - \text{Suc } 0]. \ (\text{output-fun} \circ i\text{-Exec-Comp-Stream-Init trans-fun} \\
 &(\text{input} \odot_i k) \ c) \ t1 = \varepsilon) \\
 &\langle \text{proof} \rangle
 \end{aligned}$$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iEx-iAll-cut-greater-conv:*

$$\begin{aligned}
 &\llbracket 0 < k; m \neq \varepsilon; s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun } (\text{input} \odot_i k) \\
 &c) \rrbracket \implies \\
 &((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = m) = \\
 &(\Diamond t1 \ [t * k \dots, k - \text{Suc } 0]. \ (s \ t1 = m \wedge \\
 &(\Box t2 \ [t * k \dots, k - \text{Suc } 0] \downarrow > t1 \ . \ s \ t2 = \varepsilon))) \\
 &\langle \text{proof} \rangle
 \end{aligned}$$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iEx-iAll-cut-greater-conv2:*

$$\begin{aligned}
 &\llbracket 0 < k; m \neq \varepsilon; s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun } (\text{input} \odot_i k) \\
 &c) \rrbracket \implies \\
 &((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = m) = \\
 &(\Diamond t1 \ [\dots k - \text{Suc } 0] \oplus (t * k). \ (s \ t1 = m \wedge \\
 &(\Box t2 \ ([\dots k - \text{Suc } 0] \oplus (t * k)) \downarrow > t1 \ . \ s \ t2 = \varepsilon))) \\
 &\langle \text{proof} \rangle
 \end{aligned}$$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iSince-conv:*

$$\begin{aligned}
 &\llbracket 0 < k; m \neq \varepsilon; s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun } (\text{input} \odot_i k) \\
 &c) \rrbracket \implies \\
 &((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = m) = \\
 &(s \ t2 = \varepsilon. \ t2 \ \mathcal{S} \ t1 \ [t * k \dots, k - \text{Suc } 0]. \ s \ t1 = m) \\
 &\langle \text{proof} \rangle
 \end{aligned}$$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iSince-conv2*:

$\llbracket 0 < k; m \neq \varepsilon; s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c) \rrbracket \implies$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = m) =$
 $(s \ t2 = \varepsilon. \ t2 \ \mathcal{S} \ t1 \ [\dots k - \text{Suc } 0] \oplus (t * k). \ s \ t1 = m)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-Msg-iSince-conv*:

$\llbracket 0 < k; m \neq \varepsilon; s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream-Init trans-fun} (\text{input} \odot_i k) c) \rrbracket \implies$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = m) =$
 $(s \ t2 = \varepsilon. \ t2 \ \mathcal{S} \ t1 \ [\text{Suc } (t * k) \dots, k - \text{Suc } 0]. \ s \ t1 = m)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-iAll-iSince-conv*:

$\llbracket 0 < k; s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c) \rrbracket \implies$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = m) =$
 $((m = \varepsilon \longrightarrow (\Box \ t1 \ [t * k \dots, k - \text{Suc } 0]. \ s \ t1 = \varepsilon)) \wedge$
 $((m \neq \varepsilon \longrightarrow (s \ t2 = \varepsilon. \ t2 \ \mathcal{S} \ t1 \ [t * k \dots, k - \text{Suc } 0]. \ s \ t1 = m))))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-iAll-iSince-conv2*:

$\llbracket 0 < k; s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c) \rrbracket \implies$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = m) =$
 $((m = \varepsilon \longrightarrow (\Box \ t1 \ [\dots k - \text{Suc } 0] \oplus (t * k). \ s \ t1 = \varepsilon)) \wedge$
 $((m \neq \varepsilon \longrightarrow (s \ t2 = \varepsilon. \ t2 \ \mathcal{S} \ t1 \ [\dots k - \text{Suc } 0] \oplus (t * k). \ s \ t1 = m))))$
 $\langle \text{proof} \rangle$

5.3 *i-Exec-Comp-Stream-Acc-Output* and temporal operators with unbounded intervals and start/finish events.

lemma *i-Exec-Comp-Stream-Acc-Output--eq-NoMsg-iAll-start-event-conv*:

$\llbracket 0 < k; \bigwedge t. \text{event } t = (t \bmod k = 0); t0 = t * k;$
 $s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c) \rrbracket \implies$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = \varepsilon) =$
 $(s \ t0 = \varepsilon \wedge (\bigcirc \ t' \ t0 \ [0 \dots]. \ (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ [0 \dots] \oplus t'. \ \text{event } t2)))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-NoMsg-iAll-start-event-conv*:

$\llbracket 0 < k; \bigwedge t. \text{event } t = ((t + k - \text{Suc } 0) \bmod k = 0); t0 = \text{Suc } (t * k);$
 $s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream-Init trans-fun} (\text{input} \odot_i k) c) \rrbracket \implies$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = \varepsilon) =$
 $(s \ t0 = \varepsilon \wedge (\bigcirc \ t' \ t0 \ [0 \dots]. \ (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ [0 \dots] \oplus t'. \ \text{event } t2)))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-NoMsg-iAll-start-event2-conv*:

$\llbracket \text{Suc } 0 < k; \bigwedge t. \text{event } t = (t \bmod k = \text{Suc } 0); t0 = \text{Suc } (t * k);$
 $s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream-Init trans-fun} (\text{input} \odot_i k) c) \rrbracket \implies$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) \ t = \varepsilon) =$

$(s \ t0 = \varepsilon \wedge (\bigcirc t' \ t0 \ [0\dots]. (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ [0\dots] \oplus t'. \ event \ t2)))$
 $\langle proof \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iUntil-start-event-conv:*

$\llbracket 0 < k; m \neq \varepsilon; \bigwedge t. \ event \ t = (t \ mod \ k = 0); t0 = t * k;$
 $s = (output_fun \circ i-Exec-Comp-Stream \ trans_fun \ (input \ \odot_i \ k) \ c) \rrbracket \implies$
 $((i-Exec-Comp-Stream-Acc-Output \ k \ output_fun \ trans_fun \ input \ c) \ t = m) = ($
 $(s \ t0 = m \wedge (\bigcirc t' \ t0 \ [0\dots]. (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ ([0\dots] \oplus t'). \ event \ t2))) \vee$
 $(\bigcirc t' \ t0 \ [0\dots]. (\neg \ event \ t1. \ t1 \ \mathcal{U} \ t2 \ ([0\dots] \oplus t'). ($
 $s \ t2 = m \wedge \neg \ event \ t2 \wedge (\bigcirc t'' \ t2 \ [0\dots].$
 $(s \ t3 = \varepsilon. \ t3 \ \mathcal{U} \ t4 \ ([0\dots] \oplus t''). \ event \ t4))))))$
 $\langle proof \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-Msg-iUntil-start-event-conv:*

$\llbracket 0 < k; m \neq \varepsilon; \bigwedge t. \ event \ t = ((t + k - Suc \ 0) \ mod \ k = 0); t0 = Suc \ (t * k);$
 $s = (output_fun \circ i-Exec-Comp-Stream-Init \ trans_fun \ (input \ \odot_i \ k) \ c) \rrbracket \implies$
 $((i-Exec-Comp-Stream-Acc-Output \ k \ output_fun \ trans_fun \ input \ c) \ t = m) = ($
 $(s \ t0 = m \wedge (\bigcirc t' \ t0 \ [0\dots]. (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ ([0\dots] \oplus t'). \ event \ t2))) \vee$
 $(\bigcirc t' \ t0 \ [0\dots]. (\neg \ event \ t1. \ t1 \ \mathcal{U} \ t2 \ ([0\dots] \oplus t'). ($
 $s \ t2 = m \wedge \neg \ event \ t2 \wedge (\bigcirc t'' \ t2 \ [0\dots].$
 $(s \ t3 = \varepsilon. \ t3 \ \mathcal{U} \ t4 \ ([0\dots] \oplus t''). \ event \ t4))))))$
 $\langle proof \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-Msg-iUntil-start-event2-conv:*

$\llbracket Suc \ 0 < k; m \neq \varepsilon; \bigwedge t. \ event \ t = (t \ mod \ k = Suc \ 0); t0 = Suc \ (t * k);$
 $s = (output_fun \circ i-Exec-Comp-Stream-Init \ trans_fun \ (input \ \odot_i \ k) \ c) \rrbracket \implies$
 $((i-Exec-Comp-Stream-Acc-Output \ k \ output_fun \ trans_fun \ input \ c) \ t = m) = ($
 $(s \ t0 = m \wedge (\bigcirc t' \ t0 \ [0\dots]. (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ ([0\dots] \oplus t'). \ event \ t2))) \vee$
 $(\bigcirc t' \ t0 \ [0\dots]. (\neg \ event \ t1. \ t1 \ \mathcal{U} \ t2 \ ([0\dots] \oplus t'). ($
 $s \ t2 = m \wedge \neg \ event \ t2 \wedge (\bigcirc t'' \ t2 \ [0\dots].$
 $(s \ t3 = \varepsilon. \ t3 \ \mathcal{U} \ t4 \ ([0\dots] \oplus t''). \ event \ t4))))))$
 $\langle proof \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-NoMsg-iAll-finish-event-conv:*

$\llbracket Suc \ 0 < k; \bigwedge t. \ event \ t = (t \ mod \ k = k - Suc \ 0); t0 = t * k;$
 $s = (output_fun \circ i-Exec-Comp-Stream \ trans_fun \ (input \ \odot_i \ k) \ c) \rrbracket \implies$
 $((i-Exec-Comp-Stream-Acc-Output \ k \ output_fun \ trans_fun \ input \ c) \ t = \varepsilon) =$
 $(s \ t0 = \varepsilon \wedge (\bigcirc t' \ t0 \ [0\dots]. (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ [0\dots] \oplus t'. \ event \ t2 \wedge s \ t2 = \varepsilon)))$
 $\langle proof \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-NoMsg-iAll-finish-event-conv:*

$\llbracket Suc \ 0 < k; \bigwedge t. \ event \ t = (t \ mod \ k = 0); t0 = Suc \ (t * k);$
 $s = (output_fun \circ i-Exec-Comp-Stream-Init \ trans_fun \ (input \ \odot_i \ k) \ c) \rrbracket \implies$
 $((i-Exec-Comp-Stream-Acc-Output \ k \ output_fun \ trans_fun \ input \ c) \ t = \varepsilon) =$
 $(s \ t0 = \varepsilon \wedge (\bigcirc t' \ t0 \ [0\dots]. (s \ t1 = \varepsilon. \ t1 \ \mathcal{U} \ t2 \ [0\dots] \oplus t'. \ event \ t2 \wedge s \ t2 = \varepsilon)))$
 $\langle proof \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iUntil-finish-event-conv:*

$\llbracket 0 < k; m \neq \varepsilon; \bigwedge t. \ event \ t = (t \ mod \ k = k - Suc \ 0); t0 = t * k;$

$s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c) \mathbb{I} \Longrightarrow$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) t = m) =$
 $((\neg \text{event } t1. t1 \mathcal{U} t2 ([0\dots] \oplus t0). \text{event } t2 \wedge s t2 = m) \vee$
 $(\neg \text{event } t1. t1 \mathcal{U} t2 ([0\dots] \oplus t0). (\neg \text{event } t2 \wedge s t2 = m \wedge ($
 $\quad \circ t' t2 [0\dots]. (s t3 = \varepsilon. t3 \mathcal{U} t4 ([0\dots] \oplus t'). \text{event } t4 \wedge s t4 = \varepsilon))))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--Init--eq-Msg-iUntil-finish-event-conv:*

$\mathbb{I} \text{ Suc } 0 < k; m \neq \varepsilon; \bigwedge t. \text{event } t = (t \bmod k = 0); t0 = \text{Suc } (t * k);$
 $s = (\text{output-fun} \circ i\text{-Exec-Comp-Stream-Init trans-fun} (\text{input} \odot_i k) c) \mathbb{I} \Longrightarrow$
 $((i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c) t = m) =$
 $((\neg \text{event } t1. t1 \mathcal{U} t2 ([0\dots] \oplus t0). \text{event } t2 \wedge s t2 = m) \vee$
 $(\neg \text{event } t1. t1 \mathcal{U} t2 ([0\dots] \oplus t0). (\neg \text{event } t2 \wedge s t2 = m \wedge ($
 $\quad \circ t' t2 [0\dots]. (s t3 = \varepsilon. t3 \mathcal{U} t4 ([0\dots] \oplus t'). \text{event } t4 \wedge s t4 = \varepsilon))))$
 $\langle \text{proof} \rangle$

5.4 *i-Exec-Comp-Stream-Acc-Output* and temporal operators with idle states.

lemma *i-Exec-Comp-Stream-Acc-Output--eq-NoMsg-State-Idle-conv:*

$\mathbb{I} 0 < k;$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\quad i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c t);$
 $t0 = t * k;$
 $s = i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c \mathbb{I} \Longrightarrow$
 $(i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c t = \varepsilon) =$
 $(\text{output-fun } (s t1) = \varepsilon. t1 \mathcal{U} t2 ([0\dots] \oplus t0). ($
 $\quad \text{output-fun } (s t2) = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun } (\text{localState } (s$
 $\quad t2))))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-with-State-Idle-imp:*

$\mathbb{I} 0 < k;$
 $s = i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c;$
 $t0 = t * k;$
 $t1 \in [0\dots, k - \text{Suc } 0] \oplus t0;$
 $\text{State-Idle localState output-fun trans-fun } (\text{localState } (s t1));$
 $\text{output-fun } (s t1) \neq \varepsilon \mathbb{I} \Longrightarrow$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c t = \text{output-fun } (s$
 $t1)$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-with-State-Idle-conv2:*

$\mathbb{I} 0 < k;$
 $\text{State-Idle localState output-fun trans-fun } ($
 $\quad i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c t);$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = i\text{-Exec-Comp-Stream trans-fun} (\text{input} \odot_i k) c;$

$t1 \in [0 \dots, k - \text{Suc } 0] \oplus t0;$
 $\text{State-Idle localState output-fun trans-fun (localState (s t1));}$
 $\text{output-fun (s t1)} \neq \varepsilon \mathbb{I} \implies$
 $(i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } t = m) =$
 $(\Diamond t1 [0 \dots, k - \text{Suc } 0] \oplus t0. ($
 $\quad (\text{output-fun (s t1)} = m \wedge \text{State-Idle localState output-fun trans-fun (localState$
 $\quad (s t1))))))$
 $\langle \text{proof} \rangle$

Here the property to be checked uses only unbounded intervals suitable for LTL.

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-with-State-Idle-conv:*

$\mathbb{I} \ 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\quad i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } t);$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ } c;$
 $t1 \in [0 \dots, k - \text{Suc } 0] \oplus t0;$
 $\text{State-Idle localState output-fun trans-fun (localState (s t1));}$
 $\text{output-fun (s t1)} \neq \varepsilon \mathbb{I} \implies$
 $(i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } t = m) =$
 $((\neg \text{State-Idle localState output-fun trans-fun (localState (s t2))). } t2 \mathcal{U} t1 [0 \dots]$
 $\oplus t0. ($
 $\quad (\text{output-fun (s t1)} = m \wedge \text{State-Idle localState output-fun trans-fun (localState$
 $\quad (s t1))))))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-before-State-Idle-imp2:*

$\mathbb{I} \ \text{Suc } 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\quad i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } t);$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ } c;$
 $t1 \in [0 \dots, k - \text{Suc } 0] \oplus t0;$
 $\text{output-fun (s t1)} = m;$
 $\bigcirc t2 \ t1 [0 \dots].$
 $((\text{output-fun (s t3)} = \varepsilon. t3 \mathcal{U} t4 ([0 \dots] \oplus t2).$
 $\quad (\text{output-fun (s t4)} = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState$
 $\quad (s t4)))))) \mathbb{I} \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } t = m$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-before-State-Idle-conv2:*

$\mathbb{I} \ \text{Suc } 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\quad i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } t);$
 $m \neq \varepsilon;$

$t0 = t * k;$
 $s = i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) c;$
 $\square t1 [0 \dots, k - \text{Suc } 0] \oplus t0. \neg ($
 $\quad \text{State-Idle localState output-fun trans-fun (localState (s t1)) } \wedge$
 $\quad \text{output-fun (s t1) } \neq \varepsilon) \rrbracket \implies$
 $(i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } t = m) =$
 $(\diamond t1 [0 \dots, k - \text{Suc } 0] \oplus t0. ($
 $\quad \text{output-fun (s t1) } = m) \wedge$
 $\quad (\bigcirc t2 t1 [0 \dots].$
 $\quad \quad ((\text{output-fun (s t3) } = \varepsilon. t3 \mathcal{U} t4 ([0 \dots] \oplus t2).$
 $\quad \quad \text{output-fun (s t4) } = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState$
 $\quad \quad (s t4)))))))))$
 $\langle \text{proof} \rangle$

Here the property to be checked uses only unbounded intervals suitable for LTL.

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-before-State-Idle-imp:*

$\rrbracket \text{Suc } 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\quad i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } t);$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) c;$
 $(\neg \text{State-Idle localState output-fun trans-fun (localState (s t1)))) . t1 \mathcal{U} t2 [0 \dots]$
 $\oplus t0. ($
 $\quad \text{output-fun (s t2) } = m) \wedge$
 $\quad (\bigcirc t3 t2 [0 \dots].$
 $\quad \quad ((\text{output-fun (s t4) } = \varepsilon. t4 \mathcal{U} t5 ([0 \dots] \oplus t3).$
 $\quad \quad \text{output-fun (s t5) } = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState$
 $\quad \quad (s t5)))))) \rrbracket \implies$
 $i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } t = m$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-before-State-Idle-conv:*

$\rrbracket \text{Suc } 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\quad i\text{-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ } t);$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = i\text{-Exec-Comp-Stream trans-fun (input } \odot_i k) c;$
 $\square t1 [0 \dots, k - \text{Suc } 0] \oplus t0. \neg ($
 $\quad \text{State-Idle localState output-fun trans-fun (localState (s t1)) } \wedge$
 $\quad \text{output-fun (s t1) } \neq \varepsilon) \rrbracket \implies$
 $(i\text{-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ } t = m) =$
 $((\neg \text{State-Idle localState output-fun trans-fun (localState (s t1)))) . t1 \mathcal{U} t2 [0 \dots]$
 $\oplus t0. ($
 $\quad \text{output-fun (s t2) } = m) \wedge$
 $\quad (\bigcirc t3 t2 [0 \dots].$
 $\quad \quad ((\text{output-fun (s t4) } = \varepsilon. t4 \mathcal{U} t5 ([0 \dots] \oplus t3).$
 $\quad \quad \text{output-fun (s t5) } = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState$

(s t5)))))))))
 <proof>

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv2*:

$\llbracket \text{Suc } 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\text{ i-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ t);}$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = \text{i-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c} \rrbracket \implies$
 $(\text{i-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ t} = m) =$
 $(\Diamond t1 [0 \dots, k - \text{Suc } 0] \oplus t0. ($
 $\text{ output-fun (s t1) = } m \wedge$
 $(\text{State-Idle localState output-fun trans-fun (localState (s t1))} \vee$
 $(\bigcirc t2 \text{ t1 } [0 \dots].$
 $((\text{output-fun (s t3) = } \varepsilon. t3 \text{ U } t4 ([0 \dots] \oplus t2).$
 $(\text{output-fun (s t4) = } \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState}$
 $(s \text{ t4})))))))))$
 <proof>

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv2'*:

$\llbracket \text{Suc } 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\text{ i-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ t);}$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = \text{i-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c} \rrbracket \implies$
 $(\text{i-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ t} = m) =$
 $((\Diamond t1 [0 \dots, k - \text{Suc } 0] \oplus t0. ($
 $\text{ output-fun (s t1) = } m \wedge \text{State-Idle localState output-fun trans-fun (localState}$
 $(s \text{ t1})))) \vee$
 $(\Diamond t1 [0 \dots, k - \text{Suc } 0] \oplus t0. ($
 $((\text{output-fun (s t1) = } m) \wedge$
 $(\bigcirc t2 \text{ t1 } [0 \dots].$
 $((\text{output-fun (s t3) = } \varepsilon. t3 \text{ U } t4 ([0 \dots] \oplus t2).$
 $(\text{output-fun (s t4) = } \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState}$
 $(s \text{ t4})))))))))$
 <proof>

lemma *i-Exec-Comp-Stream-Acc-Output--eq-iAll-iUntil-State-Idle-conv2*:

$\llbracket \text{Suc } 0 < k;$
 $\text{State-Idle localState output-fun trans-fun (}$
 $\text{ i-Exec-Comp-Stream-Acc-LocalState } k \text{ localState trans-fun input } c \text{ t);}$
 $t0 = t * k;$
 $s = \text{i-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c} \rrbracket \implies$
 $(\text{i-Exec-Comp-Stream-Acc-Output } k \text{ output-fun trans-fun input } c \text{ t} = m) = ($
 $m = \varepsilon \longrightarrow$
 $(\text{output-fun (s t1) = } \varepsilon. t1 \text{ U } t2 ([0 \dots] \oplus t0). ($
 $\text{ output-fun (s t2) = } \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState}$

$(s\ t2)))))) \wedge$
 $(m \neq \varepsilon \longrightarrow$
 $(\Diamond t1\ [0\dots, k - \text{Suc } 0] \oplus t0. ($
 $\text{output-fun } (s\ t1) = m \wedge$
 $(\text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t1))) \vee$
 $(\bigcirc t2\ t1\ [0\dots].$
 $((\text{output-fun } (s\ t3) = \varepsilon. t3\ \mathcal{U}\ t4\ ([0\dots] \oplus t2).$
 $(\text{output-fun } (s\ t4) = \varepsilon \wedge \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t4))))))))))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv'*:

$\llbracket \text{Suc } 0 < k;$
 $\text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } ($
 $\text{i-Exec-Comp-Stream-Acc-LocalState } k\ \text{localState } \text{trans-fun } \text{input } c\ t);$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = \text{i-Exec-Comp-Stream } \text{trans-fun } (\text{input } \odot_i k)\ c \rrbracket \implies$
 $(\text{i-Exec-Comp-Stream-Acc-Output } k\ \text{output-fun } \text{trans-fun } \text{input } c\ t = m) =$
 $((\neg \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t2))). t2\ \mathcal{U}\ t1\ [0\dots]$
 $\oplus t0.$
 $(\text{output-fun } (s\ t1) = m \wedge \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t1)))) \vee$
 $((\neg \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t2))). t2\ \mathcal{U}\ t1\ [0\dots]$
 $\oplus t0.$
 $(\text{output-fun } (s\ t1) = m \wedge$
 $(\bigcirc t3\ t1\ [0\dots].$
 $((\text{output-fun } (s\ t4) = \varepsilon. t4\ \mathcal{U}\ t5\ ([0\dots] \oplus t3).$
 $(\text{output-fun } (s\ t5) = \varepsilon \wedge \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t5))))))))))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv*:

$\llbracket \text{Suc } 0 < k;$
 $\text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } ($
 $\text{i-Exec-Comp-Stream-Acc-LocalState } k\ \text{localState } \text{trans-fun } \text{input } c\ t);$
 $m \neq \varepsilon;$
 $t0 = t * k;$
 $s = \text{i-Exec-Comp-Stream } \text{trans-fun } (\text{input } \odot_i k)\ c \rrbracket \implies$
 $(\text{i-Exec-Comp-Stream-Acc-Output } k\ \text{output-fun } \text{trans-fun } \text{input } c\ t = m) =$
 $((\neg \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t2))). t2\ \mathcal{U}\ t1\ [0\dots]$
 $\oplus t0.$
 $(\text{output-fun } (s\ t1) = m \wedge$
 $(\text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t1))) \vee$
 $(\bigcirc t3\ t1\ [0\dots].$
 $((\text{output-fun } (s\ t4) = \varepsilon. t4\ \mathcal{U}\ t5\ ([0\dots] \oplus t3).$
 $(\text{output-fun } (s\ t5) = \varepsilon \wedge \text{State-Idle } \text{localState } \text{output-fun } \text{trans-fun } (\text{localState } (s\ t5))))))))))$
 $\langle \text{proof} \rangle$

lemma *i-Exec-Comp-Stream-Acc-Output--eq-iUntil-State-Idle-conv:*

$$\begin{aligned}
& \llbracket \text{Suc } 0 < k; \\
& \quad \text{State-Idle localState output-fun trans-fun (} \\
& \quad \quad \text{i-Exec-Comp-Stream-Acc-LocalState k localState trans-fun input c t);} \\
& \quad t0 = t * k; \\
& \quad s = \text{i-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c} \rrbracket \implies \\
& (\text{i-Exec-Comp-Stream-Acc-Output k output-fun trans-fun input c t} = m) = (\\
& (m = \varepsilon \longrightarrow \\
& \quad (\text{output-fun (s t1)} = \varepsilon. t1 \mathcal{U} t2 ([0..] \oplus t0). (\\
& \quad \quad \text{output-fun (s t2)} = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun (localState} \\
& (s t2)))))) \wedge \\
& (m \neq \varepsilon \longrightarrow \\
& \quad (((\neg \text{State-Idle localState output-fun trans-fun (localState (s t2))). t2 } \mathcal{U} t1 [0..] \\
& \oplus t0. \\
& \quad (\text{output-fun (s t1)} = m \wedge \\
& \quad \quad (\text{State-Idle localState output-fun trans-fun (localState (s t1))} \vee \\
& \quad \quad (\odot t3 t1 [0..]. \\
& \quad \quad ((\text{output-fun (s t4)} = \varepsilon. t4 \mathcal{U} t5 ([0..] \oplus t3). \\
& \quad \quad (\text{output-fun (s t5)} = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun} \\
& (\text{localState (s t5))))))))))))) \\
& \langle \text{proof} \rangle
\end{aligned}$$

Sufficient conditions for output messages.

corollary *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iEx-imp1:*

$$\begin{aligned}
& \llbracket \text{Suc } 0 < k; \\
& \quad \text{State-Idle localState output-fun trans-fun (} \\
& \quad \quad \text{i-Exec-Comp-Stream-Acc-LocalState k localState trans-fun input c t);} \\
& \quad m \neq \varepsilon; \\
& \quad t0 = t * k; \\
& \quad s = \text{i-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c;} \\
& (\diamond t1 [0.., k - \text{Suc } 0] \oplus t0. (\\
& \quad \text{output-fun (s t1)} = m \wedge \text{State-Idle localState output-fun trans-fun (localState} \\
& (s t1)))) \rrbracket \implies \\
& \quad \text{i-Exec-Comp-Stream-Acc-Output k output-fun trans-fun input c t} = m \\
& \langle \text{proof} \rangle
\end{aligned}$$

corollary *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iEx-imp2:*

$$\begin{aligned}
& \llbracket \text{Suc } 0 < k; \\
& \quad \text{State-Idle localState output-fun trans-fun (} \\
& \quad \quad \text{i-Exec-Comp-Stream-Acc-LocalState k localState trans-fun input c t);} \\
& \quad m \neq \varepsilon; \\
& \quad t0 = t * k; \\
& \quad s = \text{i-Exec-Comp-Stream trans-fun (input } \odot_i k) \text{ c;} \\
& \diamond t1 [0.., k - \text{Suc } 0] \oplus t0. (\\
& \quad (\text{output-fun (s t1)} = m) \wedge \\
& \quad (\odot t2 t1 [0..]. \\
& \quad \quad ((\text{output-fun (s t3)} = \varepsilon. t3 \mathcal{U} t4 ([0..] \oplus t2). \\
& \quad \quad (\text{output-fun (s t4)} = \varepsilon \wedge \text{State-Idle localState output-fun trans-fun}
\end{aligned}$$

$(localState\ (s\ t4)))))) \mathbb{I} \implies$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* *input* $c\ t = m$
 <proof>

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iUntil-imp1*:

$\mathbb{I}\ Suc\ 0 < k;$
State-Idle *localState* *output-fun* *trans-fun* (
i-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* *input* $c\ t$);
 $m \neq \varepsilon$;
 $t0 = t * k$;
 $s = i-Exec-Comp-Stream\ trans-fun\ (input\ \odot_i\ k)\ c$;
 $(\neg\ State-Idle\ localState\ output-fun\ trans-fun\ (localState\ (s\ t2))).\ t2\ \mathcal{U}\ t1\ [0..]$
 $\oplus\ t0.$
 $(output-fun\ (s\ t1) = m \wedge State-Idle\ localState\ output-fun\ trans-fun\ (localState\ (s\ t1))) \mathbb{I} \implies$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* *input* $c\ t = m$
 <proof>

lemma *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iUntil-imp2*:

$\mathbb{I}\ Suc\ 0 < k;$
State-Idle *localState* *output-fun* *trans-fun* (
i-Exec-Comp-Stream-Acc-LocalState k *localState* *trans-fun* *input* $c\ t$);
 $m \neq \varepsilon$;
 $t0 = t * k$;
 $s = i-Exec-Comp-Stream\ trans-fun\ (input\ \odot_i\ k)\ c$;
 $(\neg\ State-Idle\ localState\ output-fun\ trans-fun\ (localState\ (s\ t2))).\ t2\ \mathcal{U}\ t1\ [0..]$
 $\oplus\ t0.$
 $(output-fun\ (s\ t1) = m \wedge$
 $(\bigcirc\ t3\ t1\ [0..].$
 $((output-fun\ (s\ t4) = \varepsilon.\ t4\ \mathcal{U}\ t5\ ([0..] \oplus t3).$
 $(output-fun\ (s\ t5) = \varepsilon \wedge State-Idle\ localState\ output-fun\ trans-fun\ (localState\ (s\ t5)))))) \mathbb{I} \implies$
i-Exec-Comp-Stream-Acc-Output k *output-fun* *trans-fun* *input* $c\ t = m$
 <proof>

List of selected lemmas about output of accelerated components.

thm *i-Exec-Comp-Stream-Acc-Output--eq-NoMsg-iAll-conv*

thm *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iEx-iAll-cut-greater-conv*

thm *i-Exec-Comp-Stream-Acc-Output--eq-Msg-iSince-conv*

thm *i-Exec-Comp-Stream-Acc-Output--eq-iAll-iSince-conv*

thm *i-Exec-Comp-Stream-Acc-Output--eq-NoMsg-State-Idle-conv*

thm *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv2*

thm *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv*

thm *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv2'*

thm *i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-conv'*

thm *i-Exec-Comp-Stream-Acc-Output--eq-iAll-iUntil-State-Idle-conv2*

thm *i-Exec-Comp-Stream-Acc-Output--eq-iUntil-State-Idle-conv*

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thm i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iEx-imp1
thm i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iEx-imp2
thm i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iUntil-imp1
thm i-Exec-Comp-Stream-Acc-Output--eq-Msg-State-Idle-iUntil-imp2

end

```