

Slicing Guarantees Information Flow Noninterference

Daniel Wasserrab

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Abstract

In this contribution, we show how correctness proofs for intra- [8] and interprocedural slicing [9] can be used to prove that slicing is able to guarantee information flow noninterference. Moreover, we also illustrate how to lift the control flow graphs of the respective frameworks such that they fulfil the additional assumptions needed in the noninterference proofs. A detailed description of the intraprocedural proof and its interplay with the slicing framework can be found in [10].

1 Introduction

Information Flow Control (IFC) encompasses algorithms which determines if a given program leaks secret information to public entities. The major group are so called IFC type systems, where well-typed means that the respective program is secure. Several IFC type systems have been verified in proof assistants, e.g. see [1, 2, 5, 3, 7].

However, type systems have some drawbacks which can lead to false alarms. To overcome this problem, an IFC approach basing on slicing has been developed [4], which can significantly reduce the amount of false alarms. This contribution presents the first machine-checked proof that slicing is able to guarantee IFC noninterference. It bases on previously published machine-checked correctness proofs for slicing [8, 9]. Details for the intraprocedural case can be found in [10].

2 HRB Slicing guarantees IFC Noninterference

```
theory NonInterferenceInter  
  imports HRB-Slicing.FundamentalProperty  
begin
```

2.1 Assumptions of this Approach

Classical IFC noninterference, a special case of a noninterference definition using partial equivalence relations (per) [6], partitions the variables (i.e. locations) into security levels. Usually, only levels for secret or high, written H , and public or low, written L , variables are used. Basically, a program that is noninterferent has to fulfil one basic property: executing the program in two different initial states that may differ in the values of their H -variables yields two final states that again only differ in the values of their H -variables; thus the values of the H -variables did not influence those of the L -variables.

Every per-based approach makes certain assumptions: (i) all H -variables are defined at the beginning of the program, (ii) all L -variables are observed (or used in our terms) at the end and (iii) every variable is either H or L . This security label is fixed for a variable and can not be altered during a program run. Thus, we have to extend the prerequisites of the slicing framework in [9] accordingly in a new locale:

```

locale NonInterferenceInterGraph =
  SDG sourcenode targetnode kind valid-edge Entry
  get-proc get-return-edges procs Main Exit Def Use ParamDefs ParamUses
  for sourcenode :: 'edge  $\Rightarrow$  'node and targetnode :: 'edge  $\Rightarrow$  'node
  and kind :: 'edge  $\Rightarrow$  ('var,'val,'ret,'pname) edge-kind
  and valid-edge :: 'edge  $\Rightarrow$  bool
  and Entry :: 'node ((''-Entry'-)) and get-proc :: 'node  $\Rightarrow$  'pname
  and get-return-edges :: 'edge  $\Rightarrow$  'edge set
  and procs :: ('pname  $\times$  'var list  $\times$  'var list) list and Main :: 'pname
  and Exit::'node ((''-Exit'-))
  and Def :: 'node  $\Rightarrow$  'var set and Use :: 'node  $\Rightarrow$  'var set
  and ParamDefs :: 'node  $\Rightarrow$  'var list and ParamUses :: 'node  $\Rightarrow$  'var set list +
  fixes H :: 'var set
  fixes L :: 'var set
  fixes High :: 'node ((''-High'-))
  fixes Low :: 'node ((''-Low'-))
  assumes Entry-edge-Exit-or-High:
   $\llbracket$ valid-edge a; sourcenode a = (-Entry-) $\rrbracket$ 
     $\implies$  targetnode a = (-Exit-)  $\vee$  targetnode a = (-High-)
  and High-target-Entry-edge:
   $\exists$  a. valid-edge a  $\wedge$  sourcenode a = (-Entry-)  $\wedge$  targetnode a = (-High-)  $\wedge$ 
    kind a = ( $\lambda$ s. True) $\surd$ 
  and Entry-predecessor-of-High:
   $\llbracket$ valid-edge a; targetnode a = (-High-) $\rrbracket \implies$  sourcenode a = (-Entry-)
  and Exit-edge-Entry-or-Low:  $\llbracket$ valid-edge a; targetnode a = (-Exit-) $\rrbracket$ 
     $\implies$  sourcenode a = (-Entry-)  $\vee$  sourcenode a = (-Low-)
  and Low-source-Exit-edge:
   $\exists$  a. valid-edge a  $\wedge$  sourcenode a = (-Low-)  $\wedge$  targetnode a = (-Exit-)  $\wedge$ 
    kind a = ( $\lambda$ s. True) $\surd$ 
  and Exit-successor-of-Low:
   $\llbracket$ valid-edge a; sourcenode a = (-Low-) $\rrbracket \implies$  targetnode a = (-Exit-)

```

```

and DefHigh: Def (-High-) = H
and UseHigh: Use (-High-) = H
and UseLow: Use (-Low-) = L
and HighLowDistinct:  $H \cap L = \{\}$ 
and HighLowUNIV:  $H \cup L = UNIV$ 

begin

lemma Low-neq-Exit: assumes  $L \neq \{\}$  shows  $(-Low-) \neq (-Exit-)$ 
proof
  assume  $(-Low-) = (-Exit-)$ 
  have Use  $(-Exit-) = \{\}$  by fastforce
  with UseLow  $\langle L \neq \{\} \rangle \langle (-Low-) = (-Exit-) \rangle$  show False by simp
qed

lemma valid-node-High [simp]:valid-node (-High-)
  using High-target-Entry-edge by fastforce

lemma valid-node-Low [simp]:valid-node (-Low-)
  using Low-source-Exit-edge by fastforce

lemma get-proc-Low:
  get-proc (-Low-) = Main
proof –
  from Low-source-Exit-edge obtain a where valid-edge a
    and sourcenode a = (-Low-) and targetnode a = (-Exit-)
    and intra-kind (kind a) by(fastforce simp:intra-kind-def)
  from  $\langle valid-edge\ a \rangle \langle intra-kind\ (kind\ a) \rangle$ 
  have get-proc (sourcenode a) = get-proc (targetnode a) by(rule get-proc-intra)
  with  $\langle sourcenode\ a = (-Low-) \rangle \langle targetnode\ a = (-Exit-) \rangle$  get-proc-Exit
  show ?thesis by simp
qed

lemma get-proc-High:
  get-proc (-High-) = Main
proof –
  from High-target-Entry-edge obtain a where valid-edge a
    and sourcenode a = (-Entry-) and targetnode a = (-High-)
    and intra-kind (kind a) by(fastforce simp:intra-kind-def)
  from  $\langle valid-edge\ a \rangle \langle intra-kind\ (kind\ a) \rangle$ 
  have get-proc (sourcenode a) = get-proc (targetnode a) by(rule get-proc-intra)
  with  $\langle sourcenode\ a = (-Entry-) \rangle \langle targetnode\ a = (-High-) \rangle$  get-proc-Entry
  show ?thesis by simp
qed

```

lemma *Entry-path-High-path*:

assumes $(-Entry-)$ $-as \rightarrow^* n$ **and** *inner-node* n
obtains $a' as'$ **where** $as = a' \# as'$ **and** $(-High-)$ $-as' \rightarrow^* n$
and $kind\ a' = (\lambda s. True)_{\checkmark}$
proof(*atomize-elim*)
from $\langle (-Entry-) -as \rightarrow^* n \rangle \langle inner-node\ n \rangle$
show $\exists a' as'. as = a' \# as' \wedge (-High-) -as' \rightarrow^* n \wedge kind\ a' = (\lambda s. True)_{\checkmark}$
proof(*induct* $n' \equiv (-Entry-)$ *as* *n* *rule: path.induct*)
case (*Cons-path* n'' *as* n' *a*)
from $\langle n'' -as \rightarrow^* n' \rangle \langle inner-node\ n' \rangle$ **have** $n'' \neq (-Exit-)$
by(*fastforce simp: inner-node-def*)
with $\langle valid-edge\ a \rangle \langle sourcenode\ a = (-Entry-) \rangle \langle targetnode\ a = n'' \rangle$
have $n'' = (-High-)$ **by** $-(drule\ Entry-edge-Exit-or-High, auto)$
from *High-target-Entry-edge*
obtain a' **where** *valid-edge* a' **and** *sourcenode* $a' = (-Entry-)$
and *targetnode* $a' = (-High-)$ **and** $kind\ a' = (\lambda s. True)_{\checkmark}$
by *blast*
with $\langle valid-edge\ a \rangle \langle sourcenode\ a = (-Entry-) \rangle \langle targetnode\ a = n'' \rangle$
 $\langle n'' = (-High-) \rangle$
have $a = a'$ **by**(*auto dest: edge-det*)
with $\langle n'' -as \rightarrow^* n' \rangle \langle n'' = (-High-) \rangle \langle kind\ a' = (\lambda s. True)_{\checkmark} \rangle$ **show** *?case* **by**
blast
qed *fastforce*
qed

lemma *Exit-path-Low-path*:

assumes $n -as \rightarrow^* (-Exit-)$ **and** *inner-node* n
obtains $a' as'$ **where** $as = as' @ [a']$ **and** $n -as' \rightarrow^* (-Low-)$
and $kind\ a' = (\lambda s. True)_{\checkmark}$
proof(*atomize-elim*)
from $\langle n -as \rightarrow^* (-Exit-) \rangle$
show $\exists as' a'. as = as' @ [a'] \wedge n -as' \rightarrow^* (-Low-) \wedge kind\ a' = (\lambda s. True)_{\checkmark}$
proof(*induct* *as* *rule: rev-induct*)
case *Nil*
with $\langle inner-node\ n \rangle$ **show** *?case* **by** *fastforce*
next
case (*snoc* $a' as'$)
from $\langle n -as' @ [a'] \rightarrow^* (-Exit-) \rangle$
have $n -as' \rightarrow^* sourcenode\ a'$ **and** *valid-edge* a' **and** *targetnode* $a' = (-Exit-)$
by(*auto elim: path-split-snoc*)
{ assume *sourcenode* $a' = (-Entry-)$
with $\langle n -as' \rightarrow^* sourcenode\ a' \rangle$ **have** $n = (-Entry-)$
by(*blast intro!: path-Entry-target*)
with $\langle inner-node\ n \rangle$ **have** *False* **by**(*simp add: inner-node-def*) }
with $\langle valid-edge\ a' \rangle \langle targetnode\ a' = (-Exit-) \rangle$ **have** *sourcenode* $a' = (-Low-)$
by(*blast dest!: Exit-edge-Entry-or-Low*)
from *Low-source-Exit-edge*
obtain ax **where** *valid-edge* ax **and** *sourcenode* $ax = (-Low-)$

```

    and targetnode ax = (-Exit-) and kind ax = (λs. True)✓
    by blast
  with ⟨valid-edge a'⟩ ⟨targetnode a' = (-Exit-)⟩ ⟨sourcnode a' = (-Low-)⟩
  have a' = ax by(fastforce intro:edge-det)
  with ⟨n -as'→* sourcnode a'⟩ ⟨sourcnode a' = (-Low-)⟩ ⟨kind ax = (λs.
True)✓⟩
  show ?case by blast
qed
qed

```

```

lemma not-Low-High: V ∉ L ⇒ V ∈ H
  using HighLowUNIV
  by fastforce

```

```

lemma not-High-Low: V ∉ H ⇒ V ∈ L
  using HighLowUNIV
  by fastforce

```

2.2 Low Equivalence

In classical noninterference, an external observer can only see public values, in our case the L -variables. If two states agree in the values of all L -variables, these states are indistinguishable for him. *Low equivalence* groups those states in an equivalence class using the relation \approx_L :

```

definition lowEquivalence :: ('var → 'val) list ⇒ ('var → 'val) list ⇒ bool
(infixl  $\approx_L$  50)
  where  $s \approx_L s' \equiv \forall V \in L. hd\ s\ V = hd\ s'\ V$ 

```

The following lemmas connect low equivalent states with relevant variables as necessary in the correctness proof for slicing.

```

lemma relevant-vars-Entry:
  assumes V ∈ rv S (CFG-node (-Entry-)) and (-High-) ∉ [HRB-slice S]CFG
  shows V ∈ L
proof -
  from ⟨V ∈ rv S (CFG-node (-Entry-))⟩ obtain as n'
    where (-Entry-) -as→i* parent-node n'
    and n' ∈ HRB-slice S and V ∈ UseSDG n'
    and ∀ n''. valid-SDG-node n'' ∧ parent-node n'' ∈ set (sourcnodes as)
      → V ∉ DefSDG n'' by(fastforce elim:rvE)
  from ⟨(-Entry-) -as→i* parent-node n'⟩ have valid-node (parent-node n')
    by(fastforce intro:path-valid-node simp:intra-path-def)
  thus ?thesis
proof(cases parent-node n' rule:valid-node-cases)
  case Entry
  with ⟨V ∈ UseSDG n'⟩ have False
    by -(drule SDG-Use-parent-Use,simp add:Entry-empty)
  thus ?thesis by simp

```

```

next
  case Exit
  with  $\langle V \in Use_{SDG} n' \rangle$  have False
    by  $-(drule\ SDG\text{-}Use\text{-}parent\text{-}Use, simp\ add: Exit\text{-}empty)$ 
  thus ?thesis by simp
next
  case inner
  with  $\langle (-Entry)\text{-}as \rightarrow_i * parent\text{-}node\ n' \rangle$  obtain  $a'\ as'$  where  $as = a' \# as'$ 
    and  $\langle (-High)\text{-}as' \rightarrow_i * parent\text{-}node\ n' \rangle$ 
    by  $(fastforce\ elim: Entry\text{-}path\text{-}High\text{-}path\ simp: intra\text{-}path\text{-}def)$ 
  from  $\langle (-Entry)\text{-}as \rightarrow_i * parent\text{-}node\ n' \rangle$   $\langle as = a' \# as' \rangle$ 
have  $sourcenode\ a' = (-Entry)$  by  $(fastforce\ elim: path.cases\ simp: intra\text{-}path\text{-}def)$ 
show ?thesis
proof  $(cases\ as' = [])$ 
  case True
  with  $\langle (-High)\text{-}as' \rightarrow_i * parent\text{-}node\ n' \rangle$  have  $parent\text{-}node\ n' = (-High)$ 
    by  $(fastforce\ simp: intra\text{-}path\text{-}def)$ 
  with  $\langle n' \in HRB\text{-}slice\ S \rangle$   $\langle (-High)\text{-} \notin [HRB\text{-}slice\ S]_{CFG} \rangle$ 
have False
    by  $(fastforce\ dest: valid\text{-}SDG\text{-}node\text{-}in\text{-}slice\text{-}parent\text{-}node\text{-}in\text{-}slice\ simp: SDG\text{-}to\text{-}CFG\text{-}set\text{-}def)$ 
  thus ?thesis by simp
next
  case False
  with  $\langle (-High)\text{-}as' \rightarrow_i * parent\text{-}node\ n' \rangle$  have  $hd\ (sourcenodes\ as') = (-High)$ 
    by  $(fastforce\ intro: path\text{-}sourcenode\ simp: intra\text{-}path\text{-}def)$ 
  from False have  $hd\ (sourcenodes\ as') \in set\ (sourcenodes\ as')$ 
    by  $(fastforce\ intro: hd\text{-}in\text{-}set\ simp: sourcenodes\text{-}def)$ 
  with  $\langle as = a' \# as' \rangle$  have  $hd\ (sourcenodes\ as') \in set\ (sourcenodes\ as)$ 
    by  $(simp\ add: sourcenodes\text{-}def)$ 
  from  $\langle hd\ (sourcenodes\ as') = (-High) \rangle$ 
have  $valid\text{-}node\ (hd\ (sourcenodes\ as'))$  by simp
have  $valid\text{-}SDG\text{-}node\ (CFG\text{-}node\ (-High))$  by simp
  with  $\langle hd\ (sourcenodes\ as') = (-High) \rangle$ 
   $\langle hd\ (sourcenodes\ as') \in set\ (sourcenodes\ as) \rangle$ 
   $\langle \forall n''. valid\text{-}SDG\text{-}node\ n'' \wedge parent\text{-}node\ n'' \in set\ (sourcenodes\ as) \rangle$ 
   $\rightarrow V \notin Def_{SDG}\ n''$ 
have  $V \notin Def\ (-High)$ 
    by  $(fastforce\ dest: CFG\text{-}Def\text{-}SDG\text{-}Def[OF\ \langle valid\text{-}node\ (hd\ (sourcenodes\ as')) \rangle])$ 
hence  $V \notin H$  by  $(simp\ add: DefHigh)$ 
  thus ?thesis by  $(rule\ not\text{-}High\text{-}Low)$ 
qed
qed
qed

```

lemma *lowEquivalence-relevant-nodes-Entry*:
assumes $s \approx_L s'$ **and** $\langle (-High)\text{-} \notin [HRB\text{-}slice\ S]_{CFG} \rangle$

shows $\forall V \in rv\ S\ (CFG\text{-node}\ (-Entry-)).\ hd\ s\ V = hd\ s'\ V$
proof
fix V **assume** $V \in rv\ S\ (CFG\text{-node}\ (-Entry-))$
with $\langle (-High-) \notin [HRB\text{-slice}\ S]_{CFG} \rangle$ **have** $V \in L$ **by** $-(rule\ relevant\ vars\ Entry)$
with $\langle s \approx_L s' \rangle$ **show** $hd\ s\ V = hd\ s'\ V$ **by** $(simp\ add:\ lowEquivalence\ def)$
qed

2.3 The Correctness Proofs

In the following, we present two correctness proofs that slicing guarantees IFC noninterference. In both theorems, $CFG\text{-node}\ (-High-) \notin HRB\text{-slice}\ S$, where $CFG\text{-node}\ (-Low-) \in S$, makes sure that no high variable (which are all defined in $(-High-)$) can influence a low variable (which are all used in $(-Low-)$).

First, a theorem regarding $(-Entry-) -as \rightarrow^* (-Exit-)$ paths in the control flow graph (CFG), which agree to a complete program execution:

lemma *slpa-rv-Low-Use-Low*:

assumes $CFG\text{-node}\ (-Low-) \in S$
shows $\llbracket same\ level\ path\ aux\ cs\ as;\ upd\ cs\ cs\ as = \llbracket;\ same\ level\ path\ aux\ cs\ as';$
 $\forall c \in set\ cs.\ valid\ edge\ c;\ m -as \rightarrow^* (-Low-); m -as' \rightarrow^* (-Low-);$
 $\forall i < length\ cs.\ \forall V \in rv\ S\ (CFG\text{-node}\ (sourcnode\ (cs!i))).$
 $fst\ (s!Suc\ i)\ V = fst\ (s'!Suc\ i)\ V;\ \forall i < Suc\ (length\ cs).\ snd\ (s!i) = snd\ (s'!i);$
 $\forall V \in rv\ S\ (CFG\text{-node}\ m).\ state\ val\ s\ V = state\ val\ s'\ V;$
 $preds\ (slice\ kinds\ S\ as)\ s;\ preds\ (slice\ kinds\ S\ as')\ s';$
 $length\ s = Suc\ (length\ cs);\ length\ s' = Suc\ (length\ cs)\rrbracket$
 $\implies \forall V \in Use\ (-Low-).\ state\ val\ (transfers\ (slice\ kinds\ S\ as)\ s)\ V =$
 $state\ val\ (transfers\ (slice\ kinds\ S\ as')\ s')\ V$

proof $(induct\ arbitrary:m\ as'\ s\ s'\ rule:slpa\ induct)$

case $(slpa\ empty\ cs)$

from $\langle m -\llbracket \rightarrow^* (-Low-) \rangle$ **have** $m = (-Low-)$ **by** *fastforce*

from $\langle m -\llbracket \rightarrow^* (-Low-) \rangle$ **have** *valid-node m*

by $(rule\ path\ valid\ node)+$

{ fix V **assume** $V \in Use\ (-Low-)$

moreover

from $\langle valid\ node\ m \rangle \langle m = (-Low-) \rangle$ **have** $(-Low-) -\llbracket \rightarrow_{\iota}^* (-Low-) \rangle$

by $(fastforce\ intro:\ empty\ path\ simp:\ intra\ path\ def)$

moreover

from $\langle valid\ node\ m \rangle \langle m = (-Low-) \rangle \langle CFG\text{-node}\ (-Low-) \in S \rangle$

have $CFG\text{-node}\ (-Low-) \in HRB\text{-slice}\ S$

by $(fastforce\ intro:\ HRB\ slice\ refl)$

ultimately have $V \in rv\ S\ (CFG\text{-node}\ m)$

using $\langle m = (-Low-) \rangle$

by $(auto\ intro!:rvI\ CFG\ Use\ SDG\ Use\ simp:\ sourcnodes\ def)\ }$

hence $\forall V \in Use\ (-Low-).\ V \in rv\ S\ (CFG\text{-node}\ m)$ **by** *simp*

show *?case*

proof $(cases\ L = \{\})$

case *True* **with** *UseLow* **show** *?thesis* **by** *simp*

next

```

case False
from  $\langle m -as' \rightarrow^* (-Low-) \rangle \langle m = (-Low-) \rangle$  have  $as' = []$ 
proof(induct  $m$   $as'$   $m' \equiv (-Low-)$  rule: path.induct)
  case (Cons-path  $m''$   $as$   $m$ )
  from  $\langle valid-edge\ a \rangle \langle sourcenode\ a = m \rangle \langle m = (-Low-) \rangle$ 
  have  $targetnode\ a = (-Exit-)$  by  $-(rule\ Exit-successor-of-Low, simp+)$ 
  with  $\langle targetnode\ a = m'' \rangle \langle m'' -as \rightarrow^* (-Low-) \rangle$ 
  have  $(-Low-) = (-Exit-)$  by  $-(drule\ path-Exit-source, auto)$ 
  with False have False by  $-(drule\ Low-neq-Exit, simp)$ 
  thus ?case by simp
qed simp
with  $\langle \forall V \in Use\ (-Low-). V \in rv\ S\ (CFG-node\ m) \rangle$ 
   $\langle \forall V \in rv\ S\ (CFG-node\ m). state-val\ s\ V = state-val\ s'\ V \rangle Nil$ 
show ?thesis by(auto simp:slice-kinds-def)
qed
next
case (slpa-intra  $cs$   $a$   $as$ )
note  $IH = \langle \bigwedge m\ as'\ s\ s'. \llbracket upd-cs\ cs\ as = [] \rrbracket; same-level-path-aux\ cs\ as';$ 
   $\forall a \in set\ cs. valid-edge\ a; m -as \rightarrow^* (-Low-); m -as' \rightarrow^* (-Low-);$ 
   $\forall i < length\ cs. \forall V \in rv\ S\ (CFG-node\ (sourcenode\ (cs\ !\ i))).$ 
   $fst\ (s\ !\ Suc\ i)\ V = fst\ (s'\ !\ Suc\ i)\ V;$ 
   $\forall i < Suc\ (length\ cs). snd\ (s\ !\ i) = snd\ (s'\ !\ i);$ 
   $\forall V \in rv\ S\ (CFG-node\ m). state-val\ s\ V = state-val\ s'\ V;$ 
   $preds\ (slice-kinds\ S\ as)\ s; preds\ (slice-kinds\ S\ as')\ s';$ 
   $length\ s = Suc\ (length\ cs); length\ s' = Suc\ (length\ cs)\rrbracket$ 
   $\implies \forall V \in Use\ (-Low-). state-val\ (transfers(slice-kinds\ S\ as)\ s)\ V =$ 
   $state-val\ (transfers(slice-kinds\ S\ as')\ s')\ V \rangle$ 
note  $rvs = \langle \forall i < length\ cs. \forall V \in rv\ S\ (CFG-node\ (sourcenode\ (cs\ !\ i))).$ 
   $fst\ (s\ !\ Suc\ i)\ V = fst\ (s'\ !\ Suc\ i)\ V \rangle$ 
from  $\langle m -a \# as \rightarrow^* (-Low-) \rangle$  have  $sourcenode\ a = m$  and  $valid-edge\ a$ 
  and  $targetnode\ a -as \rightarrow^* (-Low-)$  by(auto elim:path-split-Cons)
show ?case
proof(cases  $L = \{\}$ )
  case True with UseLow show ?thesis by simp
next
case False
show ?thesis
proof(cases  $as'$ )
  case Nil
  with  $\langle m -as' \rightarrow^* (-Low-) \rangle$  have  $m = (-Low-)$  by fastforce
  with  $\langle valid-edge\ a \rangle \langle sourcenode\ a = m \rangle$  have  $targetnode\ a = (-Exit-)$ 
  by  $-(rule\ Exit-successor-of-Low, simp+)$ 
  from Low-source-Exit-edge obtain  $a'$  where  $valid-edge\ a'$ 
  and  $sourcenode\ a' = (-Low-)$  and  $targetnode\ a' = (-Exit-)$ 
  and  $kind\ a' = (\lambda s. True)_{\surd}$  by blast
  from  $\langle valid-edge\ a \rangle \langle sourcenode\ a = m \rangle \langle m = (-Low-) \rangle$ 
   $\langle targetnode\ a = (-Exit-) \rangle \langle valid-edge\ a' \rangle \langle sourcenode\ a' = (-Low-) \rangle$ 
   $\langle targetnode\ a' = (-Exit-) \rangle$ 
  have  $a = a'$  by(fastforce dest:edge-det)

```



```

with ⟨kind a' = (λs. True)✓⟩ have kind a = (λs. True)✓ by simp
with ⟨targetnode a = (-Exit-)⟩ ⟨targetnode a -as→* (-Low-)⟩
have (-Low-) = (-Exit-) by -(drule path-Exit-source, auto)
with False have False by -(drule Low-neq-Exit, simp)
thus ?thesis by simp
next
case (Cons ax asx)
with ⟨m -as'→* (-Low-)⟩ have sourcenode ax = m and valid-edge ax
  and targetnode ax -asx→* (-Low-) by (auto elim:path-split-Cons)
from ⟨preds (slice-kinds S (a # as)) s⟩
obtain cf cfs where [simp]: s = cf # cfs by (cases s)(auto simp:slice-kinds-def)
from ⟨preds (slice-kinds S as') s'⟩ ⟨as' = ax # asx⟩
obtain cf' cfs' where [simp]: s' = cf' # cfs'
  by (cases s')(auto simp:slice-kinds-def)
have intra-kind (kind ax)
proof (cases kind ax rule:edge-kind-cases)
  case (Call Q r p fs)
  have False
proof (cases sourcenode a ∈ [HRB-slice S]CFG)
  case True
  with ⟨intra-kind (kind a)⟩ have slice-kind S a = kind a
    by -(rule slice-intra-kind-in-slice)
  from ⟨valid-edge ax⟩ ⟨kind ax = Q:r↔pfs⟩
  have unique: ∃! a'. valid-edge a' ∧ sourcenode a' = sourcenode ax ∧
    intra-kind (kind a') by (rule call-only-one-intra-edge)
  from ⟨valid-edge ax⟩ ⟨kind ax = Q:r↔pfs⟩ obtain x
    where x ∈ get-return-edges ax by (fastforce dest:get-return-edge-call)
  with ⟨valid-edge ax⟩ obtain a' where valid-edge a'
    and sourcenode a' = sourcenode ax and kind a' = (λcf. False)✓
    by (fastforce dest:call-return-node-edge)
  with ⟨valid-edge a⟩ ⟨sourcenode a = m⟩ ⟨sourcenode ax = m⟩
    ⟨intra-kind (kind a)⟩ unique
  have a' = a by (fastforce simp:intra-kind-def)
  with ⟨kind a' = (λcf. False)✓⟩ ⟨slice-kind S a = kind a⟩
    ⟨preds (slice-kinds S (a # as)) s⟩
  have False by (cases s)(auto simp:slice-kinds-def)
  thus ?thesis by simp
next
case False
  with ⟨kind ax = Q:r↔pfs⟩ ⟨sourcenode a = m⟩ ⟨sourcenode ax = m⟩
  have slice-kind S ax = (λcf. False):r↔pfs
    by (fastforce intro:slice-kind-Call)
  with ⟨as' = ax # asx⟩ ⟨preds (slice-kinds S as') s'⟩
  have False by (cases s')(auto simp:slice-kinds-def)
  thus ?thesis by simp
qed
thus ?thesis by simp
next
case (Return Q p f)

```

```

from ⟨valid-edge ax⟩ ⟨kind ax = Q↔pf⟩ ⟨valid-edge a⟩ ⟨intra-kind (kind a)⟩
  ⟨sourcenode a = m⟩ ⟨sourcenode ax = m⟩
have False by -(drule return-edges-only, auto simp:intra-kind-def)
thus ?thesis by simp
qed simp
with ⟨same-level-path-aux cs as'⟩ ⟨as' = ax#asx⟩
have same-level-path-aux cs asx by(fastforce simp:intra-kind-def)
show ?thesis
proof(cases targetnode a = targetnode ax)
  case True
    with ⟨valid-edge a⟩ ⟨valid-edge ax⟩ ⟨sourcenode a = m⟩ ⟨sourcenode ax =
m⟩
    have a = ax by(fastforce intro:edge-det)
    with ⟨valid-edge a⟩ ⟨intra-kind (kind a)⟩ ⟨sourcenode a = m⟩
      ⟨∀ V∈rv S (CFG-node m). state-val s V = state-val s' V⟩
      ⟨preds (slice-kinds S (a # as)) s⟩
      ⟨preds (slice-kinds S as') s'⟩ ⟨as' = ax # asx⟩
    have rv:∀ V∈rv S (CFG-node (targetnode a)).
      state-val (transfer (slice-kind S a) s) V =
      state-val (transfer (slice-kind S a) s') V
      by -(rule rv-edge-slice-kinds, auto)
    from ⟨upd-cs cs (a # as) = []⟩ ⟨intra-kind (kind a)⟩
    have upd-cs cs as = [] by(fastforce simp:intra-kind-def)
    from ⟨targetnode ax -asx→* (-Low-)⟩ ⟨a = ax⟩
    have targetnode a -asx→* (-Low-) by simp
    from ⟨valid-edge a⟩ ⟨intra-kind (kind a)⟩
    obtain cfx
      where cfx:transfer (slice-kind S a) s = cfx#cfs ∧ snd cfx = snd cf
      apply(cases cf)
      apply(cases sourcenode a ∈ [HRB-slice S]CFG) apply auto
      apply(fastforce dest:slice-intra-kind-in-slice simp:intra-kind-def)
      apply(auto simp:intra-kind-def)
      apply(drule slice-kind-Upd) apply auto
      by(erule kind-Predicate-notin-slice-slice-kind-Predicate) auto
    from ⟨valid-edge a⟩ ⟨intra-kind (kind a)⟩
    obtain cfx'
      where cfx':transfer (slice-kind S a) s' = cfx'#cfs' ∧ snd cfx' = snd cf'
      apply(cases cf')
      apply(cases sourcenode a ∈ [HRB-slice S]CFG) apply auto
      apply(fastforce dest:slice-intra-kind-in-slice simp:intra-kind-def)
      apply(auto simp:intra-kind-def)
      apply(drule slice-kind-Upd) apply auto
      by(erule kind-Predicate-notin-slice-slice-kind-Predicate) auto
    with cfx ⟨∀ i < Suc (length cs). snd (s!i) = snd (s'!i)⟩
    have snds:∀ i < Suc (length cs).
      snd (transfer (slice-kind S a) s ! i) =
      snd (transfer (slice-kind S a) s' ! i)
      by auto(case-tac i, auto)
    from rvs cfx cfx' have rvs':∀ i < length cs.

```

```

     $\forall V \in rv\ S\ (CFG\text{-node}\ (sourcenode\ (cs\ !\ i))).$ 
     $fst\ (transfer\ (slice\text{-kind}\ S\ a)\ s\ !\ Suc\ i)\ V =$ 
     $fst\ (transfer\ (slice\text{-kind}\ S\ a)\ s'\ !\ Suc\ i)\ V$ 
    by fastforce
from  $\langle preds\ (slice\text{-kinds}\ S\ (a\ \# \ as))\ s \rangle$ 
have  $preds\ (slice\text{-kinds}\ S\ as)$ 
     $(transfer\ (slice\text{-kind}\ S\ a)\ s)\ \mathbf{by}(simp\ add:slice\text{-kinds}\text{-def})$ 
moreover
from  $\langle preds\ (slice\text{-kinds}\ S\ as')\ s' \rangle\ \langle as' = ax\ \# \ asx \rangle\ \langle a = ax \rangle$ 
have  $preds\ (slice\text{-kinds}\ S\ asx)\ (transfer\ (slice\text{-kind}\ S\ a)\ s')$ 
    by  $(simp\ add:slice\text{-kinds}\text{-def})$ 
moreover
from  $\langle valid\text{-edge}\ a \rangle\ \langle intra\text{-kind}\ (kind\ a) \rangle$ 
have  $length\ (transfer\ (slice\text{-kind}\ S\ a)\ s) = length\ s$ 
    by  $(cases\ sourcenode\ a \in \lfloor HRB\text{-slice}\ S \rfloor_{CFG})$ 
 $(auto\ dest:slice\text{-intra}\text{-kind}\text{-in}\text{-slice}\ slice\text{-kind}\text{-Upd}$ 
     $elim:kind\text{-Predicate}\text{-notin}\text{-slice}\text{-slice}\text{-kind}\text{-Predicate}\ simp:intra\text{-kind}\text{-def})$ 
with  $\langle length\ s = Suc\ (length\ cs) \rangle$ 
have  $length\ (transfer\ (slice\text{-kind}\ S\ a)\ s) = Suc\ (length\ cs)$ 
    by simp
moreover
from  $\langle a = ax \rangle\ \langle valid\text{-edge}\ a \rangle\ \langle intra\text{-kind}\ (kind\ a) \rangle$ 
have  $length\ (transfer\ (slice\text{-kind}\ S\ a)\ s') = length\ s'$ 
    by  $(cases\ sourcenode\ ax \in \lfloor HRB\text{-slice}\ S \rfloor_{CFG})$ 
 $(auto\ dest:slice\text{-intra}\text{-kind}\text{-in}\text{-slice}\ slice\text{-kind}\text{-Upd}$ 
     $elim:kind\text{-Predicate}\text{-notin}\text{-slice}\text{-slice}\text{-kind}\text{-Predicate}\ simp:intra\text{-kind}\text{-def})$ 
with  $\langle length\ s' = Suc\ (length\ cs) \rangle$ 
have  $length\ (transfer\ (slice\text{-kind}\ S\ a)\ s') = Suc\ (length\ cs)$ 
    by simp
moreover
from  $IH[OF\ \langle upd\text{-cs}\ cs\ as = [] \rangle\ \langle same\text{-level}\text{-path}\text{-aux}\ cs\ asx \rangle$ 
     $\langle \forall c \in set\ cs.\ valid\text{-edge}\ c \rangle\ \langle targetnode\ a\ \text{-}as \rightarrow * (-Low\text{-}) \rangle$ 
     $\langle targetnode\ a\ \text{-}asx \rightarrow * (-Low\text{-}) \rangle\ rvs'\ snds\ rv\ calculation]$ 
     $\langle as' = ax\ \# \ asx \rangle\ \langle a = ax \rangle$ 
show ?thesis by  $(simp\ add:slice\text{-kinds}\text{-def})$ 
next
case False
from  $\langle \forall i < Suc\ (length\ cs).\ snd\ (s!i) = snd\ (s'!i) \rangle$ 
have  $snd\ (hd\ s) = snd\ (hd\ s')\ \mathbf{by}(erule\ tac\ x=0\ \mathbf{in}\ allE)\ fastforce$ 
with  $\langle valid\text{-edge}\ a \rangle\ \langle valid\text{-edge}\ ax \rangle\ \langle sourcenode\ a = m \rangle$ 
     $\langle sourcenode\ ax = m \rangle\ \langle as' = ax\ \# \ asx \rangle\ \mathbf{False}$ 
     $\langle intra\text{-kind}\ (kind\ a) \rangle\ \langle intra\text{-kind}\ (kind\ ax) \rangle$ 
     $\langle preds\ (slice\text{-kinds}\ S\ (a\ \# \ as))\ s \rangle$ 
     $\langle preds\ (slice\text{-kinds}\ S\ as')\ s' \rangle$ 
     $\langle \forall V \in rv\ S\ (CFG\text{-node}\ m).\ state\text{-val}\ s\ V = state\text{-val}\ s'\ V \rangle$ 
     $\langle length\ s = Suc\ (length\ cs) \rangle\ \langle length\ s' = Suc\ (length\ cs) \rangle$ 
have False by  $(fastforce\ intro!:rv\text{-branching}\text{-edges}\text{-slice}\text{-kinds}\text{-False}[of\ a\ ax])$ 
thus ?thesis by simp
qed

```

```

qed
qed
next
case (slpa-Call cs a as Q r p fs)
note IH = ⟨ $\bigwedge m \text{ as}' s s'$ ⟩
  [[upd-cs (a # cs) as = []; same-level-path-aux (a # cs) as';
   $\forall c \in \text{set } (a \# cs). \text{valid-edge } c; m \text{ --as}\rightarrow^* \text{(-Low-)}; m \text{ --as}'\rightarrow^* \text{(-Low-)};$ 
   $\forall i < \text{length } (a \# cs). \forall V \in \text{rv } S \text{ (CFG-node (sourcenode ((a \# cs) ! i)))}. \text{fst } (s ! \text{Suc } i) V = \text{fst } (s' ! \text{Suc } i) V;$ 
   $\forall i < \text{Suc } (\text{length } (a \# cs)). \text{snd } (s ! i) = \text{snd } (s' ! i);$ 
   $\forall V \in \text{rv } S \text{ (CFG-node } m). \text{state-val } s V = \text{state-val } s' V;$ 
  preds (slice-kinds S as) s; preds (slice-kinds S as') s';
  length s = Suc (length (a # cs)); length s' = Suc (length (a # cs))]
   $\implies \forall V \in \text{Use } \text{(-Low-)}. \text{state-val } (\text{transfers}(\text{slice-kinds } S \text{ as}) s) V =$ 
   $\text{state-val } (\text{transfers}(\text{slice-kinds } S \text{ as}') s') V$ 
note rvs = ⟨ $\forall i < \text{length } cs. \forall V \in \text{rv } S \text{ (CFG-node (sourcenode (cs ! i)))}. \text{fst } (s ! \text{Suc } i) V = \text{fst } (s' ! \text{Suc } i) V$ ⟩
from ⟨m --a # as $\rightarrow^*$  (-Low-) $\rangle$  have sourcenode a = m and valid-edge a
  and targetnode a --as $\rightarrow^*$  (-Low-) by(auto elim:path-split-Cons)
from ⟨ $\forall c \in \text{set } cs. \text{valid-edge } c$ ⟩ ⟨valid-edge a⟩
have  $\forall c \in \text{set } (a \# cs). \text{valid-edge } c$  by simp
show ?case
  proof(cases L = {})
    case True with UseLow show ?thesis by simp
  next
    case False
      show ?thesis
        proof(cases as $\wedge$ )
          case Nil
            with ⟨m --as' $\rightarrow^*$  (-Low-) $\rangle$  have m = (-Low-) by fastforce
            with ⟨valid-edge a⟩ ⟨sourcenode a = m⟩ have targetnode a = (-Exit-)
              by -(rule Exit-successor-of-Low,simp+)
            from Low-source-Exit-edge obtain a' where valid-edge a'
              and sourcenode a' = (-Low-) and targetnode a' = (-Exit-)
              and kind a' = ( $\lambda s. \text{True}$ ) $\surd$  by blast
            from ⟨valid-edge a⟩ ⟨sourcenode a = m⟩ ⟨m = (-Low-) $\rangle$ 
              ⟨targetnode a = (-Exit-) $\rangle$  ⟨valid-edge a'⟩ ⟨sourcenode a' = (-Low-) $\rangle$ 
              ⟨targetnode a' = (-Exit-) $\rangle$ 
            have a = a' by(fastforce dest:edge-det)
            with ⟨kind a' = ( $\lambda s. \text{True}$ ) $\surd$ ⟩ have kind a = ( $\lambda s. \text{True}$ ) $\surd$  by simp
            with ⟨targetnode a = (-Exit-) $\rangle$  ⟨targetnode a --as $\rightarrow^*$  (-Low-) $\rangle$ 
            have (-Low-) = (-Exit-) by -(drule path-Exit-source,auto)
            with False have False by -(drule Low-neq-Exit,simp)
            thus ?thesis by simp
          next
            case (Cons ax asx)
              with ⟨m --as' $\rightarrow^*$  (-Low-) $\rangle$  have sourcenode ax = m and valid-edge ax
                and targetnode ax --asx $\rightarrow^*$  (-Low-) by(auto elim:path-split-Cons)
              from ⟨preds (slice-kinds S (a # as)) s $\rangle$ 

```

```

obtain  $cf\ cfs$  where  $[simp]:s = cf\#\ cfs$  by  $(cases\ s)(auto\ simp:slice-kinds-def)$ 
from  $\langle preds\ (slice-kinds\ S\ as')\ s' \rangle\ \langle as' = ax\ \#\ asx \rangle$ 
obtain  $cf'\ cfs'$  where  $[simp]:s' = cf'\#\ cfs'$ 
by  $(cases\ s')(auto\ simp:slice-kinds-def)$ 
have  $\exists Q\ r\ p\ fs.\ kind\ ax = Q:r\hookrightarrow\ pfs$ 
proof  $(cases\ kind\ ax\ rule:edge-kind-cases)$ 
  case Intra
  have False
  proof  $(cases\ sourcenode\ ax\ \in\ [HRB-slice\ S]_{CFG})$ 
    case True
    with  $\langle intra-kind\ (kind\ ax) \rangle$ 
    have  $slice-kind\ S\ ax = kind\ ax$ 
    by  $-(rule\ slice-intra-kind-in-slice)$ 
    from  $\langle valid-edge\ a \rangle\ \langle kind\ a = Q:r\hookrightarrow\ pfs \rangle$ 
    have  $unique:\exists!a'.\ valid-edge\ a' \wedge sourcenode\ a' = sourcenode\ a \wedge$ 
       $intra-kind(kind\ a')$  by  $(rule\ call-only-one-intra-edge)$ 
    from  $\langle valid-edge\ a \rangle\ \langle kind\ a = Q:r\hookrightarrow\ pfs \rangle$  obtain  $x$ 
    where  $x \in get-return-edges\ a$  by  $(fastforce\ dest:get-return-edge-call)$ 
    with  $\langle valid-edge\ a \rangle$  obtain  $a'$  where  $valid-edge\ a'$ 
    and  $sourcenode\ a' = sourcenode\ a$  and  $kind\ a' = (\lambda cf.\ False)\checkmark$ 
    by  $(fastforce\ dest:call-return-node-edge)$ 
    with  $\langle valid-edge\ ax \rangle\ \langle sourcenode\ ax = m \rangle\ \langle sourcenode\ a = m \rangle$ 
     $\langle intra-kind\ (kind\ ax) \rangle\ unique$ 
    have  $a' = ax$  by  $(fastforce\ simp:intra-kind-def)$ 
    with  $\langle kind\ a' = (\lambda cf.\ False)\checkmark \rangle$ 
     $\langle slice-kind\ S\ ax = kind\ ax \rangle\ \langle as' = ax\ \#\ asx \rangle$ 
     $\langle preds\ (slice-kinds\ S\ as')\ s' \rangle$ 
    have False by  $(simp\ add:slice-kinds-def)$ 
    thus  $?thesis$  by simp
  next
  case False
  with  $\langle kind\ a = Q:r\hookrightarrow\ pfs \rangle\ \langle sourcenode\ ax = m \rangle\ \langle sourcenode\ a = m \rangle$ 
  have  $slice-kind\ S\ a = (\lambda cf.\ False):r\hookrightarrow\ pfs$ 
  by  $(fastforce\ intro:slice-kind-Call)$ 
  with  $\langle preds\ (slice-kinds\ S\ (a\ \#\ as))\ s \rangle$ 
  have False by  $(simp\ add:slice-kinds-def)$ 
  thus  $?thesis$  by simp
  qed
  thus  $?thesis$  by simp
next
  case  $(Return\ Q'\ p'\ f')$ 
  from  $\langle valid-edge\ ax \rangle\ \langle kind\ ax = Q'\hookrightarrow\ p'\ f' \rangle\ \langle valid-edge\ a \rangle\ \langle kind\ a = Q:r\hookrightarrow\ pfs \rangle$ 
   $\langle sourcenode\ a = m \rangle\ \langle sourcenode\ ax = m \rangle$ 
  have False by  $-(drule\ return-edges-only,auto)$ 
  thus  $?thesis$  by simp
qed simp
have  $sourcenode\ a \in [HRB-slice\ S]_{CFG}$ 
proof  $(rule\ ccontr)$ 
  assume  $sourcenode\ a \notin [HRB-slice\ S]_{CFG}$ 

```

```

from this  $\langle \text{kind } a = Q:r \hookrightarrow pfs \rangle$ 
have slice-kind  $S a = (\lambda cf. \text{False}):r \hookrightarrow pfs$ 
  by (rule slice-kind-Call)
with  $\langle \text{preds } (\text{slice-kinds } S (a \# as)) s \rangle$ 
show False by (simp add:slice-kinds-def)
qed
with  $\langle \text{preds } (\text{slice-kinds } S (a \# as)) s \rangle \langle \text{kind } a = Q:r \hookrightarrow pfs \rangle$ 
have pred (kind  $a$ )  $s$ 
  by (fastforce dest:slice-kind-Call-in-slice simp:slice-kinds-def)
from  $\langle \text{sourcenode } a \in \lfloor \text{HRB-slice } S \rfloor_{CFG} \rangle$ 
   $\langle \text{sourcenode } a = m \rangle \langle \text{sourcenode } ax = m \rangle$ 
have sourcenode  $ax \in \lfloor \text{HRB-slice } S \rfloor_{CFG}$  by simp
with  $\langle as' = ax \# asx \rangle \langle \text{preds } (\text{slice-kinds } S as') s' \rangle$ 
   $\langle \exists Q r p fs. \text{kind } ax = Q:r \hookrightarrow pfs \rangle$ 
have pred (kind  $ax$ )  $s'$ 
  by (fastforce dest:slice-kind-Call-in-slice simp:slice-kinds-def)
{ fix  $V$  assume  $V \in \text{Use } (\text{sourcenode } a)$ 
  from  $\langle \text{valid-edge } a \rangle$  have sourcenode  $a - [] \rightarrow_i^* \text{sourcenode } a$ 
    by (fastforce intro:empty-path simp:intra-path-def)
  with  $\langle \text{sourcenode } a \in \lfloor \text{HRB-slice } S \rfloor_{CFG} \rangle$ 
     $\langle \text{valid-edge } a \rangle \langle V \in \text{Use } (\text{sourcenode } a) \rangle$ 
  have  $V \in \text{rv } S (CFG\text{-node } (\text{sourcenode } a))$ 
  by (auto intro!:rvI CFG-Use-SDG-Use simp:SDG-to-CFG-set-def sourcenodes-def)
}
with  $\langle \forall V \in \text{rv } S (CFG\text{-node } m). \text{state-val } s V = \text{state-val } s' V \rangle$ 
   $\langle \text{sourcenode } a = m \rangle$ 
have Use: $\forall V \in \text{Use } (\text{sourcenode } a). \text{state-val } s V = \text{state-val } s' V$  by simp
from  $\langle \forall i < \text{Suc } (\text{length } cs). \text{snd } (s ! i) = \text{snd } (s' ! i) \rangle$ 
have snd (hd  $s$ ) = snd (hd  $s'$ ) by fastforce
with  $\langle \text{valid-edge } a \rangle \langle \text{kind } a = Q:r \hookrightarrow pfs \rangle \langle \text{valid-edge } ax \rangle$ 
   $\langle \exists Q r p fs. \text{kind } ax = Q:r \hookrightarrow pfs \rangle \langle \text{sourcenode } a = m \rangle \langle \text{sourcenode } ax = m \rangle$ 
   $\langle \text{pred } (\text{kind } a) s \rangle \langle \text{pred } (\text{kind } ax) s' \rangle \text{Use } \langle \text{length } s = \text{Suc } (\text{length } cs) \rangle$ 
   $\langle \text{length } s' = \text{Suc } (\text{length } cs) \rangle$ 
have [simp]: $ax = a$  by (fastforce intro!:CFG-equal-Use-equal-call)
from  $\langle \text{same-level-path-aux } cs as' \rangle \langle as' = ax \# asx \rangle \langle \text{kind } a = Q:r \hookrightarrow pfs \rangle$ 
   $\langle \exists Q r p fs. \text{kind } ax = Q:r \hookrightarrow pfs \rangle$ 
have same-level-path-aux ( $a \# cs$ )  $asx$  by simp
  from  $\langle \text{targetnode } ax - asx \rightarrow^* (-\text{Low-}) \rangle$  have targetnode  $a - asx \rightarrow^* (-\text{Low-})$ 
by simp
from  $\langle \text{kind } a = Q:r \hookrightarrow pfs \rangle \langle \text{upd-cs } cs (a \# as) = [] \rangle$ 
have upd-cs ( $a \# cs$ )  $as = []$  by simp
from  $\langle \text{sourcenode } a \in \lfloor \text{HRB-slice } S \rfloor_{CFG} \rangle \langle \text{kind } a = Q:r \hookrightarrow pfs \rangle$ 
have slice-kind:slice-kind  $S a =$ 
   $Q:r \hookrightarrow_p (\text{cspp } (\text{targetnode } a) (\text{HRB-slice } S) fs)$ 
  by (rule slice-kind-Call-in-slice)
from  $\langle \forall i < \text{Suc } (\text{length } cs). \text{snd } (s ! i) = \text{snd } (s' ! i) \rangle$  slice-kind
have snds: $\forall i < \text{Suc } (\text{length } (a \# cs)).$ 
   $\text{snd } (\text{transfer } (\text{slice-kind } S a) s ! i) =$ 
   $\text{snd } (\text{transfer } (\text{slice-kind } S a) s' ! i)$ 

```

```

  by auto(case-tac i,auto)
from ⟨valid-edge a⟩ ⟨kind a = Q:r↦pfs⟩ obtain ins outs
  where (p,ins,outs) ∈ set procs by(fastforce dest!:callee-in-procs)
with ⟨valid-edge a⟩ ⟨kind a = Q:r↦pfs⟩
have length (ParamUses (sourcenode a)) = length ins
  by(fastforce intro:ParamUses-call-source-length)
with ⟨valid-edge a⟩
  have ∀ i < length ins. ∀ V ∈ (ParamUses (sourcenode a))!i. V ∈ Use
(sourcenode a)
  by(fastforce intro:ParamUses-in-Use)
with ⟨∀ V ∈ Use (sourcenode a). state-val s V = state-val s' V⟩
have ∀ i < length ins. ∀ V ∈ (ParamUses (sourcenode a))!i.
  state-val s V = state-val s' V
  by fastforce
with ⟨valid-edge a⟩ ⟨kind a = Q:r↦pfs⟩ ⟨(p,ins,outs) ∈ set procs⟩
  ⟨pred (kind a) s⟩ ⟨pred (kind ax) s'⟩
have ∀ i < length ins. (params fs (fst (hd s)))!i = (params fs (fst (hd s')))!i
  by(fastforce intro!:CFG-call-edge-params)
from ⟨valid-edge a⟩ ⟨kind a = Q:r↦pfs⟩ ⟨(p,ins,outs) ∈ set procs⟩
have length fs = length ins by(rule CFG-call-edge-length)
{ fix i assume i < length fs
  with ⟨length fs = length ins⟩ have i < length ins by simp
  from ⟨i < length fs⟩ have (params fs (fst cf))!i = (fs!i) (fst cf)
    by(rule params-nth)
  moreover
  from ⟨i < length fs⟩ have (params fs (fst cf'))!i = (fs!i) (fst cf')
    by(rule params-nth)
  ultimately have (fs!i) (fst (hd s)) = (fs!i) (fst (hd s'))
    using ⟨i < length ins⟩
    ⟨∀ i < length ins. (params fs (fst (hd s)))!i = (params fs (fst (hd s')))!i⟩
    by simp }
hence ∀ i < length fs. (fs ! i) (fst cf) = (fs ! i) (fst cf') by simp
{ fix i assume i < length fs
  with ⟨∀ i < length fs. (fs ! i) (fst cf) = (fs ! i) (fst cf')⟩
  have (fs ! i) (fst cf) = (fs ! i) (fst cf') by simp
  have ((csppa (targetnode a) (HRB-slice S) 0 fs)!i)(fst cf) =
    ((csppa (targetnode a) (HRB-slice S) 0 fs)!i)(fst cf')
  proof(cases Formal-in(targetnode a,i + 0) ∈ HRB-slice S)
  case True
    with ⟨i < length fs⟩
    have (csppa (targetnode a) (HRB-slice S) 0 fs)!i = fs!i
      by(rule csppa-Formal-in-in-slice)
    with ⟨(fs ! i) (fst cf) = (fs ! i) (fst cf')⟩ show ?thesis by simp
  next
  case False
    with ⟨i < length fs⟩
    have (csppa (targetnode a) (HRB-slice S) 0 fs)!i = Map.empty
      by(rule csppa-Formal-in-notin-slice)
    thus ?thesis by simp
}

```

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qed }
hence  $eq:\forall i < \text{length } fs.$ 
   $((cspp \text{ (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)!i)(fst \text{ } cf) =$ 
   $((cspp \text{ (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)!i)(fst \text{ } cf')$ 
  by  $(simp \text{ add:cspp-def})$ 
{ fix } i assume  $i < \text{length } fs$ 
  hence  $(params \text{ (cspp (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)$ 
     $(fst \text{ } cf))!i =$ 
     $((cspp \text{ (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)!i)(fst \text{ } cf)$ 
    by  $(fastforce \text{ intro:params-nth})$ 
  moreover
  from  $\langle i < \text{length } fs \rangle$ 
  have  $(params \text{ (cspp (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)$ 
     $(fst \text{ } cf'))!i =$ 
     $((cspp \text{ (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)!i)(fst \text{ } cf')$ 
    by  $(fastforce \text{ intro:params-nth})$ 
  ultimately
  have  $(params \text{ (cspp (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)$ 
     $(fst \text{ } cf))!i =$ 
     $(params \text{ (cspp (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)(fst \text{ } cf'))!i$ 
    using  $eq \langle i < \text{length } fs \rangle$  by  $simp \}$ 
  hence  $params \text{ (cspp (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)(fst \text{ } cf) =$ 
     $params \text{ (cspp (targetnode } a) \text{ (HRB-slice } S) \text{ } fs)(fst \text{ } cf')$ 
    by  $(simp \text{ add:list-eq-iff-nth-eq})$ 
  with  $slice\text{-kind } \langle (p,ins,outs) \in \text{set } procs \rangle$ 
  obtain  $cfx$  where  $[simp]:$ 
     $transfer \text{ (slice-kind } S \text{ } a) \text{ (cf \# cfs)} = cfx \# cf \# cfs$ 
     $transfer \text{ (slice-kind } S \text{ } a) \text{ (cf' \# cfs')} = cfx \# cf' \# cfs'$ 
    by  $auto$ 
  hence  $rv:\forall V \in rv \text{ } S \text{ (CFG-node (targetnode } a)).$ 
     $state\text{-val (transfer (slice-kind } S \text{ } a) \text{ } s) \text{ } V =$ 
     $state\text{-val (transfer (slice-kind } S \text{ } a) \text{ } s') \text{ } V$  by  $simp$ 
  from  $rvs \langle \forall V \in rv \text{ } S \text{ (CFG-node } m). \text{ state-val } s \text{ } V = \text{state-val } s' \text{ } V \rangle$ 
     $\langle \text{sourcenode } a = m \rangle$ 
  have  $rvs':\forall i < \text{length } (a \# cs).$ 
     $\forall V \in rv \text{ } S \text{ (CFG-node (sourcenode ((a \# cs) ! i))).}$ 
     $fst \text{ ((transfer (slice-kind } S \text{ } a) \text{ } s) ! \text{Suc } i) \text{ } V =$ 
     $fst \text{ ((transfer (slice-kind } S \text{ } a) \text{ } s') ! \text{Suc } i) \text{ } V$ 
    by  $auto(case\text{-tac } i,auto)$ 
  from  $\langle \text{preds (slice-kinds } S \text{ } (a \# as)) \text{ } s \rangle$ 
  have  $\text{preds (slice-kinds } S \text{ } as)$ 
     $(transfer \text{ (slice-kind } S \text{ } a) \text{ } s)$  by  $(simp \text{ add:slice-kinds-def})$ 
  moreover
  from  $\langle \text{preds (slice-kinds } S \text{ } as') \text{ } s' \rangle \langle as' = ax \# asx \rangle$ 
  have  $\text{preds (slice-kinds } S \text{ } asx)$ 
     $(transfer \text{ (slice-kind } S \text{ } a) \text{ } s')$  by  $(simp \text{ add:slice-kinds-def})$ 
  moreover
  from  $\langle \text{length } s = \text{Suc (length } cs) \rangle$ 
  have  $\text{length (transfer (slice-kind } S \text{ } a) \text{ } s) =$ 

```



```

    Suc (length (a # cs)) by simp
  moreover
  from ⟨length s' = Suc (length cs)⟩
  have length (transfer (slice-kind S a) s') =
    Suc (length (a # cs)) by simp
  moreover
  from IH[OF ⟨upd-cs (a # cs) as = []⟩ ⟨same-level-path-aux (a # cs) asx⟩
    ⟨∀ c ∈ set (a # cs). valid-edge c⟩ ⟨targetnode a -as→* (-Low-)⟩
    ⟨targetnode a -asx→* (-Low-)⟩ rvs' snds rv calculation] ⟨as' = ax#asx⟩
  show ?thesis by (simp add: slice-kinds-def)
qed
qed
next
case (slpa-Return cs a as Q p f c' cs')
note IH = ⟨∧ m as' s s'. [[upd-cs cs' as = []]; same-level-path-aux cs' as'];
  ∀ c ∈ set cs'. valid-edge c; m -as→* (-Low-); m -as'→* (-Low-);
  ∀ i < length cs'. ∀ V ∈ rv S (CFG-node (sourcnode (cs' ! i))).
  fst (s ! Suc i) V = fst (s' ! Suc i) V;
  ∀ i < Suc (length cs'). snd (s ! i) = snd (s' ! i);
  ∀ V ∈ rv S (CFG-node m). state-val s V = state-val s' V;
  preds (slice-kinds S as) s; preds (slice-kinds S as') s';
  length s = Suc (length cs'); length s' = Suc (length cs')]
⇒ ∀ V ∈ Use (-Low-). state-val (transfers(slice-kinds S as) s) V =
  state-val (transfers(slice-kinds S as') s') V
note rvs = ⟨∀ i < length cs. ∀ V ∈ rv S (CFG-node (sourcnode (cs ! i))).
  fst (s ! Suc i) V = fst (s' ! Suc i) V⟩
from ⟨m -a # as→* (-Low-)⟩ have sourcnode a = m and valid-edge a
  and targetnode a -as→* (-Low-) by (auto elim:path-split-Cons)
from ⟨∀ c ∈ set cs. valid-edge c⟩ ⟨cs = c' # cs'⟩
have valid-edge c' and ∀ c ∈ set cs'. valid-edge c by simp-all
show ?case
proof (cases L = {})
  case True with UseLow show ?thesis by simp
next
case False
show ?thesis
proof (cases as')
  case Nil
  with ⟨m -as'→* (-Low-)⟩ have m = (-Low-) by fastforce
  with ⟨valid-edge a⟩ ⟨sourcnode a = m⟩ have targetnode a = (-Exit-)
  by -(rule Exit-successor-of-Low,simp+)
  from Low-source-Exit-edge obtain a' where valid-edge a'
  and sourcnode a' = (-Low-) and targetnode a' = (-Exit-)
  and kind a' = (λs. True)√ by blast
  from ⟨valid-edge a⟩ ⟨sourcnode a = m⟩ ⟨m = (-Low-)⟩
  ⟨targetnode a = (-Exit-)⟩ ⟨valid-edge a'⟩ ⟨sourcnode a' = (-Low-)⟩
  ⟨targetnode a' = (-Exit-)⟩
  have a = a' by (fastforce dest:edge-det)
  with ⟨kind a' = (λs. True)√⟩ have kind a = (λs. True)√ by simp

```

```

with ⟨targetnode a = (-Exit-)⟩ ⟨targetnode a -as→* (-Low-)⟩
have (-Low-) = (-Exit-) by -(drule path-Exit-source,auto)
with False have False by -(drule Low-neq-Exit,simp)
thus ?thesis by simp
next
case (Cons ax asx)
with ⟨m -as'→* (-Low-)⟩ have sourcenode ax = m and valid-edge ax
  and targetnode ax -asx→* (-Low-) by(auto elim:path-split-Cons)
from ⟨valid-edge a⟩ ⟨valid-edge ax⟩ kind a = Q↔pf
  ⟨sourcenode a = m⟩ ⟨sourcenode ax = m⟩
have ∃ Q f. kind ax = Q↔pf by(auto dest:return-edges-only)
with ⟨same-level-path-aux cs as'⟩ ⟨as' = ax#asx⟩ ⟨cs = c' # cs'⟩
have ax ∈ get-return-edges c' and same-level-path-aux cs' asx by auto
from ⟨valid-edge c'⟩ ⟨ax ∈ get-return-edges c'⟩ ⟨a ∈ get-return-edges c'⟩
have [simp]:ax = a by(rule get-return-edges-unique)
  from ⟨targetnode ax -asx→* (-Low-)⟩ have targetnode a -asx→* (-Low-)
by simp
from ⟨upd-cs cs (a # as) = []⟩ ⟨kind a = Q↔pf⟩ ⟨cs = c' # cs'⟩
  ⟨a ∈ get-return-edges c'⟩
have upd-cs cs' as = [] by simp
from ⟨length s = Suc (length cs)⟩ ⟨cs = c' # cs'⟩
obtain cf cfx cfs where s = cf#cfx#cfs
  by(cases s,auto,case-tac list,fastforce+)
from ⟨length s' = Suc (length cs)⟩ ⟨cs = c' # cs'⟩
obtain cf' cfx' cfs' where s' = cf'#cfx'#cfs'
  by(cases s',auto,case-tac list,fastforce+)
from rvs ⟨cs = c' # cs'⟩ ⟨s = cf#cfx#cfs⟩ ⟨s' = cf'#cfx'#cfs'⟩
have rvs1:∀ i<length cs'.
  ∀ V∈rv S (CFG-node (sourcenode (cs' ! i))).
  fst ((cfx#cfs) ! Suc i) V = fst ((cfx'#cfs') ! Suc i) V
  and ∀ V∈rv S (CFG-node (sourcenode c')).
  (fst cfx) V = (fst cfx') V
  by auto
from ⟨valid-edge c'⟩ ⟨a ∈ get-return-edges c'⟩
obtain Qx rx px fsx where kind c' = Qx:rx↔pxfsx
  by(fastforce dest!:only-call-get-return-edges)
have ∀ V ∈ rv S (CFG-node (targetnode a)).
  V ∈ rv S (CFG-node (sourcenode c'))
proof
fix V assume V ∈ rv S (CFG-node (targetnode a))
from ⟨valid-edge c'⟩ ⟨a ∈ get-return-edges c'⟩
obtain a' where edge:valid-edge a' sourcenode a' = sourcenode c'
  targetnode a' = targetnode a intra-kind (kind a')
  by -(drule call-return-node-edge,auto simp:intra-kind-def)
from ⟨V ∈ rv S (CFG-node (targetnode a))⟩
obtain as n' where targetnode a -as→i* parent-node n'
  and n' ∈ HRB-slice S and V ∈ UseSDG n'
  and all:∀ n''. valid-SDG-node n'' ∧ parent-node n'' ∈ set (sourcenodes as)
  → V ∉ DefSDG n'' by(fastforce elim:rvE)

```

from $\langle \text{targetnode } a - \text{as} \rightarrow_i * \text{parent-node } n' \rangle \text{ edge}$
have $\text{sourcenode } c' - a' \# \text{as} \rightarrow_i * \text{parent-node } n'$
by (*fastforce* *intro:Cons-path simp:intra-path-def*)
from $\langle \text{valid-edge } c' \rangle \langle \text{kind } c' = Qx:rx \leftrightarrow_{px} fsx \rangle$ **have** $\text{Def } (\text{sourcenode } c') =$
by (*rule call-source-Def-empty*)
hence $\forall n''. \text{valid-SDG-node } n'' \wedge \text{parent-node } n'' = \text{sourcenode } c'$
 $\rightarrow V \notin \text{Def}_{SDG} n''$ **by** (*fastforce dest:SDG-Def-parent-Def*)
with *all* $\langle \text{sourcenode } a' = \text{sourcenode } c' \rangle$
have $\forall n''. \text{valid-SDG-node } n'' \wedge \text{parent-node } n'' \in \text{set } (\text{sourcenodes } (a' \# \text{as}))$
 $\rightarrow V \notin \text{Def}_{SDG} n''$ **by** (*fastforce simp:sourcenodes-def*)
with $\langle \text{sourcenode } c' - a' \# \text{as} \rightarrow_i * \text{parent-node } n' \rangle$
 $\langle n' \in \text{HRB-slice } S \rangle \langle V \in \text{Use}_{SDG} n' \rangle$
show $V \in \text{rv } S$ (*CFG-node (sourcenode } c')*)
by (*fastforce intro:rvI*)
qed
show *?thesis*
proof (*cases sourcenode } a \in \lfloor \text{HRB-slice } S \rfloor_{CFG}*)
case *True*
from $\langle \text{valid-edge } c' \rangle \langle a \in \text{get-return-edges } c' \rangle$
have $\text{get-proc } (\text{targetnode } c') = \text{get-proc } (\text{sourcenode } a)$
by $-(\text{drule } \text{intra-proc-additional-edge},$
auto dest:get-proc-intra simp:intra-kind-def)
moreover
from $\langle \text{valid-edge } c' \rangle \langle \text{kind } c' = Qx:rx \leftrightarrow_{px} fsx \rangle$
have $\text{get-proc } (\text{targetnode } c') = px$ **by** (*rule get-proc-call*)
moreover
from $\langle \text{valid-edge } a \rangle \langle \text{kind } a = Q \leftrightarrow_{pf} \rangle$
have $\text{get-proc } (\text{sourcenode } a) = p$ **by** (*rule get-proc-return*)
ultimately have $[simp]: px = p$ **by** *simp*
from $\langle \text{valid-edge } c' \rangle \langle \text{kind } c' = Qx:rx \leftrightarrow_{px} fsx \rangle$
obtain *ins outs* **where** $(p, \text{ins}, \text{outs}) \in \text{set } \text{procs}$
by (*fastforce dest!:callee-in-procs*)
with $\langle \text{sourcenode } a \in \lfloor \text{HRB-slice } S \rfloor_{CFG} \rangle$
 $\langle \text{valid-edge } a \rangle \langle \text{kind } a = Q \leftrightarrow_{pf} \rangle$
have $\text{slice-kind: slice-kind } S a =$
 $Q \leftrightarrow_p (\lambda cf \text{ cf}'. \text{rspp } (\text{targetnode } a) (\text{HRB-slice } S) \text{outs } cf' \text{ cf})$
by (*rule slice-kind-Return-in-slice*)
with $\langle s = cf \# cfx \# cfs \rangle \langle s' = cf' \# cfx' \# cfs' \rangle$
have $\text{sx:transfer } (\text{slice-kind } S a) s =$
 $(\text{rspp } (\text{targetnode } a) (\text{HRB-slice } S) \text{outs } (\text{fst } cfx) (\text{fst } cf),$
 $\text{snd } cfx) \# cfs$
and $\text{sx':transfer } (\text{slice-kind } S a) s' =$
 $(\text{rspp } (\text{targetnode } a) (\text{HRB-slice } S) \text{outs } (\text{fst } cfx') (\text{fst } cf'),$
 $\text{snd } cfx') \# cfs'$
by *simp-all*
with *rvs1* **have** $\text{rvs}' : \forall i < \text{length } cs'.$
 $\forall V \in \text{rv } S$ (*CFG-node (sourcenode } (cs' ! i))*).

```

fst ((transfer (slice-kind S a) s) ! Suc i) V =
fst ((transfer (slice-kind S a) s') ! Suc i) V
by fastforce
from slice-kind ⟨∀ i < Suc (length cs). snd (s ! i) = snd (s' ! i)⟩ ⟨cs = c' #
cs'⟩
⟨s = cf # cfx # cfs⟩ ⟨s' = cf' # cfx' # cfs'⟩
have snds:∀ i < Suc (length cs').
snd (transfer (slice-kind S a) s ! i) =
snd (transfer (slice-kind S a) s' ! i)
apply auto apply(case-tac i) apply auto
by(erule-tac x=Suc (Suc nat) in allE) auto
have ∀ V ∈ rv S (CFG-node (targetnode a)).
(rspp (targetnode a) (HRB-slice S) outs
(fst cfx) (fst cf)) V =
(rspp (targetnode a) (HRB-slice S) outs
(fst cfx') (fst cf')) V
proof
fix V assume V ∈ rv S (CFG-node (targetnode a))
show (rspp (targetnode a) (HRB-slice S) outs
(fst cfx) (fst cf)) V =
(rspp (targetnode a) (HRB-slice S) outs
(fst cfx') (fst cf')) V
proof(cases V ∈ set (ParamDefs (targetnode a)))
case True
then obtain i where i < length (ParamDefs (targetnode a))
and (ParamDefs (targetnode a))!i = V
by(fastforce simp:in-set-conv-nth)
from ⟨valid-edge a⟩ ⟨kind a = Q↔pf⟩ ⟨(p,ins,outs) ∈ set procs⟩
have length(ParamDefs (targetnode a)) = length outs
by(fastforce intro:ParamDefs-return-target-length)
show ?thesis
proof(cases Actual-out(targetnode a,i) ∈ HRB-slice S)
case True
with ⟨i < length (ParamDefs (targetnode a))⟩ ⟨valid-edge a⟩
⟨length(ParamDefs (targetnode a)) = length outs⟩
⟨(ParamDefs (targetnode a))!i = V⟩[THEN sym]
have rspp-eq:(rspp (targetnode a)
(HRB-slice S) outs (fst cfx) (fst cf)) V =
(fst cf)(outs!i)
(rspp (targetnode a)
(HRB-slice S) outs (fst cfx') (fst cf')) V =
(fst cf')(outs!i)
by(auto intro:rspp-Actual-out-in-slice)
from ⟨valid-edge a⟩ ⟨kind a = Q↔pf⟩ ⟨(p,ins,outs) ∈ set procs⟩
have ∀ V ∈ set outs. V ∈ Use (sourcenode a) by(fastforce dest:outs-in-Use)
have ∀ V ∈ Use (sourcenode a). V ∈ rv S (CFG-node m)
proof
fix V assume V ∈ Use (sourcenode a)
from ⟨valid-edge a⟩ ⟨sourcenode a = m⟩

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```

have parent-node (CFG-node m)  $\rightarrow_i^*$  parent-node (CFG-node m)
  by (fastforce intro:empty-path simp:intra-path-def)
with ⟨sourcnode a ∈ [HRB-slice S]CFG⟩
  ⟨V ∈ Use (sourcnode a)⟩ ⟨sourcnode a = m⟩ ⟨valid-edge a⟩
show V ∈ rv S (CFG-node m)
  by  $\text{-(rule rvI,$ 
    auto intro!:CFG-Use-SDG-Use simp:SDG-to-CFG-set-def
sourcnodes-def)
qed
with ⟨∀ V ∈ set outs. V ∈ Use (sourcnode a)⟩
have ∀ V ∈ set outs. V ∈ rv S (CFG-node m) by simp
with ⟨∀ V ∈ rv S (CFG-node m). state-val s V = state-val s' V⟩
  ⟨s = cf#cfx#cfs⟩ ⟨s' = cf'#cfx'#cfs'⟩
have ∀ V ∈ set outs. (fst cf) V = (fst cf') V by simp
with ⟨i < length (ParamDefs (targetnode a))⟩
  ⟨length(ParamDefs (targetnode a)) = length outs⟩
have (fst cf)(outs!i) = (fst cf')(outs!i) by fastforce
with rspp-eq show ?thesis by simp
next
case False
with ⟨i < length (ParamDefs (targetnode a))⟩ ⟨valid-edge a⟩
  ⟨length(ParamDefs (targetnode a)) = length outs⟩
  ⟨(ParamDefs (targetnode a))!i = V⟩[THEN sym]
have rspp-eq:(rspp (targetnode a)
  (HRB-slice S) outs (fst cfx) (fst cf)) V =
  (fst cfx)((ParamDefs (targetnode a))!i)
  (rspp (targetnode a)
  (HRB-slice S) outs (fst cfx') (fst cf')) V =
  (fst cfx')((ParamDefs (targetnode a))!i)
  by(auto intro:rspp-Actual-out-notin-slice)
from ⟨∀ V ∈ rv S (CFG-node (sourcnode c')).
  (fst cfx) V = (fst cfx') V⟩
  ⟨V ∈ rv S (CFG-node (targetnode a))⟩
  ⟨∀ V ∈ rv S (CFG-node (targetnode a)).
  V ∈ rv S (CFG-node (sourcnode c'))⟩
  ⟨(ParamDefs (targetnode a))!i = V⟩[THEN sym]
have (fst cfx) (ParamDefs (targetnode a) ! i) =
  (fst cfx') (ParamDefs (targetnode a) ! i) by fastforce
with rspp-eq show ?thesis by fastforce
qed
next
case False
with ⟨∀ V ∈ rv S (CFG-node (sourcnode c')).
  (fst cfx) V = (fst cfx') V⟩
  ⟨V ∈ rv S (CFG-node (targetnode a))⟩
  ⟨∀ V ∈ rv S (CFG-node (targetnode a)).
  V ∈ rv S (CFG-node (sourcnode c'))⟩
show ?thesis by(fastforce simp:rspp-def map-merge-def)
qed

```

```

qed
with  $sx\ sx'$ 
have  $rv':\forall V\in rv\ S\ (CFG\text{-node}\ (targetnode\ a)).$ 
   $state\text{-val}\ (transfer\ (slice\text{-kind}\ S\ a)\ s)\ V =$ 
   $state\text{-val}\ (transfer\ (slice\text{-kind}\ S\ a)\ s')\ V$ 
  by fastforce
from  $\langle preds\ (slice\text{-kinds}\ S\ (a\ \#\ as))\ s \rangle$ 
have  $preds\ (slice\text{-kinds}\ S\ as)$ 
   $(transfer\ (slice\text{-kind}\ S\ a)\ s)$ 
  by  $(simp\ add:slice\text{-kinds}\text{-def})$ 
moreover
from  $\langle preds\ (slice\text{-kinds}\ S\ as')\ s' \rangle\ \langle as' = ax\ \#\ asx \rangle$ 
have  $preds\ (slice\text{-kinds}\ S\ asx)$ 
   $(transfer\ (slice\text{-kind}\ S\ a)\ s')$ 
  by  $(simp\ add:slice\text{-kinds}\text{-def})$ 
moreover
from  $\langle length\ s = Suc\ (length\ cs) \rangle\ \langle cs = c' \ \#\ cs' \rangle\ sx$ 
have  $length\ (transfer\ (slice\text{-kind}\ S\ a)\ s) = Suc\ (length\ cs')$ 
  by  $(simp,simp\ add:\langle s = cf\ \#\ cfx\ \#\ cfs \rangle)$ 
moreover
from  $\langle length\ s' = Suc\ (length\ cs) \rangle\ \langle cs = c' \ \#\ cs' \rangle\ sx'$ 
have  $length\ (transfer\ (slice\text{-kind}\ S\ a)\ s') = Suc\ (length\ cs')$ 
  by  $(simp,simp\ add:\langle s' = cf' \ \#\ cfx' \ \#\ cfs' \rangle)$ 
moreover
from  $IH[OF\ \langle upd\text{-cs}\ cs'\ as = [] \rangle\ \langle same\text{-level}\text{-path}\text{-aux}\ cs'\ asx \rangle$ 
   $\langle \forall c\in set\ cs'.\ valid\text{-edge}\ c \rangle\ \langle targetnode\ a -as\ \rightarrow* (-Low)\ \rangle$ 
   $\langle targetnode\ a -asx\ \rightarrow* (-Low)\ \rangle\ rvs\ snds\ rv'\ calculation]\ \langle as' = ax\ \#\ asx \rangle$ 
show ?thesis by  $(simp\ add:slice\text{-kinds}\text{-def})$ 
next
case False
from  $this\ \langle kind\ a = Q\ \leftrightarrow\ pf \rangle$ 
have  $slice\text{-kind}:slice\text{-kind}\ S\ a = (\lambda cf.\ True)\ \leftrightarrow\ p(\lambda cf\ cf'.\ cf')$ 
  by  $(rule\ slice\text{-kind}\text{-Return})$ 
with  $\langle s = cf\ \#\ cfx\ \#\ cfs \rangle\ \langle s' = cf' \ \#\ cfx' \ \#\ cfs' \rangle$ 
have  $[simp]:transfer\ (slice\text{-kind}\ S\ a)\ s = cfx\ \#\ cfs$ 
   $transfer\ (slice\text{-kind}\ S\ a)\ s' = cfx' \ \#\ cfs'$  by simp-all
from  $slice\text{-kind}\ \langle \forall i < Suc\ (length\ cs).\ snd\ (s\ !\ i) = snd\ (s' \ !\ i) \rangle$ 
   $\langle cs = c' \ \#\ cs' \rangle\ \langle s = cf\ \#\ cfx\ \#\ cfs \rangle\ \langle s' = cf' \ \#\ cfx' \ \#\ cfs' \rangle$ 
have  $snds:\forall i < Suc\ (length\ cs').$ 
   $snd\ (transfer\ (slice\text{-kind}\ S\ a)\ s\ !\ i) =$ 
   $snd\ (transfer\ (slice\text{-kind}\ S\ a)\ s' \ !\ i)$  by fastforce
from  $rvs1$  have  $rvs':\forall i < length\ cs'.$ 
   $\forall V\in rv\ S\ (CFG\text{-node}\ (sourcenode\ (cs' \ !\ i))).$ 
   $fst\ ((transfer\ (slice\text{-kind}\ S\ a)\ s)\ !\ Suc\ i)\ V =$ 
   $fst\ ((transfer\ (slice\text{-kind}\ S\ a)\ s')\ !\ Suc\ i)\ V$ 
  by fastforce
from  $\langle \forall V \in rv\ S\ (CFG\text{-node}\ (targetnode\ a)).$ 
   $V \in rv\ S\ (CFG\text{-node}\ (sourcenode\ c')) \rangle$ 
   $\langle \forall V\in rv\ S\ (CFG\text{-node}\ (sourcenode\ c')).$ 

```

```

    (fst cfx) V = (fst cfx') V
  have rv': $\forall V \in rv\ S$  (CFG-node (targetnode a)).
    state-val (transfer (slice-kind S a) s) V =
    state-val (transfer (slice-kind S a) s') V by simp
  from <preds (slice-kinds S (a # as)) s>
  have preds (slice-kinds S as)
    (transfer (slice-kind S a) s)
    by (simp add:slice-kinds-def)
  moreover
  from <preds (slice-kinds S as') s'> <as' = ax#asx>
  have preds (slice-kinds S asx)
    (transfer (slice-kind S a) s')
    by (simp add:slice-kinds-def)
  moreover
  from <length s = Suc (length cs)> <cs = c' # cs'>
  have length (transfer (slice-kind S a) s) = Suc (length cs')
    by (simp, simp add:<s = cf#cfx#cfs>)
  moreover
  from <length s' = Suc (length cs)> <cs = c' # cs'>
  have length (transfer (slice-kind S a) s') = Suc (length cs')
    by (simp, simp add:<s' = cf'#cfx'#cfs'>)
  moreover
  from IH[OF <upd-cs cs' as = []> <same-level-path-aux cs' asx>
    < $\forall c \in set\ cs'.\ valid\_edge\ c$ > <targetnode a -as $\rightarrow$ * (-Low-)>
    <targetnode a -asx $\rightarrow$ * (-Low-)> rvs' sn ds rv' calculation] <as' = ax#asx>
  show ?thesis by (simp add:slice-kinds-def)
qed
qed
qed
qed

```

lemma *rv-Low-Use-Low*:

```

  assumes  $m -as \rightarrow \sqrt{*} (-Low-)$  and  $m -as' \rightarrow \sqrt{*} (-Low-)$  and get-proc  $m = Main$ 
  and  $\forall V \in rv\ S$  (CFG-node  $m$ ).  $cf\ V = cf'\ V$ 
  and preds (slice-kinds S as) [(cf,undefined)]
  and preds (slice-kinds S as') [(cf',undefined)]
  and CFG-node (-Low-)  $\in S$ 
  shows  $\forall V \in Use\ (-Low-)$ .
    state-val (transfers(slice-kinds S as) [(cf,undefined)]) V =
    state-val (transfers(slice-kinds S as') [(cf',undefined)]) V
  proof (cases as)
  case Nil
  with < $m -as \rightarrow \sqrt{*} (-Low-)$ > have valid-node  $m$  and  $m = (-Low-)$ 
  by (auto intro:path-valid-node simp:vp-def)
  { fix V assume  $V \in Use\ (-Low-)$ 
  moreover
  from <valid-node  $m$ > < $m = (-Low-)$ > have (-Low-)  $-\square \rightarrow_t^* (-Low-)$ 
  by (fastforce intro:empty-path simp:intra-path-def)
  }
  }

```

```

moreover
from  $\langle \text{valid-node } m \rangle \langle m = (-\text{Low-}) \rangle \langle \text{CFG-node } (-\text{Low-}) \in S \rangle$ 
have  $\text{CFG-node } (-\text{Low-}) \in \text{HRB-slice } S$ 
  by(fastforce intro:HRB-slice-refl)
ultimately have  $V \in \text{rv } S \text{ (CFG-node } m)$  using  $\langle m = (-\text{Low-}) \rangle$ 
  by(auto intro!:rvI CFG-Use-SDG-Use simp:sourcenodes-def) }
hence  $\forall V \in \text{Use } (-\text{Low-}). V \in \text{rv } S \text{ (CFG-node } m)$  by simp
show ?thesis
proof(cases L = {})
  case True with UseLow show ?thesis by simp
next
  case False
from  $\langle m -as' \rightarrow_{\sqrt{*}} (-\text{Low-}) \rangle$  have  $m -as' \rightarrow^* (-\text{Low-})$  by(simp add:vp-def)
from  $\langle m -as' \rightarrow^* (-\text{Low-}) \rangle \langle m = (-\text{Low-}) \rangle$  have  $as' = []$ 
proof(induct m as' m'  $\equiv$  (-Low-) rule:path.induct)
  case (Cons-path m'' as a m)
from  $\langle \text{valid-edge } a \rangle \langle \text{sourcenode } a = m \rangle \langle m = (-\text{Low-}) \rangle$ 
have  $\text{targetnode } a = (-\text{Exit-})$  by  $\text{-(rule Exit-successor-of-Low,simp+)}$ 
with  $\langle \text{targetnode } a = m'' \rangle \langle m'' -as \rightarrow^* (-\text{Low-}) \rangle$ 
have  $(-\text{Low-}) = (-\text{Exit-})$  by  $\text{-(drule path-Exit-source,auto)}$ 
with False have False by  $\text{-(drule Low-neq-Exit,simp)}$ 
thus ?case by simp
qed simp
with Nil  $\langle \forall V \in \text{rv } S \text{ (CFG-node } m). \text{cf } V = \text{cf}' V \rangle$ 
   $\langle \forall V \in \text{Use } (-\text{Low-}). V \in \text{rv } S \text{ (CFG-node } m) \rangle$ 
show ?thesis by(fastforce simp:slice-kinds-def)
qed
next
  case (Cons ax asx)
with  $\langle m -as \rightarrow_{\sqrt{*}} (-\text{Low-}) \rangle$  have  $\text{sourcenode } ax = m$  and  $\text{valid-edge } ax$ 
  and  $\text{targetnode } ax -asx \rightarrow^* (-\text{Low-})$ 
by(auto elim:path-split-Cons simp:vp-def)
show ?thesis
proof(cases L = {})
  case True with UseLow show ?thesis by simp
next
  case False
show ?thesis
proof(cases as')
  case Nil
with  $\langle m -as' \rightarrow_{\sqrt{*}} (-\text{Low-}) \rangle$  have  $m = (-\text{Low-})$  by(fastforce simp:vp-def)
with  $\langle \text{valid-edge } ax \rangle \langle \text{sourcenode } ax = m \rangle$  have  $\text{targetnode } ax = (-\text{Exit-})$ 
  by  $\text{-(rule Exit-successor-of-Low,simp+)}$ 
from Low-source-Exit-edge obtain  $a'$  where  $\text{valid-edge } a'$ 
  and  $\text{sourcenode } a' = (-\text{Low-})$  and  $\text{targetnode } a' = (-\text{Exit-})$ 
  and  $\text{kind } a' = (\lambda s. \text{True})_{\sqrt{*}}$  by blast
from  $\langle \text{valid-edge } ax \rangle \langle \text{sourcenode } ax = m \rangle \langle m = (-\text{Low-}) \rangle$ 
   $\langle \text{targetnode } ax = (-\text{Exit-}) \rangle \langle \text{valid-edge } a' \rangle \langle \text{sourcenode } a' = (-\text{Low-}) \rangle$ 
   $\langle \text{targetnode } a' = (-\text{Exit-}) \rangle$ 

```



```

have  $ax = a'$  by (fastforce dest:edge-det)
with  $\langle kind\ a' = (\lambda s. True)_{\surd} \rangle$  have  $kind\ ax = (\lambda s. True)_{\surd}$  by simp
with  $\langle targetnode\ ax = (-Exit-) \rangle$   $\langle targetnode\ ax\ -asx \rightarrow^* (-Low-) \rangle$ 
have  $(-Low-) = (-Exit-)$  by  $-(drule\ path-Exit-source, auto)$ 
with False have False by  $-(drule\ Low-neq-Exit, simp)$ 
thus ?thesis by simp
next
case (Cons  $ax'\ asx'$ )
from  $\langle m\ -as \rightarrow_{\surd}^* (-Low-) \rangle$  have valid-path-aux []  $as$  and  $m\ -as \rightarrow^* (-Low-)$ 
by (simp-all add:vp-def valid-path-def)
from this  $\langle as = ax\ \# asx \rangle$   $\langle get-proc\ m = Main \rangle$ 
have same-level-path-aux []  $as \wedge upd-cs$  []  $as = []$ 
by  $-(rule\ vpa-Main-slpa[of\ -\ -\ m\ (-Low-)],$ 
  (fastforce intro!:get-proc-Low simp:valid-call-list-def)+)
hence same-level-path-aux []  $as$  and  $upd-cs$  []  $as = []$  by simp-all
from  $\langle m\ -as' \rightarrow_{\surd}^* (-Low-) \rangle$  have valid-path-aux []  $as'$  and  $m\ -as' \rightarrow^* (-Low-)$ 
by (simp-all add:vp-def valid-path-def)
from this  $\langle as' = ax'\ \# asx' \rangle$   $\langle get-proc\ m = Main \rangle$ 
have same-level-path-aux []  $as' \wedge upd-cs$  []  $as' = []$ 
by  $-(rule\ vpa-Main-slpa[of\ -\ -\ m\ (-Low-)],$ 
  (fastforce intro!:get-proc-Low simp:valid-call-list-def)+)
hence same-level-path-aux []  $as'$  by simp
from  $\langle same-level-path-aux [] as \rangle$   $\langle upd-cs [] as = [] \rangle$ 
 $\langle same-level-path-aux [] as' \rangle$   $\langle m\ -as \rightarrow^* (-Low-) \rangle$   $\langle m\ -as' \rightarrow^* (-Low-) \rangle$ 
 $\langle \forall V \in rv\ S\ (CFG-node\ m). cf\ V = cf'\ V \rangle$   $\langle CFG-node\ (-Low-) \in S \rangle$ 
 $\langle preds\ (slice-kinds\ S\ as)\ [(cf, undefined)] \rangle$ 
 $\langle preds\ (slice-kinds\ S\ as')\ [(cf', undefined)] \rangle$ 
show ?thesis by  $-(erule\ slpa-rv-Low-Use-Low, auto)$ 
qed
qed
qed

```

lemma *nonInterference-path-to-Low*:

```

assumes  $[cf] \approx_L [cf']$  and  $(-High-) \notin [HRB-slice\ S]_{CFG}$ 
and  $CFG-node\ (-Low-) \in S$ 
and  $(-Entry-) -as \rightarrow_{\surd}^* (-Low-)$  and  $preds\ (kinds\ as)\ [(cf, undefined)]$ 
and  $(-Entry-) -as' \rightarrow_{\surd}^* (-Low-)$  and  $preds\ (kinds\ as')\ [(cf', undefined)]$ 
shows  $map\ fst\ (transfers\ (kinds\ as)\ [(cf, undefined)]) \approx_L$ 
   $map\ fst\ (transfers\ (kinds\ as')\ [(cf', undefined)])$ 

```

proof –

```

from  $\langle (-Entry-) -as \rightarrow_{\surd}^* (-Low-) \rangle$   $\langle preds\ (kinds\ as)\ [(cf, undefined)] \rangle$ 
 $\langle CFG-node\ (-Low-) \in S \rangle$ 
obtain  $asx$  where  $preds\ (slice-kinds\ S\ asx)\ [(cf, undefined)]$ 
and  $\forall V \in Use\ (-Low-).$ 
   $state-val\ (transfers\ (slice-kinds\ S\ asx)\ [(cf, undefined)])\ V =$ 
   $state-val\ (transfers\ (kinds\ as)\ [(cf, undefined)])\ V$ 
and  $slice-edges\ S [] as = slice-edges\ S [] asx$ 

```

and *transfers* (*kinds as*) [(*cf*,*undefined*)] ≠ []
and (-*Entry*-) -*as* →_{√*} (-*Low*-)
by(*erule fundamental-property-of-static-slicing*)
from ⟨(-*Entry*-) -*as*' →_{√*} (-*Low*-)⟩ ⟨*preds* (*kinds as*') [(*cf*',*undefined*)]⟩
⟨*CFG-node* (-*Low*-) ∈ *S*⟩
obtain *asx'* **where** *preds* (*slice-kinds S asx'*) [(*cf*',*undefined*)]
and ∀ *V* ∈ *Use* (-*Low*-).
state-val (*transfers*(*slice-kinds S asx'*) [(*cf*',*undefined*)]) *V* =
state-val (*transfers*(*kinds as*') [(*cf*',*undefined*)]) *V*
and *slice-edges S* [] *as'* =
slice-edges S [] *asx'*
and *transfers* (*kinds as*') [(*cf*',*undefined*)] ≠ []
and (-*Entry*-) -*asx'* →_{√*} (-*Low*-)
by(*erule fundamental-property-of-static-slicing*)
from ⟨[*cf*] ≈_L [*cf*']⟩ ⟨(-*High*-) ∉ [HRB-slice *S*]_{CFG}⟩
have ∀ *V* ∈ *rv S* (*CFG-node* (-*Entry*-)). *cf V* = *cf' V*
by(*fastforce dest:lowEquivalence-relevant-nodes-Entry*)
with ⟨(-*Entry*-) -*as* →_{√*} (-*Low*-)⟩ ⟨(-*Entry*-) -*asx'* →_{√*} (-*Low*-)⟩
⟨*CFG-node* (-*Low*-) ∈ *S*⟩ ⟨*preds* (*slice-kinds S asx*) [(*cf*,*undefined*)]⟩
⟨*preds* (*slice-kinds S asx'*) [(*cf*',*undefined*)]⟩
have ∀ *V* ∈ *Use* (-*Low*-).
state-val (*transfers*(*slice-kinds S asx*) [(*cf*,*undefined*)]) *V* =
state-val (*transfers*(*slice-kinds S asx'*) [(*cf*',*undefined*)]) *V*
by -(*rule rv-Low-Use-Low,auto intro:get-proc-Entry*)
with ⟨∀ *V* ∈ *Use* (-*Low*-).
state-val (*transfers* (*slice-kinds S asx*) [(*cf*,*undefined*)]) *V* =
state-val (*transfers* (*kinds as*) [(*cf*,*undefined*)]) *V*⟩
⟨∀ *V* ∈ *Use* (-*Low*-).
state-val (*transfers*(*slice-kinds S asx'*) [(*cf*',*undefined*)]) *V* =
state-val (*transfers*(*kinds as*') [(*cf*',*undefined*)]) *V*⟩
⟨*transfers* (*kinds as*) [(*cf*,*undefined*)] ≠ []⟩
⟨*transfers* (*kinds as*') [(*cf*',*undefined*)] ≠ []⟩
show ?*thesis* **by**(*fastforce simp:lowEquivalence-def UseLow neq-Nil-conv*)
qed

theorem *nonInterference-path*:

assumes [*cf*] ≈_L [*cf*'] **and** (-*High*-) ∉ [HRB-slice *S*]_{CFG}
and *CFG-node* (-*Low*-) ∈ *S*
and (-*Entry*-) -*as* →_{√*} (-*Exit*-) **and** *preds* (*kinds as*) [(*cf*,*undefined*)]
and (-*Entry*-) -*as'* →_{√*} (-*Exit*-) **and** *preds* (*kinds as*') [(*cf*',*undefined*)]
shows *map fst* (*transfers* (*kinds as*) [(*cf*,*undefined*)]) ≈_L
map fst (*transfers* (*kinds as*') [(*cf*',*undefined*)])
proof -
from ⟨(-*Entry*-) -*as* →_{√*} (-*Exit*-)⟩ **obtain** *x xs* **where** *as* = *x#xs*
and (-*Entry*-) = *sourcenode x* **and** *valid-edge x*
and *targetnode x* -*xs* →* (-*Exit*-)
apply(*cases as* = [])
apply(*clarsimp simp:vp-def,drule empty-path-nodes,drule Entry-noteq-Exit,simp*)

```

  by(fastforce elim:path-split-Cons simp:vp-def)
from ⟨(-Entry-) -as→√* (-Exit-)⟩ have valid-path as by(simp add:vp-def)
from ⟨valid-edge x⟩ have valid-node (targetnode x) by simp
hence inner-node (targetnode x)
proof(cases rule:valid-node-cases)
  case Entry
  with ⟨valid-edge x⟩ have False by(rule Entry-target)
  thus ?thesis by simp
next
case Exit
with ⟨targetnode x -xs→* (-Exit-)⟩ have xs = []
  by -(drule path-Exit-source,auto)
from Entry-Exit-edge obtain z where valid-edge z
  and sourcenode z = (-Entry-) and targetnode z = (-Exit-)
  and kind z = (λs. False)√ by blast
from ⟨valid-edge x⟩ ⟨valid-edge z⟩ ⟨(-Entry-) = sourcenode x⟩
  ⟨sourcenode z = (-Entry-)⟩ Exit ⟨targetnode z = (-Exit-)⟩
have x = z by(fastforce intro:edge-det)
with ⟨preds (kinds as) [(cf,undefined)]⟩ ⟨as = x#xs⟩ ⟨xs = []⟩
  ⟨kind z = (λs. False)√⟩
have False by(simp add:kinds-def)
thus ?thesis by simp
qed simp
with ⟨targetnode x -xs→* (-Exit-)⟩ obtain x' xs' where xs = xs'@[x']
  and targetnode x -xs'→* (-Low-) and kind x' = (λs. True)√
  by(fastforce elim:Exit-path-Low-path)
with ⟨(-Entry-) = sourcenode x⟩ ⟨valid-edge x⟩
have (-Entry-) -x#xs'→* (-Low-) by(fastforce intro:Cons-path)
from ⟨valid-path as⟩ ⟨as = x#xs⟩ ⟨xs = xs'@[x']⟩
have valid-path (x#xs')
  by(simp add:valid-path-def del:valid-path-aux.simps)
  (rule valid-path-aux-split,simp)
with ⟨(-Entry-) -x#xs'→* (-Low-)⟩ have (-Entry-) -x#xs'→√* (-Low-)
  by(simp add:vp-def)
from ⟨as = x#xs⟩ ⟨xs = xs'@[x']⟩ have as = (x#xs')@[x'] by simp
with ⟨preds (kinds as) [(cf,undefined)]⟩
have preds (kinds (x#xs')) [(cf,undefined)]
  by(simp add:kinds-def preds-split)
from ⟨(-Entry-) -as'→√* (-Exit-)⟩ obtain y ys where as' = y#ys
  and (-Entry-) = sourcenode y and valid-edge y
  and targetnode y -ys→* (-Exit-)
  apply(cases as' = [])
  apply(clarsimp simp:vp-def,drule empty-path-nodes,drule Entry-noteq-Exit,simp)
  by(fastforce elim:path-split-Cons simp:vp-def)
from ⟨(-Entry-) -as'→√* (-Exit-)⟩ have valid-path as' by(simp add:vp-def)
from ⟨valid-edge y⟩ have valid-node (targetnode y) by simp
hence inner-node (targetnode y)
proof(cases rule:valid-node-cases)
  case Entry

```

```

with ⟨valid-edge y⟩ have False by(rule Entry-target)
thus ?thesis by simp
next
case Exit
with ⟨targetnode y -ys→* (-Exit-)⟩ have ys = []
  by -(drule path-Exit-source,auto)
from Entry-Exit-edge obtain z where valid-edge z
  and sourcenode z = (-Entry-) and targetnode z = (-Exit-)
  and kind z = (λs. False)✓ by blast
from ⟨valid-edge y⟩ ⟨valid-edge z⟩ ⟨(-Entry-) = sourcenode y⟩
  ⟨sourcenode z = (-Entry-)⟩ Exit ⟨targetnode z = (-Exit-)⟩
have y = z by(fastforce intro:edge-det)
with ⟨preds (kinds as') [(cf',undefined)]⟩ ⟨as' = y#ys⟩ ⟨ys = []⟩
  ⟨kind z = (λs. False)✓⟩
have False by(simp add:kinds-def)
thus ?thesis by simp
qed simp
with ⟨targetnode y -ys→* (-Exit-)⟩ obtain y' ys' where ys = ys'@[y']
  and targetnode y -ys'→* (-Low-) and kind y' = (λs. True)✓
  by(fastforce elim:Exit-path-Low-path)
with ⟨(-Entry-) = sourcenode y⟩ ⟨valid-edge y⟩
have (-Entry-) -y#ys'→* (-Low-) by(fastforce intro:Cons-path)
from ⟨valid-path as'⟩ ⟨as' = y#ys⟩ ⟨ys = ys'@[y']⟩
have valid-path (y#ys')
  by(simp add:valid-path-def del:valid-path-aux.simps)
  (rule valid-path-aux-split,simp)
with ⟨(-Entry-) -y#ys'→* (-Low-)⟩ have (-Entry-) -y#ys'→✓* (-Low-)
  by(simp add:vp-def)
from ⟨as' = y#ys⟩ ⟨ys = ys'@[y']⟩ have as' = (y#ys')@[y'] by simp
with ⟨preds (kinds as') [(cf',undefined)]⟩
have preds (kinds (y#ys')) [(cf',undefined)]
  by(simp add:kinds-def preds-split)
from ⟨[cf] ≈L [cf']⟩ ⟨(-High-) ∉ [HRB-slice S]CFG⟩ ⟨CFG-node (-Low-) ∈ S⟩
  ⟨(-Entry-) -x#xs'→✓* (-Low-)⟩ ⟨preds (kinds (x#xs')) [(cf',undefined)]⟩
  ⟨(-Entry-) -y#ys'→✓* (-Low-)⟩ ⟨preds (kinds (y#ys')) [(cf',undefined)]⟩
have map fst (transfers (kinds (x#xs')) [(cf',undefined)]) ≈L
  map fst (transfers (kinds (y#ys')) [(cf',undefined)])
  by(rule nonInterference-path-to-Low)
with ⟨as = x#xs⟩ ⟨xs = xs'@[x']⟩ ⟨kind x' = (λs. True)✓⟩
  ⟨as' = y#ys⟩ ⟨ys = ys'@[y']⟩ ⟨kind y' = (λs. True)✓⟩
show ?thesis
  apply(cases transfers (map kind xs') (transfer (kind x) [(cf',undefined)]))
  apply (auto simp add:kinds-def transfers-split)
  by((cases transfers (map kind ys') (transfer (kind y) [(cf',undefined)])),
    (auto simp add:kinds-def transfers-split))+
qed

```

end

The second theorem assumes that we have a operational semantics, whose evaluations are written $\langle c, s \rangle \Rightarrow \langle c', s' \rangle$ and which conforms to the CFG. The correctness theorem then states that if no high variable influenced a low variable and the initial states were low equivalent, the resulting states are again low equivalent:

```

locale NonInterferenceInter =
  NonInterferenceInterGraph sourcenode targetnode kind valid-edge Entry
  get-proc get-return-edges procs Main Exit Def Use ParamDefs ParamUses
  H L High Low +
  SemanticsProperty sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit Def Use ParamDefs ParamUses sem identifies
for sourcenode :: 'edge  $\Rightarrow$  'node and targetnode :: 'edge  $\Rightarrow$  'node
and kind :: 'edge  $\Rightarrow$  ('var, 'val, 'ret, 'pname) edge-kind
and valid-edge :: 'edge  $\Rightarrow$  bool
and Entry :: 'node (('Entry-')) and get-proc :: 'node  $\Rightarrow$  'pname
and get-return-edges :: 'edge  $\Rightarrow$  'edge set
and procs :: ('pname  $\times$  'var list  $\times$  'var list) list and Main :: 'pname
and Exit::'node (('Exit-'))
and Def :: 'node  $\Rightarrow$  'var set and Use :: 'node  $\Rightarrow$  'var set
and ParamDefs :: 'node  $\Rightarrow$  'var list and ParamUses :: 'node  $\Rightarrow$  'var set list
and sem :: 'com  $\Rightarrow$  ('var  $\rightarrow$  'val) list  $\Rightarrow$  'com  $\Rightarrow$  ('var  $\rightarrow$  'val) list  $\Rightarrow$  bool
  (((1<-,->)  $\Rightarrow$  / (1<-,->)) [0,0,0,0] 81)
and identifies :: 'node  $\Rightarrow$  'com  $\Rightarrow$  bool (-  $\triangleq$  - [51,0] 80)
and H :: 'var set and L :: 'var set
and High :: 'node (('High-')) and Low :: 'node (('Low-')) +
fixes final :: 'com  $\Rightarrow$  bool
assumes final-edge-Low:  $\llbracket$ final c; n  $\triangleq$  c $\rrbracket$ 
   $\implies \exists a. \text{valid-edge } a \wedge \text{sourcenode } a = n \wedge \text{targetnode } a = (-\text{Low-}) \wedge \text{kind } a =$ 
 $\uparrow id$ 
begin

```

The following theorem needs the explicit edge from $(-\text{High-})$ to n . An approach using a *init* predicate for initial statements, being reachable from $(-\text{High-})$ via a $(\lambda s. \text{True})_{\surd}$ edge, does not work as the same statement could be identified by several nodes, some initial, some not. E.g., in the program `while (True) Skip;;Skip` two nodes identify this initial statement: the initial node and the node within the loop (because of loop unrolling).

theorem *nonInterference*:

```

assumes [cf1]  $\approx_L$  [cf2] and  $(-\text{High-}) \notin [\text{HRB-slice } S]_{\text{CFG}}$ 
and CFG-node  $(-\text{Low-}) \in S$ 
and valid-edge a and sourcenode a =  $(-\text{High-})$  and targetnode a = n
and kind a =  $(\lambda s. \text{True})_{\surd}$  and n  $\triangleq$  c and final c'
and  $\langle c, [cf_1] \rangle \Rightarrow \langle c', s_1 \rangle$  and  $\langle c, [cf_2] \rangle \Rightarrow \langle c', s_2 \rangle$ 
shows s1  $\approx_L$  s2

```

proof –

```

from High-target-Entry-edge obtain ax where valid-edge ax
and sourcenode ax =  $(-\text{Entry-})$  and targetnode ax =  $(-\text{High-})$ 
and kind ax =  $(\lambda s. \text{True})_{\surd}$  by blast

```

```

from  $\langle n \triangleq c \rangle \langle c, [cf_1] \rangle \Rightarrow \langle c', s_1 \rangle$ 
obtain  $n_1$   $as_1$   $cfs_1$  where  $n - as_1 \rightarrow_{\sqrt{*}} n_1$  and  $n_1 \triangleq c'$ 
  and  $preds$  ( $kinds$   $as_1$ )  $[(cf_1, undefined)]$ 
  and  $transfers$  ( $kinds$   $as_1$ )  $[(cf_1, undefined)] = cfs_1$  and  $map$   $fst$   $cfs_1 = s_1$ 
  by( $fastforce$   $dest: fundamental-property$ )
from  $\langle n - as_1 \rightarrow_{\sqrt{*}} n_1 \rangle \langle valid-edge\ a \rangle \langle sourcenode\ a = (-High-) \rangle \langle targetnode\ a =$ 
 $n \rangle$ 
   $\langle kind\ a = (\lambda s. True)_{\sqrt{*}} \rangle$ 
have  $(-High-) - a \# as_1 \rightarrow_{\sqrt{*}} n_1$  by( $fastforce$   $intro: Cons-path\ simp: vp-def\ valid-path-def$ )
from  $\langle final\ c' \rangle \langle n_1 \triangleq c' \rangle$ 
obtain  $a_1$  where  $valid-edge\ a_1$  and  $sourcenode\ a_1 = n_1$ 
  and  $targetnode\ a_1 = (-Low-)$  and  $kind\ a_1 = \uparrow id$  by( $fastforce$   $dest: final-edge-Low$ )
hence  $n_1 - [a_1] \rightarrow_{\sqrt{*}} (-Low-)$  by( $fastforce$   $intro: path-edge$ )
with  $\langle (-High-) - a \# as_1 \rightarrow_{\sqrt{*}} n_1 \rangle$  have  $(-High-) - (a \# as_1) @ [a_1] \rightarrow_{\sqrt{*}} (-Low-)$ 
  by( $fastforce$   $intro!: path-Append\ simp: vp-def$ )
with  $\langle valid-edge\ ax \rangle \langle sourcenode\ ax = (-Entry-) \rangle \langle targetnode\ ax = (-High-) \rangle$ 
have  $(-Entry-) - ax \# ((a \# as_1) @ [a_1]) \rightarrow_{\sqrt{*}} (-Low-)$  by  $(-rule\ Cons-path)$ 
moreover
from  $\langle (-High-) - a \# as_1 \rightarrow_{\sqrt{*}} n_1 \rangle$  have  $valid-path-aux \ []\ (a \# as_1)$ 
  by( $simp\ add: vp-def\ valid-path-def$ )
with  $\langle kind\ a_1 = \uparrow id \rangle$  have  $valid-path-aux \ []\ ((a \# as_1) @ [a_1])$ 
  by( $fastforce$   $intro: valid-path-aux-Append$ )
with  $\langle kind\ ax = (\lambda s. True)_{\sqrt{*}} \rangle$  have  $valid-path-aux \ []\ (ax \# ((a \# as_1) @ [a_1]))$ 
  by  $simp$ 
ultimately have  $(-Entry-) - ax \# ((a \# as_1) @ [a_1]) \rightarrow_{\sqrt{*}} (-Low-)$ 
  by( $simp\ add: vp-def\ valid-path-def$ )
from  $\langle valid-edge\ a \rangle \langle kind\ a = (\lambda s. True)_{\sqrt{*}} \rangle \langle sourcenode\ a = (-High-) \rangle$ 
 $\langle targetnode\ a = n \rangle$ 
have  $get-proc\ n = get-proc\ (-High-)$ 
  by( $fastforce$   $dest: get-proc-intra\ simp: intra-kind-def$ )
with  $get-proc-High$  have  $get-proc\ n = Main$  by  $simp$ 
from  $\langle valid-edge\ a_1 \rangle \langle sourcenode\ a_1 = n_1 \rangle \langle targetnode\ a_1 = (-Low-) \rangle \langle kind\ a_1 =$ 
 $\uparrow id \rangle$ 
have  $get-proc\ n_1 = get-proc\ (-Low-)$ 
  by( $fastforce$   $dest: get-proc-intra\ simp: intra-kind-def$ )
with  $get-proc-Low$  have  $get-proc\ n_1 = Main$  by  $simp$ 
from  $\langle n - as_1 \rightarrow_{\sqrt{*}} n_1 \rangle$  have  $n - as_1 \rightarrow_{st^*} n_1$ 
  by( $cases\ as_1$ )
  ( $auto\ dest!: vpa-Main-slp\ intro: \langle get-proc\ n_1 = Main \rangle \langle get-proc\ n = Main \rangle$ 
   $simp: vp-def\ valid-path-def\ valid-call-list-def\ slp-def$ 
   $same-level-path-def\ simp\ del: valid-path-aux.simps$ )
then obtain  $cfx\ r$  where  $cfx: transfers$  ( $map\ kind\ as_1$ )  $[(cf_1, undefined)] =$ 
 $[(cfx, r)]$ 
  by( $fastforce\ elim: slp-callstack-length-equal\ simp: kinds-def$ )
from  $\langle kind\ ax = (\lambda s. True)_{\sqrt{*}} \rangle \langle kind\ a = (\lambda s. True)_{\sqrt{*}} \rangle$ 
 $\langle preds$  ( $kinds$   $as_1$ )  $[(cf_1, undefined)] \rangle \langle kind\ a_1 = \uparrow id \rangle$   $cfx$ 
have  $preds$  ( $kinds$  ( $ax \# ((a \# as_1) @ [a_1])$ ))  $[(cf_1, undefined)]$ 
  by( $auto\ simp: kinds-def\ preds-split$ )
from  $\langle n \triangleq c \rangle \langle c, [cf_2] \rangle \Rightarrow \langle c', s_2 \rangle$ 

```

```

obtain  $n_2$   $as_2$   $cfs_2$  where  $n - as_2 \rightarrow_{\sqrt{*}} n_2$  and  $n_2 \triangleq c'$ 
  and  $preds$  ( $kinds$   $as_2$ ) [( $cf_2, undefined$ )]
  and  $transfers$  ( $kinds$   $as_2$ ) [( $cf_2, undefined$ )] =  $cfs_2$  and  $map$   $fst$   $cfs_2 = s_2$ 
  by( $fastforce$   $dest: fundamental-property$ )
from  $\langle n - as_2 \rightarrow_{\sqrt{*}} n_2 \rangle$   $\langle valid-edge\ a \rangle$   $\langle sourcenode\ a = (-High-) \rangle$   $\langle targetnode\ a =$ 
 $n \rangle$ 
   $\langle kind\ a = (\lambda s. True)_{\sqrt{*}} \rangle$ 
have  $(-High-) - a\#as_2 \rightarrow_{\sqrt{*}} n_2$  by( $fastforce$   $intro: Cons-path\ simp: vp-def\ valid-path-def$ )
from  $\langle final\ c' \rangle$   $\langle n_2 \triangleq c' \rangle$ 
obtain  $a_2$  where  $valid-edge\ a_2$  and  $sourcenode\ a_2 = n_2$ 
  and  $targetnode\ a_2 = (-Low-)$  and  $kind\ a_2 = \uparrow id$  by( $fastforce$   $dest: final-edge-Low$ )
hence  $n_2 - [a_2] \rightarrow_{\sqrt{*}} (-Low-)$  by( $fastforce$   $intro: path-edge$ )
with  $\langle (-High-) - a\#as_2 \rightarrow_{\sqrt{*}} n_2 \rangle$  have  $(-High-) - (a\#as_2)@[a_2] \rightarrow_{\sqrt{*}} (-Low-)$ 
  by( $fastforce$   $intro!: path-Append\ simp: vp-def$ )
with  $\langle valid-edge\ ax \rangle$   $\langle sourcenode\ ax = (-Entry-) \rangle$   $\langle targetnode\ ax = (-High-) \rangle$ 
have  $(-Entry-) - ax\#((a\#as_2)@[a_2]) \rightarrow_{\sqrt{*}} (-Low-)$  by  $(-rule\ Cons-path)$ 
moreover
from  $\langle (-High-) - a\#as_2 \rightarrow_{\sqrt{*}} n_2 \rangle$  have  $valid-path-aux$  [] ( $a\#as_2$ )
  by( $simp$   $add: vp-def\ valid-path-def$ )
with  $\langle kind\ a_2 = \uparrow id \rangle$  have  $valid-path-aux$  [] ( $(a\#as_2)@[a_2]$ )
  by( $fastforce$   $intro: valid-path-aux-Append$ )
with  $\langle kind\ ax = (\lambda s. True)_{\sqrt{*}} \rangle$  have  $valid-path-aux$  [] ( $ax\#((a\#as_2)@[a_2])$ )
  by  $simp$ 
ultimately have  $(-Entry-) - ax\#((a\#as_2)@[a_2]) \rightarrow_{\sqrt{*}} (-Low-)$ 
  by( $simp$   $add: vp-def\ valid-path-def$ )
from  $\langle valid-edge\ a \rangle$   $\langle kind\ a = (\lambda s. True)_{\sqrt{*}} \rangle$   $\langle sourcenode\ a = (-High-) \rangle$ 
   $\langle targetnode\ a = n \rangle$ 
have  $get-proc\ n = get-proc\ (-High-)$ 
  by( $fastforce$   $dest: get-proc-intra\ simp: intra-kind-def$ )
with  $get-proc-High$  have  $get-proc\ n = Main$  by  $simp$ 
from  $\langle valid-edge\ a_2 \rangle$   $\langle sourcenode\ a_2 = n_2 \rangle$   $\langle targetnode\ a_2 = (-Low-) \rangle$   $\langle kind\ a_2 =$ 
 $\uparrow id \rangle$ 
have  $get-proc\ n_2 = get-proc\ (-Low-)$ 
  by( $fastforce$   $dest: get-proc-intra\ simp: intra-kind-def$ )
with  $get-proc-Low$  have  $get-proc\ n_2 = Main$  by  $simp$ 
from  $\langle n - as_2 \rightarrow_{\sqrt{*}} n_2 \rangle$  have  $n - as_2 \rightarrow_{st^*} n_2$ 
  by( $cases\ as_2$ )
  ( $auto$   $dest!: vpa-Main-slp\ intro: \langle get-proc\ n_2 = Main \rangle \langle get-proc\ n = Main \rangle$ 
     $simp: vp-def\ valid-path-def\ valid-call-list-def\ slp-def$ 
     $same-level-path-def\ simp\ del: valid-path-aux.simps$ )
then obtain  $cfx'\ r'$ 
  where  $cfx': transfers$  ( $map\ kind\ as_2$ ) [( $cf_2, undefined$ )] = [( $cfx', r'$ )]
  by( $fastforce$   $elim: slp-callstack-length-equal\ simp: kinds-def$ )
from  $\langle kind\ ax = (\lambda s. True)_{\sqrt{*}} \rangle$   $\langle kind\ a = (\lambda s. True)_{\sqrt{*}} \rangle$ 
   $\langle preds$  ( $kinds$   $as_2$ ) [( $cf_2, undefined$ )]  $\rangle$   $\langle kind\ a_2 = \uparrow id \rangle$   $cfx'$ 
have  $preds$  ( $kinds$  ( $ax\#((a\#as_2)@[a_2])$ )) [( $cf_2, undefined$ )]
  by( $auto$   $simp: kinds-def\ preds-split$ )
from  $\langle [cf_1] \approx_L [cf_2] \rangle$   $\langle (-High-) \notin [HRB-slice\ S]_{CFG} \rangle$   $\langle CFG-node\ (-Low-) \in S \rangle$ 
   $\langle (-Entry-) - ax\#((a\#as_1)@[a_1]) \rightarrow_{\sqrt{*}} (-Low-) \rangle$ 

```

```

  ⟨preds (kinds (ax#((a#as1)@[a1]))) [(cf1,undefined)]⟩
  ⟨(-Entry-) -ax#((a#as2)@[a2])→✓* (-Low-)⟩
  ⟨preds (kinds (ax#((a#as2)@[a2]))) [(cf2,undefined)]⟩
  have map fst (transfers (kinds (ax#((a#as1)@[a1]))) [(cf1,undefined)]) ≈L
    map fst (transfers (kinds (ax#((a#as2)@[a2]))) [(cf2,undefined)])
  by(rule nonInterference-path-to-Low)
  with ⟨kind ax = (λs. True)✓⟩ ⟨kind a = (λs. True)✓⟩ ⟨kind a1 = ↑id⟩ ⟨kind a2
= ↑id⟩
  ⟨transfers (kinds as1) [(cf1,undefined)] = cfs1⟩ ⟨map fst cfs1 = s1⟩
  ⟨transfers (kinds as2) [(cf2,undefined)] = cfs2⟩ ⟨map fst cfs2 = s2⟩
  show ?thesis by(cases s1)(cases s2,(fastforce simp:kinds-def transfers-split)+)
qed

end

end

```

3 Framework Graph Lifting for Noninterference

```

theory LiftingInter
imports NonInterferenceInter
begin

```

In this section, we show how a valid CFG from the slicing framework in [8] can be lifted to fulfil all properties of the *NonInterferenceIntraGraph* locale. Basically, we redefine the hitherto existing *Entry* and *Exit* nodes as new *High* and *Low* nodes, and introduce two new nodes *NewEntry* and *NewExit*. Then, we have to lift all functions to operate on this new graph.

3.1 Liftings

3.1.1 The datatypes

```

datatype 'node LDCFG-node = Node 'node
  | NewEntry
  | NewExit

```

```

type-synonym ('edge,'node,'var,'val,'ret,'pname) LDCFG-edge =
  'node LDCFG-node × (('var,'val,'ret,'pname) edge-kind) × 'node LDCFG-node

```

3.1.2 Lifting basic definitions using 'edge and 'node

```

inductive lift-valid-edge :: ('edge ⇒ bool) ⇒ ('edge ⇒ 'node) ⇒ ('edge ⇒ 'node)
⇒
  ('edge ⇒ ('var,'val,'ret,'pname) edge-kind) ⇒ 'node ⇒ 'node ⇒
  ('edge,'node,'var,'val,'ret,'pname) LDCFG-edge ⇒
  bool

```


for *valid-edge*::'edge \Rightarrow bool **and** *src*::'edge \Rightarrow 'node **and** *trg*::'edge \Rightarrow 'node
and *knd*::'edge \Rightarrow ('var,'val,'ret,'pname) edge-kind **and** *E*::'node **and** *X*::'node

where *lve-edge*:

[[*valid-edge* *a*; *src* *a* \neq *E* \vee *trg* *a* \neq *X*;
e = (*Node* (*src* *a*),*knd* *a*,*Node* (*trg* *a*))]]
 \Rightarrow *lift-valid-edge* *valid-edge* *src* *trg* *knd* *E* *X* *e*

| *lve-Entry-edge*:

e = (*NewEntry*,($\lambda s.$ *True*) \surd ,*Node* *E*)
 \Rightarrow *lift-valid-edge* *valid-edge* *src* *trg* *knd* *E* *X* *e*

| *lve-Exit-edge*:

e = (*Node* *X*,($\lambda s.$ *True*) \surd ,*NewExit*)
 \Rightarrow *lift-valid-edge* *valid-edge* *src* *trg* *knd* *E* *X* *e*

| *lve-Entry-Exit-edge*:

e = (*NewEntry*,($\lambda s.$ *False*) \surd ,*NewExit*)
 \Rightarrow *lift-valid-edge* *valid-edge* *src* *trg* *knd* *E* *X* *e*

lemma [*simp*]: \neg *lift-valid-edge* *valid-edge* *src* *trg* *knd* *E* *X* (*Node* *E*,*et*,*Node* *X*)
by(*auto elim:lift-valid-edge.cases*)

fun *lift-get-proc* :: ('node \Rightarrow 'pname) \Rightarrow 'pname \Rightarrow 'node *LDCFG-node* \Rightarrow 'pname
where *lift-get-proc* *get-proc* *Main* (*Node* *n*) = *get-proc* *n*
| *lift-get-proc* *get-proc* *Main* *NewEntry* = *Main*
| *lift-get-proc* *get-proc* *Main* *NewExit* = *Main*

inductive-set *lift-get-return-edges* :: ('edge \Rightarrow 'edge set) \Rightarrow ('edge \Rightarrow bool) \Rightarrow
('edge \Rightarrow 'node) \Rightarrow ('edge \Rightarrow 'node) \Rightarrow ('edge \Rightarrow ('var,'val,'ret,'pname) edge-kind)

\Rightarrow ('edge,'node,'var,'val,'ret,'pname) *LDCFG-edge*
 \Rightarrow ('edge,'node,'var,'val,'ret,'pname) *LDCFG-edge set*

for *get-return-edges* :: 'edge \Rightarrow 'edge set **and** *valid-edge* :: 'edge \Rightarrow bool
and *src*::'edge \Rightarrow 'node **and** *trg*::'edge \Rightarrow 'node
and *knd*::'edge \Rightarrow ('var,'val,'ret,'pname) edge-kind
and *e*::('edge,'node,'var,'val,'ret,'pname) *LDCFG-edge*

where *lift-get-return-edgesI*:

[[*e* = (*Node* (*src* *a*),*knd* *a*,*Node* (*trg* *a*)); *valid-edge* *a*; *a'* \in *get-return-edges* *a*;
e' = (*Node* (*src* *a'*),*knd* *a'*,*Node* (*trg* *a'*))]]
 \Rightarrow *e'* \in *lift-get-return-edges* *get-return-edges* *valid-edge* *src* *trg* *knd* *e*

3.1.3 Lifting the Def and Use sets

inductive-set *lift-Def-set* :: ('node \Rightarrow 'var set) \Rightarrow 'node \Rightarrow 'node \Rightarrow

$'var\ set \Rightarrow 'var\ set \Rightarrow ('node\ LDCFG\text{-}node \times 'var)\ set$

for $Def::('node \Rightarrow 'var\ set)$ **and** $E::'node$ **and** $X::'node$
and $H::'var\ set$ **and** $L::'var\ set$

where *lift-Def-node*:

$V \in Def\ n \Longrightarrow (Node\ n, V) \in lift\text{-}Def\text{-}set\ Def\ E\ X\ H\ L$

| *lift-Def-High*:

$V \in H \Longrightarrow (Node\ E, V) \in lift\text{-}Def\text{-}set\ Def\ E\ X\ H\ L$

abbreviation *lift-Def* :: $('node \Rightarrow 'var\ set) \Rightarrow 'node \Rightarrow 'node \Rightarrow$

$'var\ set \Rightarrow 'var\ set \Rightarrow 'node\ LDCFG\text{-}node \Rightarrow 'var\ set$

where *lift-Def* $Def\ E\ X\ H\ L\ n \equiv \{V. (n, V) \in lift\text{-}Def\text{-}set\ Def\ E\ X\ H\ L\}$

inductive-set *lift-Use-set* :: $('node \Rightarrow 'var\ set) \Rightarrow 'node \Rightarrow 'node \Rightarrow$

$'var\ set \Rightarrow 'var\ set \Rightarrow ('node\ LDCFG\text{-}node \times 'var)\ set$

for $Use::'node \Rightarrow 'var\ set$ **and** $E::'node$ **and** $X::'node$

and $H::'var\ set$ **and** $L::'var\ set$

where

lift-Use-node:

$V \in Use\ n \Longrightarrow (Node\ n, V) \in lift\text{-}Use\text{-}set\ Use\ E\ X\ H\ L$

| *lift-Use-High*:

$V \in H \Longrightarrow (Node\ E, V) \in lift\text{-}Use\text{-}set\ Use\ E\ X\ H\ L$

| *lift-Use-Low*:

$V \in L \Longrightarrow (Node\ X, V) \in lift\text{-}Use\text{-}set\ Use\ E\ X\ H\ L$

abbreviation *lift-Use* :: $('node \Rightarrow 'var\ set) \Rightarrow 'node \Rightarrow 'node \Rightarrow$

$'var\ set \Rightarrow 'var\ set \Rightarrow 'node\ LDCFG\text{-}node \Rightarrow 'var\ set$

where *lift-Use* $Use\ E\ X\ H\ L\ n \equiv \{V. (n, V) \in lift\text{-}Use\text{-}set\ Use\ E\ X\ H\ L\}$

fun *lift-ParamUses* :: $('node \Rightarrow 'var\ set\ list) \Rightarrow 'node\ LDCFG\text{-}node \Rightarrow 'var\ set\ list$

where *lift-ParamUses* $ParamUses\ (Node\ n) = ParamUses\ n$

| *lift-ParamUses* $ParamUses\ NewEntry = []$

| *lift-ParamUses* $ParamUses\ NewExit = []$

fun *lift-ParamDefs* :: $('node \Rightarrow 'var\ list) \Rightarrow 'node\ LDCFG\text{-}node \Rightarrow 'var\ list$

where *lift-ParamDefs* $ParamDefs\ (Node\ n) = ParamDefs\ n$

| *lift-ParamDefs* $ParamDefs\ NewEntry = []$

| *lift-ParamDefs* $ParamDefs\ NewExit = []$

3.2 The lifting lemmas

3.2.1 Lifting the CFG locales

abbreviation $src :: ('edge, 'node, 'var, 'val, 'ret, 'pname) LDCFG\text{-edge} \Rightarrow 'node LD\text{-CFG}\text{-node}$

where $src\ a \equiv fst\ a$

abbreviation $trg :: ('edge, 'node, 'var, 'val, 'ret, 'pname) LDCFG\text{-edge} \Rightarrow 'node LD\text{-CFG}\text{-node}$

where $trg\ a \equiv snd(snd\ a)$

abbreviation $knd :: ('edge, 'node, 'var, 'val, 'ret, 'pname) LDCFG\text{-edge} \Rightarrow ('var, 'val, 'ret, 'pname)\ edge\text{-kind}$

where $knd\ a \equiv fst(snd\ a)$

lemma *lift-CFG*:

assumes $wf: CFGExit\text{-wf}\ sourcenode\ targetnode\ kind\ valid\text{-edge}\ Entry\ get\text{-proc}\ get\text{-return}\text{-edges}\ procs\ Main\ Exit\ Def\ Use\ Param\ Defs\ Param\ Uses$

and $pd: Postdomination\ sourcenode\ targetnode\ kind\ valid\text{-edge}\ Entry\ get\text{-proc}\ get\text{-return}\text{-edges}\ procs\ Main\ Exit$

shows $CFG\ src\ trg\ knd$

$(lift\text{-valid}\text{-edge}\ valid\text{-edge}\ sourcenode\ targetnode\ kind\ Entry\ Exit)\ NewEntry$

$(lift\text{-get}\text{-proc}\ get\text{-proc}\ Main)$

$(lift\text{-get}\text{-return}\text{-edges}\ get\text{-return}\text{-edges}\ valid\text{-edge}\ sourcenode\ targetnode\ kind)\ procs\ Main$

proof –

interpret $CFGExit\text{-wf}\ sourcenode\ targetnode\ kind\ valid\text{-edge}\ Entry\ get\text{-proc}\ get\text{-return}\text{-edges}\ procs\ Main\ Exit\ Def\ Use\ Param\ Defs\ Param\ Uses$

by(rule wf)

interpret $Postdomination\ sourcenode\ targetnode\ kind\ valid\text{-edge}\ Entry\ get\text{-proc}\ get\text{-return}\text{-edges}\ procs\ Main\ Exit$

by(rule pd)

show $?thesis$

proof

fix a **assume** $lift\text{-valid}\text{-edge}\ valid\text{-edge}\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a$

and $trg\ a = NewEntry$

thus $False$ **by**(fastforce elim: $lift\text{-valid}\text{-edge}\text{-cases}$)

next

show $lift\text{-get}\text{-proc}\ get\text{-proc}\ Main\ NewEntry = Main$ **by** $simp$

next

fix $a\ Q\ r\ p\ fs$

assume $lift\text{-valid}\text{-edge}\ valid\text{-edge}\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a$

and $knd\ a = Q:r \hookrightarrow pfs$ **and** $src\ a = NewEntry$

thus $False$ **by**(fastforce elim: $lift\text{-valid}\text{-edge}\text{-cases}$)

next

fix $a\ a'$

assume $lift\text{-valid}\text{-edge}\ valid\text{-edge}\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a$

and $lift\text{-valid}\text{-edge}\ valid\text{-edge}\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a'$

```

    and src a = src a' and trg a = trg a'
  thus a = a'
  proof(induct rule:lift-valid-edge.induct)
    case we-edge thus ?case by -(erule lift-valid-edge.cases,auto dest:edge-det)
  qed(auto elim:lift-valid-edge.cases)
next
  fix a Q r f
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and knd a = Q:r↦Mainf
  thus False by(fastforce elim:lift-valid-edge.cases dest:Main-no-call-target)
next
  fix a Q' f'
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and knd a = Q'↦Mainf'
  thus False by(fastforce elim:lift-valid-edge.cases dest:Main-no-return-source)
next
  fix a Q r p fs
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and knd a = Q:r↦pfs
  thus ∃ ins outs. (p, ins, outs) ∈ set procs
    by(fastforce elim:lift-valid-edge.cases intro:callee-in-procs)
next
  fix a assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and intra-kind (knd a)
  thus lift-get-proc get-proc Main (src a) = lift-get-proc get-proc Main (trg a)
    by(fastforce elim:lift-valid-edge.cases intro:get-proc-intra
      simp:get-proc-Entry get-proc-Exit)
next
  fix a Q r p fs
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and knd a = Q:r↦pfs
  thus lift-get-proc get-proc Main (trg a) = p
    by(fastforce elim:lift-valid-edge.cases intro:get-proc-call)
next
  fix a Q' p f'
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and knd a = Q'↦pf'
  thus lift-get-proc get-proc Main (src a) = p
    by(fastforce elim:lift-valid-edge.cases intro:get-proc-return)
next
  fix a Q r p fs
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and knd a = Q:r↦pfs
  then obtain ax where valid-edge ax and kind ax = Q:r↦pfs
    and sourcenode ax ≠ Entry ∨ targetnode ax ≠ Exit
    and src a = Node (sourcenode ax) and trg a = Node (targetnode ax)
    by(fastforce elim:lift-valid-edge.cases)
  from ⟨valid-edge ax⟩ ⟨kind ax = Q:r↦pfs⟩
  have all:∀ a'. valid-edge a' ∧ targetnode a' = targetnode ax ⟶

```

```

      (∃ Qx rx fsx. kind a' = Qx:rx↔pfsx)
    by(auto dest:call-edges-only)
  { fix a'
    assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'
      and trg a' = trg a
    hence ∃ Qx rx fsx. knd a' = Qx:rx↔pfsx
    proof(induct rule:lift-valid-edge.induct)
      case (lve-edge ax' e)
      note [simp] = ⟨e = (Node (sourcenode ax'), kind ax', Node (targetnode ax'))⟩
      from ⟨trg e = trg a⟩ ⟨trg a = Node (targetnode ax)⟩
      have targetnode ax' = targetnode ax by simp
      with ⟨valid-edge ax'⟩ all have ∃ Qx rx fsx. kind ax' = Qx:rx↔pfsx by blast
      thus ?case by simp
    next
      case (lve-Entry-edge e)
      from ⟨e = (NewEntry, (λs. True)√, Node Entry)⟩ ⟨trg e = trg a⟩
        ⟨trg a = Node (targetnode ax)⟩
      have targetnode ax = Entry by simp
      with ⟨valid-edge ax⟩ have False by(rule Entry-target)
      thus ?case by simp
    next
      case (lve-Exit-edge e)
      from ⟨e = (Node Exit, (λs. True)√, NewExit)⟩ ⟨trg e = trg a⟩
        ⟨trg a = Node (targetnode ax)⟩ have False by simp
      thus ?case by simp
    next
      case (lve-Entry-Exit-edge e)
      from ⟨e = (NewEntry, (λs. False)√, NewExit)⟩ ⟨trg e = trg a⟩
        ⟨trg a = Node (targetnode ax)⟩ have False by simp
      thus ?case by simp
    qed }
  thus ∀ a'. lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a' ∧
    trg a' = trg a → (∃ Qx rx fsx. knd a' = Qx:rx↔pfsx) by simp
next
  fix a Q' p f'
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and knd a = Q'↔pf'
  then obtain ax where valid-edge ax and kind ax = Q'↔pf'
    and sourcenode ax ≠ Entry ∨ targetnode ax ≠ Exit
    and src a = Node (sourcenode ax) and trg a = Node (targetnode ax)
  by(fastforce elim:lift-valid-edge.cases)
  from ⟨valid-edge ax⟩ ⟨kind ax = Q'↔pf'⟩
  have all:∀ a'. valid-edge a' ∧ sourcenode a' = sourcenode ax →
    (∃ Qx fx. kind a' = Qx↔pfx)
  by(auto dest:return-edges-only)
  { fix a'
    assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'
      and src a' = src a
    hence ∃ Qx fx. knd a' = Qx↔pfx
  }

```

```

proof(induct rule:lift-valid-edge.induct)
  case (lve-edge ax' e)
  note [simp] =  $\langle e = (\text{Node } (\text{sourcenode } ax'), \text{kind } ax', \text{Node } (\text{targetnode } ax')) \rangle$ 
  from  $\langle \text{src } e = \text{src } a \rangle \langle \text{src } a = \text{Node } (\text{sourcenode } ax) \rangle$ 
  have sourcenode ax' = sourcenode ax by simp
  with  $\langle \text{valid-edge } ax' \rangle$  all have  $\exists Qx \text{ fx. kind } ax' = Qx \leftrightarrow_p \text{fx}$  by blast
  thus ?case by simp
next
  case (lve-Entry-edge e)
  from  $\langle e = (\text{NewEntry}, (\lambda s. \text{True})_{\surd}, \text{Node } \text{Entry}) \rangle \langle \text{src } e = \text{src } a \rangle$ 
   $\langle \text{src } a = \text{Node } (\text{sourcenode } ax) \rangle$  have False by simp
  thus ?case by simp
next
  case (lve-Exit-edge e)
  from  $\langle e = (\text{Node } \text{Exit}, (\lambda s. \text{True})_{\surd}, \text{NewExit}) \rangle \langle \text{src } e = \text{src } a \rangle$ 
   $\langle \text{src } a = \text{Node } (\text{sourcenode } ax) \rangle$  have sourcenode ax = Exit by simp
  with  $\langle \text{valid-edge } ax \rangle$  have False by(rule Exit-source)
  thus ?case by simp
next
  case (lve-Entry-Exit-edge e)
  from  $\langle e = (\text{NewEntry}, (\lambda s. \text{False})_{\surd}, \text{NewExit}) \rangle \langle \text{src } e = \text{src } a \rangle$ 
   $\langle \text{src } a = \text{Node } (\text{sourcenode } ax) \rangle$  have False by simp
  thus ?case by simp
qed }
thus  $\forall a'. \text{lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit } a' \wedge$ 
 $\text{src } a' = \text{src } a \longrightarrow (\exists Qx \text{ fx. kind } a' = Qx \leftrightarrow_p \text{fx})$  by simp
next
fix a Q r p fs
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
and knd a = Q:r $\leftrightarrow$ pfs
thus lift-get-return-edges get-return-edges valid-edge
sourcenode targetnode kind a  $\neq$  {}
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge ax e)
  from  $\langle e = (\text{Node } (\text{sourcenode } ax), \text{kind } ax, \text{Node } (\text{targetnode } ax)) \rangle$ 
 $\langle \text{knd } e = Q:r \leftrightarrow_p \text{fs} \rangle$ 
  have kind ax = Q:r $\leftrightarrow$ pfs by simp
  with  $\langle \text{valid-edge } ax \rangle$  have get-return-edges ax  $\neq$  {}
  by(rule get-return-edge-call)
  then obtain ax' where ax'  $\in$  get-return-edges ax by blast
  with  $\langle e = (\text{Node } (\text{sourcenode } ax), \text{kind } ax, \text{Node } (\text{targetnode } ax)) \rangle \langle \text{valid-edge}$ 
ax  $\rangle$ 
  have  $(\text{Node } (\text{sourcenode } ax'), \text{kind } ax', \text{Node } (\text{targetnode } ax')) \in$ 
lift-get-return-edges get-return-edges valid-edge
sourcenode targetnode kind e
  by(fastforce intro:lift-get-return-edgesI)
  thus ?case by fastforce
qed simp-all
next

```

```

fix a a'
assume a' ∈ lift-get-return-edges get-return-edges valid-edge
  sourcenode targetnode kind a
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
thus lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'
proof (induct rule:lift-get-return-edges.induct)
  case (lift-get-return-edgesI ax a' e')
  from ⟨valid-edge ax⟩ ⟨a' ∈ get-return-edges ax⟩ have valid-edge a'
    by(rule get-return-edges-valid)
  from ⟨valid-edge ax⟩ ⟨a' ∈ get-return-edges ax⟩ obtain Q r p fs
    where kind ax = Q:r↔pfs by(fastforce dest!:only-call-get-return-edges)
  with ⟨valid-edge ax⟩ ⟨a' ∈ get-return-edges ax⟩ obtain Q' f'
    where kind a' = Q'↔pf' by(fastforce dest!:call-return-edges)
  from ⟨valid-edge a'⟩ ⟨kind a' = Q'↔pf'⟩ have get-proc(sourcenode a') = p
    by(rule get-proc-return)
  have sourcenode a' ≠ Entry
proof
  assume sourcenode a' = Entry
  with get-proc-Entry ⟨get-proc(sourcenode a') = p⟩ have p = Main by simp
  with ⟨kind a' = Q'↔pf'⟩ have kind a' = Q'↔Mainf' by simp
  with ⟨valid-edge a'⟩ show False by(rule Main-no-return-source)
qed
with ⟨e' = (Node (sourcenode a'), kind a', Node (targetnode a'))⟩
  ⟨valid-edge a'⟩
  show ?case by(fastforce intro:lve-edge)
qed
next
fix a a'
assume a' ∈ lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind a
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
thus ∃ Q r p fs. kind a = Q:r↔pfs
proof (induct rule:lift-get-return-edges.induct)
  case (lift-get-return-edgesI ax a' e')
  from ⟨valid-edge ax⟩ ⟨a' ∈ get-return-edges ax⟩
  have ∃ Q r p fs. kind ax = Q:r↔pfs
    by(rule only-call-get-return-edges)
  with ⟨a = (Node (sourcenode ax), kind ax, Node (targetnode ax))⟩
  show ?case by simp
qed
next
fix a Q r p fs a'
assume a' ∈ lift-get-return-edges get-return-edges
  valid-edge sourcenode targetnode kind a and kind a = Q:r↔pfs
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
thus ∃ Q' f'. kind a' = Q'↔pf'
proof (induct rule:lift-get-return-edges.induct)
  case (lift-get-return-edgesI ax a' e')
  from ⟨a = (Node (sourcenode ax), kind ax, Node (targetnode ax))⟩

```

```

  ⟨knd a = Q:r↔pfs⟩
  have kind ax = Q:r↔pfs by simp
  with ⟨valid-edge ax⟩ ⟨a' ∈ get-return-edges ax⟩ have ∃ Q' f'. kind a' = Q'↔pf'
    by -(rule call-return-edges)
  with ⟨e' = (Node (sourcenode a'), kind a', Node (targetnode a'))⟩
  show ?case by simp
qed
next
fix a Q' p f'
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a = Q'↔pf'
thus ∃!a'. lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a' ∧
  (∃ Q r fs. knd a' = Q:r↔pfs) ∧ a ∈ lift-get-return-edges get-return-edges
  valid-edge sourcenode targetnode kind a'
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge a e)
  from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
  ⟨knd e = Q'↔pf'⟩ have kind a = Q'↔pf' by simp
  with ⟨valid-edge a⟩
  have ∃!a'. valid-edge a' ∧ (∃ Q r fs. kind a' = Q:r↔pfs) ∧
    a ∈ get-return-edges a'
    by(rule return-needs-call)
  then obtain a' Q r fs where valid-edge a' and kind a' = Q:r↔pfs
    and a ∈ get-return-edges a'
    and imp:∀x. valid-edge x ∧ (∃ Q r fs. kind x = Q:r↔pfs) ∧
    a ∈ get-return-edges x → x = a'
    by(fastforce elim:ex1E)
  let ?e' = (Node (sourcenode a'), kind a', Node (targetnode a'))
  have sourcenode a' ≠ Entry
  proof
    assume sourcenode a' = Entry
    with ⟨valid-edge a'⟩ ⟨kind a' = Q:r↔pfs⟩
    show False by(rule Entry-no-call-source)
  qed
  with ⟨valid-edge a'⟩
  have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e'
    by(fastforce intro:lift-valid-edge.lve-edge)
  moreover
  from ⟨kind a' = Q:r↔pfs⟩ have knd ?e' = Q:r↔pfs by simp
  moreover
  from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
  ⟨valid-edge a'⟩ ⟨a ∈ get-return-edges a'⟩
  have e ∈ lift-get-return-edges get-return-edges valid-edge
    sourcenode targetnode kind ?e' by(fastforce intro:lift-get-return-edgesI)
  moreover
  { fix x
    assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit x
    and ∃ Q r fs. knd x = Q:r↔pfs
    and e ∈ lift-get-return-edges get-return-edges valid-edge

```



```

    sourcenode targetnode kind x
  from ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit x⟩
    ⟨ $\exists Q r fs. \text{knd } x = Q:r\hookrightarrow pfs$ ⟩ obtain y where valid-edge y
    and  $x = (\text{Node } (\text{sourcenode } y), \text{kind } y, \text{Node } (\text{targetnode } y))$ 
    by(fastforce elim:lift-valid-edge.cases)
  with ⟨ $e \in \text{lift-get-return-edges get-return-edges valid-edge}$ 
    sourcenode targetnode kind  $x$ ⟩ ⟨valid-edge  $a$ ⟩
    ⟨ $e = (\text{Node } (\text{sourcenode } a), \text{kind } a, \text{Node } (\text{targetnode } a))$ ⟩
  have  $x = ?e'$ 
  proof(induct rule:lift-get-return-edges.induct)
    case (lift-get-return-edgesI  $ax$   $ax'$   $e$ )
    from ⟨valid-edge  $ax$ ⟩ ⟨ $ax' \in \text{get-return-edges } ax$ ⟩ have valid-edge  $ax'$ 
      by(rule get-return-edges-valid)
    from ⟨ $e = (\text{Node } (\text{sourcenode } ax'), \text{kind } ax', \text{Node } (\text{targetnode } ax'))$ ⟩
      ⟨ $e = (\text{Node } (\text{sourcenode } a), \text{kind } a, \text{Node } (\text{targetnode } a))$ ⟩
    have sourcenode  $a = \text{sourcenode } ax'$  and targetnode  $a = \text{targetnode } ax'$ 
      by simp-all
    with ⟨valid-edge  $a$ ⟩ ⟨valid-edge  $ax'$ ⟩ have [simp]: $a = ax'$  by(rule edge-det)
    from ⟨ $x = (\text{Node } (\text{sourcenode } ax), \text{kind } ax, \text{Node } (\text{targetnode } ax))$ ⟩
      ⟨ $\exists Q r fs. \text{knd } x = Q:r\hookrightarrow pfs$ ⟩ have  $\exists Q r fs. \text{knd } ax = Q:r\hookrightarrow pfs$  by simp
    with ⟨valid-edge  $ax$ ⟩ ⟨ $ax' \in \text{get-return-edges } ax$ ⟩ imp
    have  $ax = a'$  by fastforce
    with ⟨ $x = (\text{Node } (\text{sourcenode } ax), \text{kind } ax, \text{Node } (\text{targetnode } ax))$ ⟩
    show ?thesis by simp
  qed }
  ultimately show ?case by(blast intro:ex1I)
qed simp-all
next
fix  $a$   $a'$ 
assume  $a' \in \text{lift-get-return-edges get-return-edges valid-edge sourcenode}$ 
  targetnode kind  $a$ 
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit  $a$ 
thus  $\exists a''. \text{lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit } a'' \wedge$ 
   $\text{src } a'' = \text{trg } a \wedge \text{trg } a'' = \text{src } a' \wedge \text{knd } a'' = (\lambda cf. \text{False})_{\surd}$ 
proof(induct rule:lift-get-return-edges.induct)
  case (lift-get-return-edgesI  $ax$   $a'$   $e'$ )
  from ⟨valid-edge  $ax$ ⟩ ⟨ $a' \in \text{get-return-edges } ax$ ⟩
  obtain  $ax'$  where valid-edge  $ax'$  and sourcenode  $ax' = \text{targetnode } ax$ 
    and targetnode  $ax' = \text{sourcenode } a'$  and kind  $ax' = (\lambda cf. \text{False})_{\surd}$ 
    by(fastforce dest:intra-proc-additional-edge)
  let ? $ex = (\text{Node } (\text{sourcenode } ax'), \text{kind } ax', \text{Node } (\text{targetnode } ax'))$ 
  have targetnode  $ax \neq \text{Entry}$ 
  proof
    assume targetnode  $ax = \text{Entry}$ 
    with ⟨valid-edge  $ax$ ⟩ show False by(rule Entry-target)
  qed
  with ⟨sourcenode  $ax' = \text{targetnode } ax$ ⟩ have sourcenode  $ax' \neq \text{Entry}$  by simp
  with ⟨valid-edge  $ax'$ ⟩
  have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ? $ex$ 

```

```

    by(fastforce intro:lve-edge)
  with ⟨e' = (Node (sourcenode a'), kind a', Node (targetnode a'))⟩
    ⟨a = (Node (sourcenode ax), kind ax, Node (targetnode ax))⟩
    ⟨e' = (Node (sourcenode a'), kind a', Node (targetnode a'))⟩
    ⟨sourcenode ax' = targetnode ax⟩ ⟨targetnode ax' = sourcenode a'⟩
    ⟨kind ax' = (λcf. False)⟩
  show ?case by simp
qed
next
fix a a'
assume a' ∈ lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind a
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
thus ∃ a''. lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'' ∧
  src a'' = src a ∧ trg a'' = trg a' ∧ knd a'' = (λcf. False)
proof(induct rule:lift-get-return-edges.induct)
  case (lift-get-return-edgesI ax a' e')
  from ⟨valid-edge ax⟩ ⟨a' ∈ get-return-edges ax⟩
  obtain ax' where valid-edge ax' and sourcenode ax' = sourcenode ax
    and targetnode ax' = targetnode a' and kind ax' = (λcf. False)
  by(fastforce dest:call-return-node-edge)
  let ?ex = (Node (sourcenode ax'), kind ax', Node (targetnode ax'))
  from ⟨valid-edge ax⟩ ⟨a' ∈ get-return-edges ax⟩
  obtain Q r p fs where kind ax = Q:r↔pfs
  by(fastforce dest!:only-call-get-return-edges)
  have sourcenode ax ≠ Entry
  proof
    assume sourcenode ax = Entry
    with ⟨valid-edge ax⟩ ⟨kind ax = Q:r↔pfs⟩ show False
    by(rule Entry-no-call-source)
  qed
  with ⟨sourcenode ax' = sourcenode ax⟩ have sourcenode ax' ≠ Entry by simp
  with ⟨valid-edge ax'⟩
  have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?ex
  by(fastforce intro:lve-edge)
  with ⟨e' = (Node (sourcenode a'), kind a', Node (targetnode a'))⟩
    ⟨a = (Node (sourcenode ax), kind ax, Node (targetnode ax))⟩
    ⟨e' = (Node (sourcenode a'), kind a', Node (targetnode a'))⟩
    ⟨sourcenode ax' = sourcenode ax⟩ ⟨targetnode ax' = targetnode a'⟩
    ⟨kind ax' = (λcf. False)⟩
  show ?case by simp
qed
next
fix a Q r p fs
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a = Q:r↔pfs
thus ∃!a'. lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a' ∧
  src a' = src a ∧ intra-kind (knd a')
proof(induct rule:lift-valid-edge.induct)

```

```

case (lve-edge a e)
  from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩ ⟨knd e =
Q:r↔pfs⟩
  have kind a = Q:r↔pfs by simp
  with ⟨valid-edge a⟩ have ∃!a'. valid-edge a' ∧ sourcenode a' = sourcenode a
  ∧
    intra-kind(kind a') by(rule call-only-one-intra-edge)
  then obtain a' where valid-edge a' and sourcenode a' = sourcenode a
    and intra-kind(kind a')
    and imp:∀x. valid-edge x ∧ sourcenode x = sourcenode a ∧ intra-kind(kind
x)
    → x = a' by(fastforce elim:ex1E)
  let ?e' = (Node (sourcenode a'), kind a', Node (targetnode a'))
  have sourcenode a ≠ Entry
  proof
    assume sourcenode a = Entry
    with ⟨valid-edge a⟩ ⟨kind a = Q:r↔pfs⟩ show False
    by(rule Entry-no-call-source)
  qed
  with ⟨sourcenode a' = sourcenode a⟩ have sourcenode a' ≠ Entry by simp
  with ⟨valid-edge a'⟩
  have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e'
    by(fastforce intro:lift-valid-edge.lve-edge)
  moreover
  from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
    ⟨sourcenode a' = sourcenode a⟩
  have src ?e' = src e by simp
  moreover
  from ⟨intra-kind(kind a')⟩ have intra-kind (knd ?e') by simp
  moreover
  { fix x
    assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit x
      and src x = src e and intra-kind (knd x)
    from ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit x⟩
    have x = ?e'
    proof(induct rule:lift-valid-edge.cases)
      case (lve-edge ax ex)
      from ⟨intra-kind (knd x)⟩ ⟨x = ex⟩ ⟨src x = src e⟩
        ⟨ex = (Node (sourcenode ax), kind ax, Node (targetnode ax))⟩
        ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
      have intra-kind (kind ax) and sourcenode ax = sourcenode a by simp-all
      with ⟨valid-edge ax⟩ imp have ax = a' by fastforce
      with ⟨x = ex⟩ ⟨ex = (Node (sourcenode ax), kind ax, Node (targetnode
ax))⟩
      show ?case by simp
    next
      case (lve-Entry-edge ex)
      with ⟨src x = src e⟩
        ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩

```

```

    have False by simp
    thus ?case by simp
  next
    case (lve-Exit-edge ex)
    with ⟨src x = src e⟩
      ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
    have sourcenode a = Exit by simp
    with ⟨valid-edge a⟩ have False by (rule Exit-source)
    thus ?case by simp
  next
    case (lve-Entry-Exit-edge ex)
    with ⟨src x = src e⟩
      ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
    have False by simp
    thus ?case by simp
  qed }
ultimately show ?case by (blast intro:ex1I)
qed simp-all
next
fix a Q' p f'
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
and knd a = Q'↔pf'
thus ∃!a'. lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a' ∧
trg a' = trg a ∧ intra-kind (knd a')
proof (induct rule:lift-valid-edge.induct)
case (lve-edge a e)
from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩ ⟨knd e =
Q'↔pf'⟩
have kind a = Q'↔pf' by simp
with ⟨valid-edge a⟩ have ∃!a'. valid-edge a' ∧ targetnode a' = targetnode a ∧
intra-kind(kind a') by (rule return-only-one-intra-edge)
then obtain a' where valid-edge a' and targetnode a' = targetnode a
and intra-kind(kind a')
and imp:∀ x. valid-edge x ∧ targetnode x = targetnode a ∧ intra-kind(kind
x)
→ x = a' by (fastforce elim:ex1E)
let ?e' = (Node (sourcenode a'), kind a', Node (targetnode a'))
have targetnode a ≠ Exit
proof
assume targetnode a = Exit
with ⟨valid-edge a⟩ ⟨kind a = Q'↔pf'⟩ show False
by (rule Exit-no-return-target)
qed
with ⟨targetnode a' = targetnode a⟩ have targetnode a' ≠ Exit by simp
with ⟨valid-edge a'⟩
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e'
by (fastforce intro:lift-valid-edge.lve-edge)
moreover
from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩

```

```

    ⟨targetnode a' = targetnode a⟩
  have trg ?e' = trg e by simp
  moreover
  from ⟨intra-kind(kind a')⟩ have intra-kind (knd ?e') by simp
  moreover
  { fix x
    assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit x
      and trg x = trg e and intra-kind (knd x)
    from ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit x⟩
    have x = ?e'
    proof(induct rule:lift-valid-edge.cases)
      case (lve-edge ax ex)
        from ⟨intra-kind (knd x)⟩ ⟨x = ex⟩ ⟨trg x = trg e⟩
          ⟨ex = (Node (sourcenode ax), kind ax, Node (targetnode ax))⟩
          ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
        have intra-kind (kind ax) and targetnode ax = targetnode a by simp-all
        with ⟨valid-edge ax⟩ imp have ax = a' by fastforce
        with ⟨x = ex⟩ ⟨ex = (Node (sourcenode ax), kind ax, Node (targetnode
ax))⟩
      show ?case by simp
    next
      case (lve-Entry-edge ex)
        with ⟨trg x = trg e⟩
          ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
        have targetnode a = Entry by simp
        with ⟨valid-edge a⟩ have False by(rule Entry-target)
        thus ?case by simp
    next
      case (lve-Exit-edge ex)
        with ⟨trg x = trg e⟩
          ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
        have False by simp
        thus ?case by simp
    next
      case (lve-Entry-Exit-edge ex)
        with ⟨trg x = trg e⟩
          ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
        have False by simp
        thus ?case by simp
    qed }
  ultimately show ?case by(blast intro:ex1I)
  qed simp-all
next
fix a a' Q1 r1 p fs1 Q2 r2 fs2
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'
  and knd a = Q1:r1↦pfs1 and knd a' = Q2:r2↦pfs2
then obtain x x' where valid-edge x
  and a:a = (Node (sourcenode x),kind x,Node (targetnode x)) and valid-edge

```

```

x'
  and a':a' = (Node (sourcenode x'),kind x',Node (targetnode x'))
  by(auto elim!:lift-valid-edge.cases)
  with ⟨knd a = Q1:r1↦pfs1⟩ ⟨knd a' = Q2:r2↦pfs2⟩
  have kind x = Q1:r1↦pfs1 and kind x' = Q2:r2↦pfs2 by simp-all
  with ⟨valid-edge x⟩ ⟨valid-edge x'⟩ have targetnode x = targetnode x'
  by(rule same-proc-call-unique-target)
  with a a' show trg a = trg a' by simp
next
  from unique-callers show distinct-fst procs .
next
  fix p ins outs
  assume (p, ins, outs) ∈ set procs
  from distinct-formal-ins[OF this] show distinct ins .
next
  fix p ins outs
  assume (p, ins, outs) ∈ set procs
  from distinct-formal-outs[OF this] show distinct outs .
qed
qed

```

lemma *lift-CFG-wf*:

```

  assumes wf:CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit Def Use ParamDefs ParamUses
  and pd:Postdomination sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit
  shows CFG-wf src trg knd
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) NewEntry
  (lift-get-proc get-proc Main)
  (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
  procs Main (lift-Def Def Entry Exit H L) (lift-Use Use Entry Exit H L)
  (lift-ParamDefs ParamDefs) (lift-ParamUses ParamUses)

```

proof –

```

  interpret CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit Def Use ParamDefs ParamUses
  by(rule wf)
  interpret Postdomination sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit
  by(rule pd)
  interpret CFG:CFG src trg knd
  lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit NewEntry
  lift-get-proc get-proc Main
  lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
  procs Main
  by(fastforce intro:lift-CFG wf pd)
  show ?thesis
proof
  show lift-Def Def Entry Exit H L NewEntry = {} ∧

```

```

lift-Use Use Entry Exit H L NewEntry = {}
by(fastforce elim:lift-Use-set.cases lift-Def-set.cases)
next
fix a Q r p fs ins outs
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
and knd a = Q:r↔pfs and (p, ins, outs) ∈ set procs
thus length (lift-ParamUses ParamUses (src a)) = length ins
proof(induct rule:lift-valid-edge.induct)
case (lve-edge a e)
from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩ ⟨knd e =
Q:r↔pfs⟩
have kind a = Q:r↔pfs and src e = Node (sourcenode a) by simp-all
with ⟨valid-edge a⟩ ⟨(p,ins,outs) ∈ set procs⟩
have length(ParamUses (sourcenode a)) = length ins
by -(rule ParamUses-call-source-length)
with ⟨src e = Node (sourcenode a)⟩ show ?case by simp
qed simp-all
next
fix a assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
thus distinct (lift-ParamDefs ParamDefs (trg a))
proof(induct rule:lift-valid-edge.induct)
case (lve-edge a e)
from ⟨valid-edge a⟩ have distinct (ParamDefs (targetnode a))
by(rule distinct-ParamDefs)
with ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
show ?case by simp
next
case (lve-Entry-edge e)
have ParamDefs Entry = []
proof(rule ccontr)
assume ParamDefs Entry ≠ []
then obtain V Vs where ParamDefs Entry = V#Vs
by(cases ParamDefs Entry) auto
hence V ∈ set (ParamDefs Entry) by fastforce
hence V ∈ Def Entry by(fastforce intro:ParamDefs-in-Def)
with Entry-empty show False by simp
qed
with ⟨e = (NewEntry, (λs. True)√, Node Entry)⟩ show ?case by simp
qed simp-all
next
fix a Q' p f' ins outs
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
and knd a = Q'↔pf' and (p, ins, outs) ∈ set procs
thus length (lift-ParamDefs ParamDefs (trg a)) = length outs
proof(induct rule:lift-valid-edge.induct)
case (lve-edge a e)
from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
⟨knd e = Q'↔pf'⟩
have kind a = Q'↔pf' and trg e = Node (targetnode a) by simp-all

```

```

    with ⟨valid-edge a⟩ ⟨(p,ins,outs) ∈ set procs⟩
    have length(ParamDefs (targetnode a)) = length outs
      by -(rule ParamDefs-return-target-length)
    with ⟨trg e = Node (targetnode a)⟩ show ?case by simp
qed simp-all
next
fix n V
assume CFG.CFG.valid-node src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) n
  and V ∈ set (lift-ParamDefs ParamDefs n)
  hence ((n = NewEntry) ∨ n = NewExit) ∨ (∃ m. n = Node m ∧ valid-node
m)
    by(auto elim:lift-valid-edge.cases simp:CFG.valid-node-def)
  thus V ∈ lift-Def Def Entry Exit H L n apply -
  proof(erule disjE)+
    assume n = NewEntry
    with ⟨V ∈ set (lift-ParamDefs ParamDefs n)⟩ show ?thesis by simp
  next
    assume n = NewExit
    with ⟨V ∈ set (lift-ParamDefs ParamDefs n)⟩ show ?thesis by simp
  next
    assume ∃ m. n = Node m ∧ valid-node m
    then obtain m where n = Node m and valid-node m by blast
    from ⟨n = Node m⟩ ⟨V ∈ set (lift-ParamDefs ParamDefs n)⟩
    have V ∈ set (ParamDefs m) by simp
    with ⟨valid-node m⟩ have V ∈ Def m by(rule ParamDefs-in-Def)
    with ⟨n = Node m⟩ show ?thesis by(fastforce intro:lift-Def-node)
  qed
next
fix a Q r p fs ins outs V
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a = Q:r↔pfs and (p, ins, outs) ∈ set procs and V ∈ set ins
  thus V ∈ lift-Def Def Entry Exit H L (trg a)
  proof(induct rule:lift-valid-edge.induct)
    case (lve-edge a e)
    from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩ ⟨knd e =
Q:r↔pfs⟩
    have kind a = Q:r↔pfs by simp
    from ⟨valid-edge a⟩ ⟨kind a = Q:r↔pfs⟩ ⟨(p, ins, outs) ∈ set procs⟩ ⟨V ∈ set
ins⟩
    have V ∈ Def (targetnode a) by(rule ins-in-Def)
    from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
    have trg e = Node (targetnode a) by simp
    with ⟨V ∈ Def (targetnode a)⟩ show ?case by(fastforce intro:lift-Def-node)
  qed simp-all
next
fix a Q r p fs
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a = Q:r↔pfs

```



```

thus lift-Def Def Entry Exit H L (src a) = {}
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge a e)
  show ?case
  proof(rule ccontr)
    assume lift-Def Def Entry Exit H L (src e) ≠ {}
    then obtain x where x ∈ lift-Def Def Entry Exit H L (src e) by blast
    from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩ ⟨knd e =
Q:r↦pfs⟩
    have kind a = Q:r↦pfs by simp
    with ⟨valid-edge a⟩ have Def (sourcenode a) = {}
      by(rule call-source-Def-empty)
    have sourcenode a ≠ Entry
    proof
      assume sourcenode a = Entry
      with ⟨valid-edge a⟩ ⟨kind a = Q:r↦pfs⟩
      show False by(rule Entry-no-call-source)
    qed
    from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
    have src e = Node (sourcenode a) by simp
    with ⟨Def (sourcenode a) = {}⟩ ⟨x ∈ lift-Def Def Entry Exit H L (src e)⟩
      ⟨sourcenode a ≠ Entry⟩
    show False by(fastforce elim:lift-Def-set.cases)
    qed
  qed simp-all
next
fix n V
assume CFG.CFG.valid-node src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) n
  and V ∈ ⋃(set (lift-ParamUses ParamUses n))
  hence ((n = NewEntry) ∨ n = NewExit) ∨ (∃ m. n = Node m ∧ valid-node
m)
  by(auto elim:lift-valid-edge.cases simp:CFG.valid-node-def)
thus V ∈ lift-Use Use Entry Exit H L n apply -
proof(erule disjE)+
  assume n = NewEntry
  with ⟨V ∈ ⋃(set (lift-ParamUses ParamUses n))⟩ show ?thesis by simp
next
  assume n = NewExit
  with ⟨V ∈ ⋃(set (lift-ParamUses ParamUses n))⟩ show ?thesis by simp
next
  assume ∃ m. n = Node m ∧ valid-node m
  then obtain m where n = Node m and valid-node m by blast
  from ⟨V ∈ ⋃(set (lift-ParamUses ParamUses n))⟩ ⟨n = Node m⟩
  have V ∈ ⋃(set (ParamUses m)) by simp
  with ⟨valid-node m⟩ have V ∈ Use m by(rule ParamUses-in-Use)
  with ⟨n = Node m⟩ show ?thesis by(fastforce intro:lift-Use-node)
  qed
next

```

```

fix a Q p f ins outs V
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a = Q $\leftrightarrow$ pf and (p, ins, outs)  $\in$  set procs and V  $\in$  set outs
thus V  $\in$  lift-Use Use Entry Exit H L (src a)
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge a e)
    from  $\langle e = (\text{Node } (\text{sourcenode } a), \text{kind } a, \text{Node } (\text{targetnode } a)) \rangle \langle \text{knd } e =$ 
Q $\leftrightarrow$ pf $\rangle$ 
    have kind a = Q $\leftrightarrow$ pf by simp
    from  $\langle \text{valid-edge } a \rangle \langle \text{kind } a = Q\leftrightarrow pf \rangle \langle (p, \text{ins}, \text{outs}) \in \text{set procs} \rangle \langle V \in \text{set}$ 
outs $\rangle$ 
    have V  $\in$  Use (sourcenode a) by(rule outs-in-Use)
    from  $\langle e = (\text{Node } (\text{sourcenode } a), \text{kind } a, \text{Node } (\text{targetnode } a)) \rangle$ 
    have src e = Node (sourcenode a) by simp
    with  $\langle V \in \text{Use } (\text{sourcenode } a) \rangle$  show ?case by(fastforce intro:lift-Use-node)
qed simp-all
next
fix a V s
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and V  $\notin$  lift-Def Def Entry Exit H L (src a) and intra-kind (knd a)
  and pred (knd a) s
thus state-val (transfer (knd a) s) V = state-val s V
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge a e)
    from  $\langle e = (\text{Node } (\text{sourcenode } a), \text{kind } a, \text{Node } (\text{targetnode } a)) \rangle$ 
 $\langle \text{intra-kind } (\text{knd } e) \rangle \langle \text{pred } (\text{knd } e) s \rangle$ 
    have intra-kind (kind a) and pred (kind a) s
      and knd e = kind a and src e = Node (sourcenode a) by simp-all
    from  $\langle V \notin \text{lift-Def Def Entry Exit H L } (\text{src } e) \rangle \langle \text{src } e = \text{Node } (\text{sourcenode}$ 
a) $\rangle$ 
    have V  $\notin$  Def (sourcenode a) by (auto dest: lift-Def-node)
    from  $\langle \text{valid-edge } a \rangle \langle V \notin \text{Def } (\text{sourcenode } a) \rangle \langle \text{intra-kind } (\text{kind } a) \rangle$ 
 $\langle \text{pred } (\text{kind } a) s \rangle$ 
    have state-val (transfer (kind a) s) V = state-val s V
      by(rule CFG-intra-edge-no-Def-equal)
    with  $\langle \text{knd } e = \text{kind } a \rangle$  show ?case by simp
next
  case (lve-Entry-edge e)
    from  $\langle e = (\text{NewEntry}, (\lambda s. \text{True})_{\surd}, \text{Node Entry}) \rangle \langle \text{pred } (\text{knd } e) s \rangle$ 
    show ?case by(cases s) auto
next
  case (lve-Exit-edge e)
    from  $\langle e = (\text{Node Exit}, (\lambda s. \text{True})_{\surd}, \text{NewExit}) \rangle \langle \text{pred } (\text{knd } e) s \rangle$ 
    show ?case by(cases s) auto
next
  case (lve-Entry-Exit-edge e)
    from  $\langle e = (\text{NewEntry}, (\lambda s. \text{False})_{\surd}, \text{NewExit}) \rangle \langle \text{pred } (\text{knd } e) s \rangle$ 
    have False by(cases s) auto
    thus ?case by simp

```

```

qed
next
fix a s s'
assume assms:lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
a
  ∀ V ∈ lift-Use Use Entry Exit H L (src a). state-val s V = state-val s' V
  intra-kind (knd a) pred (knd a) s pred (knd a) s'
show ∀ V ∈ lift-Def Def Entry Exit H L (src a).
  state-val (transfer (knd a) s) V = state-val (transfer (knd a) s') V
proof
  fix V assume V ∈ lift-Def Def Entry Exit H L (src a)
  with assms
  show state-val (transfer (knd a) s) V = state-val (transfer (knd a) s') V
  proof(induct rule:lift-valid-edge.induct)
    case (lve-edge a e)
    from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
      ⟨intra-kind (knd e)⟩ have intra-kind (kind a) by simp
    show ?case
    proof (cases Node (sourcenode a) = Node Entry)
      case True
      hence sourcenode a = Entry by simp
      from Entry-Exit-edge obtain a' where valid-edge a'
        and sourcenode a' = Entry and targetnode a' = Exit
        and kind a' = (λs. False)√ by blast
      have ∃ Q. kind a = (Q)√
      proof (cases targetnode a = Exit)
        case True
        with ⟨valid-edge a⟩ ⟨valid-edge a'⟩ ⟨sourcenode a = Entry⟩
          ⟨sourcenode a' = Entry⟩ ⟨targetnode a' = Exit⟩
          have a = a' by (fastforce dest:edge-det)
          with ⟨kind a' = (λs. False)√⟩ show ?thesis by simp
        case False
        with ⟨valid-edge a⟩ ⟨valid-edge a'⟩ ⟨sourcenode a = Entry⟩
          ⟨sourcenode a' = Entry⟩ ⟨targetnode a' = Exit⟩
          ⟨intra-kind (kind a)⟩ ⟨kind a' = (λs. False)√⟩
          show ?thesis by (auto dest:deterministic simp:intra-kind-def)
      case False
    qed
  from True ⟨V ∈ lift-Def Def Entry Exit H L (src e)⟩ Entry-empty
    ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
  have V ∈ H by (fastforce elim:lift-Def-set.cases)
  from True ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
    ⟨sourcenode a ≠ Entry ∨ targetnode a ≠ Exit⟩
  have ∀ V ∈ H. V ∈ lift-Use Use Entry Exit H L (src e)
    by (fastforce intro:lift-Use-High)
  with ⟨∀ V ∈ lift-Use Use Entry Exit H L (src e).
    state-val s V = state-val s' V⟩ ⟨V ∈ H⟩
  have state-val s V = state-val s' V by simp
  with ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩

```

```

    ⟨ $\exists Q. \text{kind } a = (Q)_{\surd}$ ⟩ ⟨ $\text{pred } (knd \ e) \ s$ ⟩ ⟨ $\text{pred } (knd \ e) \ s'$ ⟩
  show ?thesis by(cases s,auto,cases s',auto)
next
case False
{ fix V' assume V' ∈ Use (sourcenode a)
  with ⟨ $e = (\text{Node } (sourcenode \ a), \text{kind } a, \text{Node } (targetnode \ a))$ ⟩
  have V' ∈ lift-Use Use Entry Exit H L (src e)
    by(fastforce intro:lift-Use-node)
}
with ⟨ $\forall V \in \text{lift-Use Use Entry Exit H L } (src \ e).$ 
  state-val s V = state-val s' V⟩
have  $\forall V \in \text{Use } (sourcenode \ a).$  state-val s V = state-val s' V
  by fastforce
from ⟨valid-edge a⟩ this ⟨ $\text{pred } (knd \ e) \ s$ ⟩ ⟨ $\text{pred } (knd \ e) \ s'$ ⟩
  ⟨ $e = (\text{Node } (sourcenode \ a), \text{kind } a, \text{Node } (targetnode \ a))$ ⟩
  ⟨intra-kind (knd e)⟩
have  $\forall V \in \text{Def } (sourcenode \ a).$  state-val (transfer (kind a) s) V =
  state-val (transfer (kind a) s') V
  by -(erule CFG-intra-edge-transfer-uses-only-Use,auto)
from ⟨ $V \in \text{lift-Def Def Entry Exit H L } (src \ e)$ ⟩ False
  ⟨ $e = (\text{Node } (sourcenode \ a), \text{kind } a, \text{Node } (targetnode \ a))$ ⟩
have V ∈ Def (sourcenode a) by(fastforce elim:lift-Def-set.cases)
with ⟨ $\forall V \in \text{Def } (sourcenode \ a).$  state-val (transfer (kind a) s) V =
  state-val (transfer (kind a) s') V⟩
  ⟨ $e = (\text{Node } (sourcenode \ a), \text{kind } a, \text{Node } (targetnode \ a))$ ⟩
show ?thesis by simp
qed
next
case (lve-Entry-edge e)
from ⟨ $V \in \text{lift-Def Def Entry Exit H L } (src \ e)$ ⟩
  ⟨ $e = (\text{NewEntry}, (\lambda s. \text{True})_{\surd}, \text{Node Entry})$ ⟩
have False by(fastforce elim:lift-Def-set.cases)
thus ?case by simp
next
case (lve-Exit-edge e)
from ⟨ $V \in \text{lift-Def Def Entry Exit H L } (src \ e)$ ⟩
  ⟨ $e = (\text{Node Exit}, (\lambda s. \text{True})_{\surd}, \text{NewExit})$ ⟩
have False
  by(fastforce elim:lift-Def-set.cases intro!:Entry-noteq-Exit simp:Exit-empty)
thus ?case by simp
next
case (lve-Entry-Exit-edge e)
thus ?case by(cases s) auto
qed
qed
next
fix a s s'
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and pred (knd a) s and snd (hd s) = snd (hd s')
```

```

    and  $\forall V \in \text{lift-Use Use Entry Exit H L (src a). state-val } s \ V = \text{state-val } s' \ V$ 
    and  $\text{length } s = \text{length } s'$ 
  thus  $\text{pred (knd a) } s'$ 
  proof(induct rule:lift-valid-edge.induct)
    case (lve-edge a e)
    from  $\langle e = (\text{Node (sourcenode a), kind a, Node (targetnode a)}) \rangle \langle \text{pred (knd e) } s \rangle$ 
  have  $\text{pred (kind a) } s$  and  $\text{src } e = \text{Node (sourcenode a)}$  by simp-all
  from  $\langle \text{src } e = \text{Node (sourcenode a)} \rangle$ 
   $\langle \forall V \in \text{lift-Use Use Entry Exit H L (src e). state-val } s \ V = \text{state-val } s' \ V \rangle$ 
  have  $\forall V \in \text{Use (sourcenode a). state-val } s \ V = \text{state-val } s' \ V$ 
  by(auto dest:lift-Use-node)
  from  $\langle \text{valid-edge a} \rangle \langle \text{pred (kind a) } s \rangle \langle \text{snd (hd } s) = \text{snd (hd } s') \rangle$ 
  this  $\langle \text{length } s = \text{length } s' \rangle$ 
  have  $\text{pred (kind a) } s'$  by(rule CFG-edge-Uses-pred-equal)
  with  $\langle e = (\text{Node (sourcenode a), kind a, Node (targetnode a)}) \rangle$ 
  show ?case by simp
next
  case (lve-Entry-edge e)
  thus ?case by(cases s') auto
next
  case (lve-Exit-edge e)
  thus ?case by(cases s') auto
next
  case (lve-Entry-Exit-edge e)
  thus ?case by(cases s) auto
qed
next
  fix a Q r p fs ins outs
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and  $\text{knd a} = Q:r \hookrightarrow pfs$  and  $(p, \text{ins}, \text{outs}) \in \text{set procs}$ 
  thus  $\text{length } fs = \text{length } \text{ins}$ 
  proof(induct rule:lift-valid-edge.induct)
    case (lve-edge a e)
    from  $\langle e = (\text{Node (sourcenode a), kind a, Node (targetnode a)}) \rangle \langle \text{knd } e = Q:r \hookrightarrow pfs \rangle$ 
    have  $\text{kind a} = Q:r \hookrightarrow pfs$  by simp
    from  $\langle \text{valid-edge a} \rangle \langle \text{kind a} = Q:r \hookrightarrow pfs \rangle \langle (p, \text{ins}, \text{outs}) \in \text{set procs} \rangle$ 
    show ?case by(rule CFG-call-edge-length)
  qed simp-all
next
  fix a Q r p fs a' Q' r' p' fs' s s'
  assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and  $\text{knd a} = Q:r \hookrightarrow pfs$  and  $\text{knd a}' = Q':r' \hookrightarrow p'fs'$ 
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'
  and  $\text{src a} = \text{src a}'$  and  $\text{pred (knd a) } s$  and  $\text{pred (knd a}') } s$ 
  from  $\langle \text{lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a} \rangle$ 
   $\langle \text{knd a} = Q:r \hookrightarrow pfs \rangle \langle \text{pred (knd a) } s \rangle$ 
  obtain x where  $a:a = (\text{Node (sourcenode } x), \text{kind } x, \text{Node (targetnode } x))$ 

```

```

and valid-edge x and src a = Node (sourcenode x)
and kind x = Q:r↔pfs and pred (kind x) s
by(fastforce elim:lift-valid-edge.cases)
from ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a⟩
  ⟨knd a = Q:r↔pfs⟩ ⟨pred (knd a) s⟩
obtain x' where a:a' = (Node (sourcenode x'),kind x',Node (targetnode x'))
  and valid-edge x' and src a' = Node (sourcenode x')
  and kind x' = Q:r↔pfs' and pred (kind x') s
  by(fastforce elim:lift-valid-edge.cases)
from ⟨src a = Node (sourcenode x)⟩ ⟨src a' = Node (sourcenode x')⟩
  ⟨src a = src a'⟩
have sourcenode x = sourcenode x' by simp
from ⟨valid-edge x⟩ ⟨kind x = Q:r↔pfs⟩ ⟨valid-edge x'⟩ ⟨kind x' = Q:r↔pfs'⟩
  ⟨sourcenode x = sourcenode x'⟩ ⟨pred (kind x) s⟩ ⟨pred (kind x') s⟩
have x = x' by(rule CFG-call-determ)
with a a' show a = a' by simp
next
fix a Q r p fs i ins outs s s'
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a = Q:r↔pfs and i < length ins and (p, ins, outs) ∈ set procs
  and pred (knd a) s and pred (knd a) s'
  and ∀ V ∈ lift-ParamUses ParamUses (src a) ! i. state-val s V = state-val s' V
thus params fs (state-val s) ! i = CFG.params fs (state-val s') ! i
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge a e)
    from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩ ⟨knd e =
Q:r↔pfs⟩
    ⟨pred (knd e) s⟩ ⟨pred (knd e) s'⟩
    have kind a = Q:r↔pfs and pred (kind a) s and pred (kind a) s'
    and src e = Node (sourcenode a)
    by simp-all
    from ⟨∀ V ∈ lift-ParamUses ParamUses (src e) ! i. state-val s V = state-val s'
V⟩
    ⟨src e = Node (sourcenode a)⟩
    have ∀ V ∈ (ParamUses (sourcenode a))!i. state-val s V = state-val s' V by
simp
    with ⟨valid-edge a⟩ ⟨kind a = Q:r↔pfs⟩ ⟨i < length ins⟩
    ⟨(p, ins, outs) ∈ set procs⟩ ⟨pred (kind a) s⟩ ⟨pred (kind a) s'⟩
    show ?case by(rule CFG-call-edge-params)
  qed simp-all
next
fix a Q' p f' ins outs cf cf'
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a = Q'↔pf' and (p, ins, outs) ∈ set procs
thus f' cf cf' = cf'(lift-ParamDefs ParamDefs (trg a) [:=] map cf outs)
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge a e)
    from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩ ⟨knd e =
Q'↔pf'⟩

```

```

    have kind a = Q'↔pf' and trg e = Node (targetnode a) by simp-all
    from ⟨valid-edge a⟩ ⟨kind a = Q'↔pf'⟩ ⟨(p, ins, outs) ∈ set procs⟩
    have f' cf cf' = cf'(ParamDefs (targetnode a) [:=] map cf outs)
      by(rule CFG-return-edge-fun)
    with ⟨trg e = Node (targetnode a)⟩ show ?case by simp
  qed simp-all
next
fix a a'
assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'
  and src a = src a' and trg a ≠ trg a'
  and intra-kind (knd a) and intra-kind (knd a')
thus ∃ Q Q'. knd a = (Q)✓ ∧ knd a' = (Q')✓ ∧
  (∀ s. (Q s → ¬ Q' s) ∧ (Q' s → ¬ Q s))
proof(induct rule:lift-valid-edge.induct)
  case (lve-edge a e)
  from ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a'⟩
  ⟨valid-edge a⟩ ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
  ⟨src e = src a'⟩ ⟨trg e ≠ trg a'⟩ ⟨intra-kind (knd e)⟩ ⟨intra-kind (knd a')⟩
  show ?case
  proof(induct rule:lift-valid-edge.induct)
    case lve-edge thus ?case by(auto dest:deterministic)
  next
  case (lve-Exit-edge e')
  from ⟨e = (Node (sourcenode a), kind a, Node (targetnode a))⟩
  ⟨e' = (Node Exit, (λs. True)✓, NewExit)⟩ ⟨src e = src e'⟩
  have sourcenode a = Exit by simp
  with ⟨valid-edge a⟩ have False by(rule Exit-source)
  thus ?case by simp
  qed auto
  qed (fastforce elim:lift-valid-edge.cases)+
qed
qed
qed

```

lemma *lift-CFGExit*:

```

  assumes wf:CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit Def Use ParamDefs ParamUses
  and pd:Postdomination sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit
  shows CFGExit src trg knd
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) NewEntry
  (lift-get-proc get-proc Main)
  (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
  procs Main NewExit
proof –
  interpret CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit Def Use ParamDefs ParamUses
  by(rule wf)

```

```

interpret Postdomination sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit
  by(rule pd)
interpret CFG:CFG src trg kn
  lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit NewEntry
  lift-get-proc get-proc Main
  lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
  procs Main
  by(fastforce intro:lift-CFG wf pd)
show ?thesis
proof
  fix a assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and src a = NewExit
    thus False by(fastforce elim:lift-valid-edge.cases)
  next
    show lift-get-proc get-proc Main NewExit = Main by simp
  next
    fix a Q p f
    assume lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    and kn a = Q  $\leftarrow$  pf and trg a = NewExit
    thus False by(fastforce elim:lift-valid-edge.cases)
  next
    show  $\exists a.$  lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a  $\wedge$ 
      src a = NewEntry  $\wedge$  trg a = NewExit  $\wedge$  kn a = ( $\lambda s.$  False) $\surd$ 
    by(fastforce intro:lve-Entry-Exit-edge)
  qed
qed

```

lemma *lift-CFGExit-wf*:

```

assumes wf:CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit Def Use ParamDefs ParamUses
and pd:Postdomination sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit
shows CFGExit-wf src trg kn
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) NewEntry
  (lift-get-proc get-proc Main)
  (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
  procs Main NewExit (lift-Def Def Entry Exit H L) (lift-Use Use Entry Exit H L)
  (lift-ParamDefs ParamDefs) (lift-ParamUses ParamUses)

```

proof –

```

interpret CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit Def Use ParamDefs ParamUses
  by(rule wf)
interpret Postdomination sourcenode targetnode kind valid-edge Entry get-proc
  get-return-edges procs Main Exit
  by(rule pd)
interpret CFG-wf:CFG-wf src trg kn
  lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit NewEntry

```



```

lift-get-proc get-proc Main
lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
procs Main lift-Def Def Entry Exit H L lift-Use Use Entry Exit H L
lift-ParamDefs ParamDefs lift-ParamUses ParamUses
by(fastforce intro:lift-CFG-wf wf pd)
interpret CFGExit:CFGExit src trg kno
lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit NewEntry
lift-get-proc get-proc Main
lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
procs Main NewExit
by(fastforce intro:lift-CFGExit wf pd)
show ?thesis
proof
show lift-Def Def Entry Exit H L NewExit = {} ∧
lift-Use Use Entry Exit H L NewExit = {}
by(fastforce elim:lift-Def-set.cases lift-Use-set.cases)
qed
qed

```

3.2.2 Lifting the SDG

lemma *lift-Postdomination*:

```

assumes wf:CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
get-return-edges procs Main Exit Def Use ParamDefs ParamUses
and pd:Postdomination sourcenode targetnode kind valid-edge Entry get-proc
get-return-edges procs Main Exit
and inner:CFGExit.inner-node sourcenode targetnode valid-edge Entry Exit nx
shows Postdomination src trg kno
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) NewEntry
(lift-get-proc get-proc Main)
(lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
procs Main NewExit

```

proof –

```

interpret CFGExit-wf sourcenode targetnode kind valid-edge Entry get-proc
get-return-edges procs Main Exit Def Use ParamDefs ParamUses
by(rule wf)

```

```

interpret Postdomination sourcenode targetnode kind valid-edge Entry get-proc
get-return-edges procs Main Exit
by(rule pd)

```

```

interpret CFGExit:CFGExit src trg kno
lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit NewEntry
lift-get-proc get-proc Main
lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
procs Main NewExit
by(fastforce intro:lift-CFGExit wf pd)

```

```

{ fix m assume valid-node m
then obtain a where valid-edge a and m = sourcenode a ∨ m = targetnode a
by(auto simp:valid-node-def)
from ⟨m = sourcenode a ∨ m = targetnode a⟩

```

```

have CFG.CFG.valid-node src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) (Node m)
proof
  assume m = sourcenode a
  show ?thesis
  proof(cases m = Entry)
    case True
    have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
      (NewEntry, (λs. True)√, Node Entry) by(fastforce intro:lve-Entry-edge)
    with ⟨m = Entry⟩ show ?thesis by(fastforce simp:CFGExit.valid-node-def)
  next
    case False
    with ⟨m = sourcenode a⟩ ⟨valid-edge a⟩
    have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
      (Node (sourcenode a), kind a, Node(targetnode a))
    by(fastforce intro:lve-edge)
    with ⟨m = sourcenode a⟩ show ?thesis by(fastforce simp:CFGExit.valid-node-def)
  qed
next
  assume m = targetnode a
  show ?thesis
  proof(cases m = Exit)
    case True
    have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
      (Node Exit, (λs. True)√, NewExit) by(fastforce intro:lve-Exit-edge)
    with ⟨m = Exit⟩ show ?thesis by(fastforce simp:CFGExit.valid-node-def)
  next
    case False
    with ⟨m = targetnode a⟩ ⟨valid-edge a⟩
    have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
      (Node (sourcenode a), kind a, Node(targetnode a))
    by(fastforce intro:lve-edge)
    with ⟨m = targetnode a⟩ show ?thesis by(fastforce simp:CFGExit.valid-node-def)
  qed
qed }
note lift-valid-node = this
{ fix n as n' cs m m'
  assume valid-path-aux cs as and m -as→* m' and ∀ c ∈ set cs. valid-edge c
  and m ≠ Entry ∨ m' ≠ Exit
  hence ∃ cs' es. CFG.CFG.valid-path-aux kn
    (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
    cs' es ∧
    list-all2 (λc c'. c' = (Node (sourcenode c), kind c, Node (targetnode c))) cs cs'
    ∧ CFG.CFG.path src trg
    (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
    (Node m) es (Node m')
  proof(induct arbitrary:m rule:vpa-induct)
    case (vpa-empty cs)
    from ⟨m -[]→* m'⟩ have [simp]:m = m' by fastforce
```

```

from ⟨ $m - [] \rightarrow^* m'$ ⟩ have valid-node m by(rule path-valid-node)
obtain  $cs'$  where  $cs' =$ 
   $map (\lambda c. (Node (sourcenode c), kind c, Node (targetnode c))) cs$  by simp
hence list-all2
   $(\lambda c c'. c' = (Node (sourcenode c), kind c, Node (targetnode c))) cs cs'$ 
  by(simp add:list-all2-conv-all-nth)
with ⟨valid-node m⟩ show ?case
  apply(rule-tac x=cs' in exI)
  apply(rule-tac x=[] in exI)
  by(fastforce intro:CFGExit.empty-path lift-valid-node)
next
case (vpa-intra cs a as)
note  $IH = \langle \bigwedge m. [m - as \rightarrow^* m'; \forall c \in set cs. \text{valid-edge } c; m \neq \text{Entry} \vee m' \neq$ 
Exit]  $\implies$ 
   $\exists cs' es. CFG.valid-path-aux\ kn d$ 
  (lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind)  $cs' es \wedge$ 
  list-all2  $(\lambda c c'. c' = (Node (sourcenode c), kind c, Node (targetnode c))) cs$ 
   $cs' \wedge CFG.path\ src\ trg$ 
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node m)  $es$  (Node m')
from ⟨ $m - a \# as \rightarrow^* m'$ ⟩ have  $m = \text{sourcenode } a$  and valid-edge a
and  $\text{targetnode } a - as \rightarrow^* m'$  by(auto elim:path-split-Cons)
show ?case
proof(cases sourcenode a = Entry  $\wedge$  targetnode a = Exit)
  case True
  with ⟨ $m = \text{sourcenode } a$ ⟩ ⟨ $m \neq \text{Entry} \vee m' \neq \text{Exit}$ ⟩
  have  $m' \neq \text{Exit}$  by simp
  from True have  $\text{targetnode } a = \text{Exit}$  by simp
  with ⟨ $\text{targetnode } a - as \rightarrow^* m'$ ⟩ have  $m' = \text{Exit}$ 
    by  $-(\text{drule } path\text{-Exit-source, auto})$ 
  with ⟨ $m' \neq \text{Exit}$ ⟩ have False by simp
  thus ?thesis by simp
next
case False
let  $?e = (Node (sourcenode a), kind a, Node (targetnode a))$ 
from False ⟨valid-edge a⟩
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e
  by(fastforce intro:lve-edge)
have  $\text{targetnode } a \neq \text{Entry}$ 
proof
  assume  $\text{targetnode } a = \text{Entry}$ 
  with ⟨valid-edge a⟩ show False by(rule Entry-target)
qed
hence  $\text{targetnode } a \neq \text{Entry} \vee m' \neq \text{Exit}$  by simp
from  $IH[OF \langle \text{targetnode } a - as \rightarrow^* m' \rangle \langle \forall c \in set cs. \text{valid-edge } c \rangle \text{this}]$ 
obtain  $cs' es$ 
  where valid-path:CFG.valid-path-aux kn d
  (lift-get-return-edges get-return-edges valid-edge sourcenode

```

```

    targetnode kind) cs' es
  and list:list-all2
  (λc c'. c' = (Node (sourcenode c), kind c, Node (targetnode c))) cs cs'
  and path:CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node (targetnode a)) es (Node m') by blast
  from ⟨intra-kind (kind a)⟩ valid-path have CFG.valid-path-aux kno
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) cs' (?e#es) by(fastforce simp:intra-kind-def)
  moreover
  from path ⟨m = sourcenode a⟩
  ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e⟩
  have CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node m) (?e#es) (Node m') by(fastforce intro:CFGExit.Cons-path)
  ultimately show ?thesis using list by blast
qed
next
case (vpa-Call cs a as Q r p fs)
note IH = ⟨∧m. [m -as→* m'; ∀c∈set (a # cs). valid-edge c;
m ≠ Entry ∨ m' ≠ Exit] ⇒
∃cs' es. CFG.valid-path-aux kno
(lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind) cs' es ∧
list-all2 (λc c'. c' = (Node (sourcenode c), kind c, Node (targetnode c)))
(a#cs) cs' ∧ CFG.path src trg
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(Node m) es (Node m')⟩
from ⟨m -a # as→* m'⟩ have m = sourcenode a and valid-edge a
and targetnode a -as→* m' by(auto elim:path-split-Cons)
from ⟨∀c∈set cs. valid-edge c⟩ ⟨valid-edge a⟩
have ∀c∈set (a # cs). valid-edge c by simp
let ?e = (Node (sourcenode a),kind a,Node (targetnode a))
have sourcenode a ≠ Entry
proof
  assume sourcenode a = Entry
  with ⟨valid-edge a⟩ ⟨kind a = Q:r↦pfs⟩
  show False by(rule Entry-no-call-source)
qed
with ⟨valid-edge a⟩
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e
by(fastforce intro:lve-edge)
have targetnode a ≠ Entry
proof
  assume targetnode a = Entry
  with ⟨valid-edge a⟩ show False by(rule Entry-target)
qed
hence targetnode a ≠ Entry ∨ m' ≠ Exit by simp
from IH[OF ⟨targetnode a -as→* m'⟩ ⟨∀c∈set (a # cs). valid-edge c⟩ this]

```

```

obtain  $cs' es$ 
  where  $valid\text{-}path: CFG.valid\text{-}path\text{-}aux\ knnd$ 
    ( $lift\text{-}get\text{-}return\text{-}edges\ get\text{-}return\text{-}edges\ valid\text{-}edge\ sourcenode$ 
      $targetnode\ kind$ )  $cs' es$ 
  and  $list: list\text{-}all2$ 
    ( $\lambda c\ c'.\ c' = (Node\ (sourcenode\ c),\ kind\ c,\ Node\ (targetnode\ c))$ ) ( $a\#\ cs$ )  $cs'$ 
  and  $path: CFG.path\ src\ trg$ 
    ( $lift\text{-}valid\text{-}edge\ valid\text{-}edge\ sourcenode\ targetnode\ kind\ Entry\ Exit$ )
    ( $Node\ (targetnode\ a)$ )  $es\ (Node\ m')$  by  $blast$ 
from  $list$  obtain  $cx\ csx$  where  $cs' = cx\#\ csx$ 
  and  $cx: cx = (Node\ (sourcenode\ a),\ kind\ a,\ Node\ (targetnode\ a))$ 
  and  $list': list\text{-}all2$ 
    ( $\lambda c\ c'.\ c' = (Node\ (sourcenode\ c),\ kind\ c,\ Node\ (targetnode\ c))$ )  $cs\ csx$ 
  by ( $fastforce\ simp: list\text{-}all2\text{-}Cons1$ )
from  $valid\text{-}path\ cx\ \langle cs' = cx\#\ csx \rangle\ \langle kind\ a = Q: r\leftrightarrow pfs \rangle$ 
have  $CFG.valid\text{-}path\text{-}aux\ knnd$ 
    ( $lift\text{-}get\text{-}return\text{-}edges\ get\text{-}return\text{-}edges\ valid\text{-}edge\ sourcenode$ 
      $targetnode\ kind$ )  $csx\ (?e\#\ es)$  by  $simp$ 
moreover
from  $path\ \langle m = sourcenode\ a \rangle$ 
   $\langle lift\text{-}valid\text{-}edge\ valid\text{-}edge\ sourcenode\ targetnode\ kind\ Entry\ Exit\ ?e \rangle$ 
have  $CFG.path\ src\ trg$ 
    ( $lift\text{-}valid\text{-}edge\ valid\text{-}edge\ sourcenode\ targetnode\ kind\ Entry\ Exit$ )
    ( $Node\ m$ ) ( $?e\#\ es$ ) ( $Node\ m'$ ) by ( $fastforce\ intro: CFG.Exit.Cons\text{-}path$ )
ultimately show  $?case$  using  $list'$  by  $blast$ 
next
case ( $vpa\text{-}ReturnEmpty\ cs\ a\ as\ Q\ p\ f$ )
note  $IH = \langle \bigwedge m. \llbracket m - as \rightarrow * m'; \forall c \in set\ [].\ valid\text{-}edge\ c; m \neq Entry \vee m' \neq$ 
 $Exit \rrbracket \implies$ 
   $\exists cs' es. CFG.valid\text{-}path\text{-}aux\ knnd$ 
    ( $lift\text{-}get\text{-}return\text{-}edges\ get\text{-}return\text{-}edges\ valid\text{-}edge\ sourcenode$ 
      $targetnode\ kind$ )  $cs' es \wedge$ 
     $list\text{-}all2\ (\lambda c\ c'.\ c' = (Node\ (sourcenode\ c),\ kind\ c,\ Node\ (targetnode\ c)))$ 
     $\llbracket cs' \wedge CFG.path\ src\ trg$ 
    ( $lift\text{-}valid\text{-}edge\ valid\text{-}edge\ sourcenode\ targetnode\ kind\ Entry\ Exit$ )
    ( $Node\ m$ )  $es\ (Node\ m') \rangle$ 
from  $\langle m - a \# as \rightarrow * m' \rangle$  have  $m = sourcenode\ a$  and  $valid\text{-}edge\ a$ 
  and  $targetnode\ a - as \rightarrow * m'$  by ( $auto\ elim: path\text{-}split\text{-}Cons$ )
let  $?e = (Node\ (sourcenode\ a),\ kind\ a,\ Node\ (targetnode\ a))$ 
have  $targetnode\ a \neq Exit$ 
proof
  assume  $targetnode\ a = Exit$ 
with  $\langle valid\text{-}edge\ a \rangle\ \langle kind\ a = Q\leftrightarrow pf \rangle$  show  $False$  by ( $rule\ Exit\text{-}no\text{-}return\text{-}target$ )
qed
with  $\langle valid\text{-}edge\ a \rangle$ 
have  $lift\text{-}valid\text{-}edge\ valid\text{-}edge\ sourcenode\ targetnode\ kind\ Entry\ Exit\ ?e$ 
  by ( $fastforce\ intro: lve\text{-}edge$ )
have  $targetnode\ a \neq Entry$ 
proof

```

```

assume targetnode a = Entry
with ⟨valid-edge a⟩ show False by(rule Entry-target)
qed
hence targetnode a ≠ Entry ∨ m' ≠ Exit by simp
from IH[OF ⟨targetnode a -as→* m'⟩ - this] obtain es
  where valid-path:CFG.valid-path-aux knid
    (lift-get-return-edges get-return-edges valid-edge sourcenode
    targetnode kind) [] es
  and path:CFG.path src trg
    (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
    (Node (targetnode a)) es (Node m') by auto
from valid-path ⟨kind a = Q↔pf⟩
have CFG.valid-path-aux knid
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) [] (?e#es) by simp
moreover
from path ⟨m = sourcenode a⟩
  ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e⟩
have CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node m) (?e#es) (Node m') by(fastforce intro:CFGExit.Cons-path)
ultimately show ?case using ⟨cs = []⟩ by blast
next
case (vpa-ReturnCons cs a as Q p f c' cs')
note IH = ⟨∧m. [m -as→* m'; ∀c∈set cs'. valid-edge c; m ≠ Entry ∨ m'
≠ Exit] ⇒
  ∃csx es. CFG.valid-path-aux knid
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) csx es ∧
  list-all2 (λc c'. c' = (Node (sourcenode c), kind c, Node (targetnode c)))
  cs' csx ∧ CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node m) es (Node m')⟩
from ⟨m -a # as→* m'⟩ have m = sourcenode a and valid-edge a
  and targetnode a -as→* m' by(auto elim:path-split-Cons)
from ⟨∀c∈set cs. valid-edge c⟩ ⟨cs = c' # cs'⟩
have valid-edge c' and ∀c∈set cs'. valid-edge c by simp-all
let ?e = (Node (sourcenode a),kind a,Node (targetnode a))
have targetnode a ≠ Exit
proof
  assume targetnode a = Exit
with ⟨valid-edge a⟩ ⟨kind a = Q↔pf⟩ show False by(rule Exit-no-return-target)
qed
with ⟨valid-edge a⟩
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e
  by(fastforce intro:lve-edge)
have targetnode a ≠ Entry
proof
  assume targetnode a = Entry

```

```

  with ⟨valid-edge a⟩ show False by(rule Entry-target)
qed
hence targetnode a ≠ Entry ∨ m' ≠ Exit by simp
from IH[OF ⟨targetnode a -as→* m'⟩ ⟨∀ c∈set cs'. valid-edge c⟩ this]
obtain csx es
  where valid-path:CFG.valid-path-aux kno
    (lift-get-return-edges get-return-edges valid-edge sourcenode
    targetnode kind) csx es
  and list:list-all2
    (λc c'. c' = (Node (sourcenode c), kind c, Node (targetnode c))) cs' csx
  and path:CFG.path src trg
    (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
    (Node (targetnode a)) es (Node m') by blast
from ⟨valid-edge c'⟩ ⟨a ∈ get-return-edges c'⟩
have ?e ∈ lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind (Node (sourcenode c'),kind c',Node (targetnode c'))
  by(fastforce intro:lift-get-return-edgesI)
with valid-path ⟨kind a = Q↔pf⟩
have CFG.valid-path-aux kno
  (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
  ((Node (sourcenode c'),kind c',Node (targetnode c'))#csx) (?e#es)
  by simp
moreover
from list ⟨cs = c' # cs'⟩
have list-all2
  (λc c'. c' = (Node (sourcenode c), kind c, Node (targetnode c))) cs
  ((Node (sourcenode c'),kind c',Node (targetnode c'))#csx)
  by simp
moreover
from path ⟨m = sourcenode a⟩
  ⟨lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit ?e⟩
have CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node m) (?e#es) (Node m') by(fastforce intro:CFGExit.Cons-path)
ultimately show ?case using ⟨kind a = Q↔pf⟩ by blast
qed }
hence lift-valid-path:∧m as m'. [m -as→√* m'; m ≠ Entry ∨ m' ≠ Exit]
  ⇒ ∃ es. CFG.CFG.valid-path' src trg kno
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
  (Node m) es (Node m')
by(fastforce simp:vp-def valid-path-def CFGExit.vp-def CFGExit.valid-path-def)
show ?thesis
proof
fix n assume CFG.CFG.valid-node src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) n
hence ((n = NewEntry) ∨ n = NewExit) ∨ (∃ m. n = Node m ∧ valid-node
m)
  by(auto elim:lift-valid-edge.cases simp:CFGExit.valid-node-def)

```

thus $\exists as. CFG.CFG.valid-path' src trg knid$
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
NewEntry as n **apply** –
proof(*erule disjE*)**+**
assume $n = NewEntry$
hence $CFG.CFG.valid-path' src trg knid$
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
NewEntry [] n
by(*fastforce intro:CFGExit.empty-path*
simp:CFGExit.vp-def CFGExit.valid-path-def)
thus *?thesis* **by** *blast*
next
assume $n = NewExit$
have *lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit*
(NewEntry,(\lambda s. False)_{\checkmark},NewExit) **by**(*fastforce intro:lve-Entry-Exit-edge*)
hence $CFG.CFG.path src trg$
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
NewEntry [(NewEntry,(\lambda s. False)_{\checkmark},NewExit)] NewExit
by(*fastforce dest:CFGExit.path-edge*)
with $\langle n = NewExit \rangle$ **have** $CFG.CFG.valid-path' src trg knid$
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
NewEntry [(NewEntry,(\lambda s. False)_{\checkmark},NewExit)] n
by(*fastforce simp:CFGExit.vp-def CFGExit.valid-path-def*)
thus *?thesis* **by** *blast*
next
assume $\exists m. n = Node m \wedge valid-node m$
then obtain m **where** $n = Node m$ **and** *valid-node m* **by** *blast*
from $\langle valid-node m \rangle$
show *?thesis*
proof(*cases m rule:valid-node-cases*)
case *Entry*
have *lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit*
(NewEntry,(\lambda s. True)_{\checkmark},Node Entry) **by**(*fastforce intro:lve-Entry-edge*)
with $\langle m = Entry \rangle \langle n = Node m \rangle$ **have** $CFG.CFG.path src trg$
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
NewEntry [(NewEntry,(\lambda s. True)_{\checkmark},Node Entry)] n
by(*fastforce intro:CFGExit.Cons-path CFGExit.empty-path*
simp:CFGExit.valid-node-def)
thus *?thesis* **by**(*fastforce simp:CFGExit.vp-def CFGExit.valid-path-def*)
next
case *Exit*
from *inner* **obtain** ax **where** *valid-edge ax* **and** *intra-kind (kind ax)*
and *inner-node (sourcenode ax)*
and *targetnode ax = Exit* **by**(*erule inner-node-Exit-edge*)
hence *lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit*
(Node (sourcenode ax),kind ax,Node Exit)


```

by(auto intro:lift-valid-edge.lve-edge simp:inner-node-def)
hence CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node (sourcenode ax)) [(Node (sourcenode ax),kind ax,Node Exit)]
  (Node Exit)
by(fastforce intro:CFGExit.Cons-path CFGExit.empty-path
  simp:CFGExit.valid-node-def)
with ⟨intra-kind (kind ax)⟩
have slp-edge:CFG.CFG.same-level-path' src trg kn
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind)
  (Node (sourcenode ax)) [(Node (sourcenode ax),kind ax,Node Exit)]
  (Node Exit)
by(fastforce simp:CFGExit.slp-def CFGExit.same-level-path-def
  intra-kind-def)
have sourcenode ax ≠ Exit
proof
  assume sourcenode ax = Exit
  with ⟨valid-edge ax⟩ show False by(rule Exit-source)
qed
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
  (NewEntry,(λs. True)✓,Node Entry) by(fastforce intro:lve-Entry-edge)
hence CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (NewEntry) [(NewEntry,(λs. True)✓,Node Entry)] (Node Entry)
by(fastforce intro:CFGExit.Cons-path CFGExit.empty-path
  simp:CFGExit.valid-node-def)
hence slp-edge':CFG.CFG.same-level-path' src trg kn
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind)
  (NewEntry) [(NewEntry,(λs. True)✓,Node Entry)] (Node Entry)
by(fastforce simp:CFGExit.slp-def CFGExit.same-level-path-def)
from ⟨inner-node (sourcenode ax)⟩ have valid-node (sourcenode ax)
by(rule inner-is-valid)
then obtain asx where Entry -asx →✓* sourcenode ax
by(fastforce dest:Entry-path)
with ⟨sourcenode ax ≠ Exit⟩
have ∃ es. CFG.CFG.valid-path' src trg kn
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) (Node Entry) es (Node (sourcenode ax))
by(fastforce intro:lift-valid-path)
then obtain es where CFG.CFG.valid-path' src trg kn
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) (Node Entry) es (Node (sourcenode ax)) by blast
with slp-edge have CFG.CFG.valid-path' src trg kn

```

```

      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode
       targetnode kind)
      (Node Entry) (es@[ (Node (sourcenode ax), kind ax, Node Exit)]) (Node Exit)
      by -(rule CFGExit.vp-slp-Append)
with slp-edge' have CFG.CFG.valid-path' src trg kno
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode
       targetnode kind) NewEntry
      ([[NewEntry, (λs. True)✓, Node Entry]]@
       (es@[ (Node (sourcenode ax), kind ax, Node Exit)])) (Node Exit)
      by(rule CFGExit.slp-vp-Append)
with ⟨m = Exit⟩ ⟨n = Node m⟩ show ?thesis by simp blast
next
case inner
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
      (NewEntry, (λs. True)✓, Node Entry) by(fastforce intro:lve-Entry-edge)
hence CFG.path src trg
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (NewEntry) [(NewEntry, (λs. True)✓, Node Entry)] (Node Entry)
      by(fastforce intro:CFGExit.Cons-path CFGExit.empty-path
       simp:CFGExit.valid-node-def)
hence slp-edge:CFG.CFG.same-level-path' src trg kno
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode
       targetnode kind)
      (NewEntry) [(NewEntry, (λs. True)✓, Node Entry)] (Node Entry)
      by(fastforce simp:CFGExit.slp-def CFGExit.same-level-path-def)
from ⟨valid-node m⟩ obtain as where Entry -as→✓* m
      by(fastforce dest:Entry-path)
with ⟨inner-node m⟩
have ∃ es. CFG.CFG.valid-path' src trg kno
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode
       targetnode kind) (Node Entry) es (Node m)
      by(fastforce intro:lift-valid-path simp:inner-node-def)
then obtain es where CFG.CFG.valid-path' src trg kno
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode
       targetnode kind) (Node Entry) es (Node m) by blast
with slp-edge have CFG.CFG.valid-path' src trg kno
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode
       targetnode kind) NewEntry ([[NewEntry, (λs. True)✓, Node Entry]]@es)
(Node m)
      by(rule CFGExit.slp-vp-Append)
with ⟨n = Node m⟩ show ?thesis by simp blast
qed
qed

```

```

next
  fix n assume CFG.CFG.valid-node src trg
    (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) n
  hence ((n = NewEntry) ∨ n = NewExit) ∨ (∃ m. n = Node m ∧ valid-node
m)
    by(auto elim:lift-valid-edge.cases simp:CFGExit.valid-node-def)
  thus ∃ as. CFG.CFG.valid-path' src trg kn
    (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
    (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
    n as NewExit apply -
  proof(erule disjE)+
    assume n = NewEntry
    have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
      (NewEntry,(λs. False)✓,NewExit) by(fastforce intro:lve-Entry-Exit-edge)
    hence CFG.CFG.path src trg
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      NewEntry [(NewEntry,(λs. False)✓,NewExit)] NewExit
      by(fastforce dest:CFGExit.path-edge)
    with ⟨n = NewEntry⟩ have CFG.CFG.valid-path' src trg kn
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
      n [(NewEntry,(λs. False)✓,NewExit)] NewExit
      by(fastforce simp:CFGExit.vp-def CFGExit.valid-path-def)
    thus ?thesis by blast
  next
    assume n = NewExit
    hence CFG.CFG.valid-path' src trg kn
      (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
      (lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind)
      n [] NewExit
      by(fastforce intro:CFGExit.empty-path
simp:CFGExit.vp-def CFGExit.valid-path-def)
    thus ?thesis by blast
  next
    assume ∃ m. n = Node m ∧ valid-node m
    then obtain m where n = Node m and valid-node m by blast
    from ⟨valid-node m⟩
    show ?thesis
    proof(cases m rule:valid-node-cases)
      case Entry
        from inner obtain ax where valid-edge ax and intra-kind (kind ax)
          and inner-node (targetnode ax) and sourcenode ax = Entry
          by(erule inner-node-Entry-edge)
        hence lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
          (Node Entry,kind ax,Node (targetnode ax))
          by(auto intro:lift-valid-edge.lve-edge simp:inner-node-def)
        hence CFG.path src trg
          (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
          (Node Entry) [(Node Entry,kind ax,Node (targetnode ax))]

```

```

(Node (targetnode ax))
by(fastforce intro:CFGExit.Cons-path CFGExit.empty-path
simp:CFGExit.valid-node-def)
with ⟨intra-kind (kind ax)⟩
have slp-edge:CFG.CFG.same-level-path' src trg kno
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind)
(Node Entry) [(Node Entry,kind ax,Node (targetnode ax))]
(Node (targetnode ax))
by(fastforce simp:CFGExit.slp-def CFGExit.same-level-path-def
intra-kind-def)
have targetnode ax ≠ Entry
proof
assume targetnode ax = Entry
with ⟨valid-edge ax⟩ show False by(rule Entry-target)
qed
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
(Node Exit,(λs. True)✓,NewExit) by(fastforce intro:lve-Exit-edge)
hence CFG.path src trg
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(Node Exit) [(Node Exit,(λs. True)✓,NewExit)] NewExit
by(fastforce intro:CFGExit.Cons-path CFGExit.empty-path
simp:CFGExit.valid-node-def)
hence slp-edge':CFG.CFG.same-level-path' src trg kno
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind)
(Node Exit) [(Node Exit,(λs. True)✓,NewExit)] NewExit
by(fastforce simp:CFGExit.slp-def CFGExit.same-level-path-def)
from ⟨inner-node (targetnode ax)⟩ have valid-node (targetnode ax)
by(rule inner-is-valid)
then obtain asx where targetnode ax -asx→✓* Exit
by(fastforce dest:Exit-path)
with ⟨targetnode ax ≠ Entry⟩
have ∃ es. CFG.CFG.valid-path' src trg kno
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind) (Node (targetnode ax)) es (Node Exit)
by(fastforce intro:lift-valid-path)
then obtain es where CFG.CFG.valid-path' src trg kno
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind) (Node (targetnode ax)) es (Node Exit) by blast
with slp-edge have CFG.CFG.valid-path' src trg kno
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
(lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind)
(Node Entry) [(Node Entry,kind ax,Node (targetnode ax))]@es (Node

```

```

Exit)
  by(rule CFGExit.slp-vp-Append)
with slp-edge' have CFG.CFG.valid-path' src trg kend
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) (Node Entry)
  ([[ (Node Entry, kind ax, Node (targetnode ax)) ] @ es) @
  [(Node Exit, (λs. True)√, NewExit)] NewExit
  by -(rule CFGExit.vp-slp-Append)
with ⟨m = Entry⟩ ⟨n = Node m⟩ show ?thesis by simp blast
next
case Exit
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
  (Node Exit, (λs. True)√, NewExit) by (fastforce intro: lve-Exit-edge)
with ⟨m = Exit⟩ ⟨n = Node m⟩ have CFG.CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  n [(Node Exit, (λs. True)√, NewExit)] NewExit
  by (fastforce intro: CFGExit.Cons-path CFGExit.empty-path
  simp: CFGExit.valid-node-def)
thus ?thesis by (fastforce simp: CFGExit.vp-def CFGExit.valid-path-def)
next
case inner
have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
  (Node Exit, (λs. True)√, NewExit) by (fastforce intro: lve-Exit-edge)
hence CFG.path src trg
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (Node Exit) [(Node Exit, (λs. True)√, NewExit)] NewExit
  by (fastforce intro: CFGExit.Cons-path CFGExit.empty-path
  simp: CFGExit.valid-node-def)
hence slp-edge: CFG.CFG.same-level-path' src trg kend
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind)
  (Node Exit) [(Node Exit, (λs. True)√, NewExit)] NewExit
  by (fastforce simp: CFGExit.slp-def CFGExit.same-level-path-def)
from ⟨valid-node m⟩ obtain as where m -as→√* Exit
  by (fastforce dest: Exit-path)
with ⟨inner-node m⟩
have ∃ es. CFG.CFG.valid-path' src trg kend
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) (Node m) es (Node Exit)
  by (fastforce intro: lift-valid-path simp: inner-node-def)
then obtain es where CFG.CFG.valid-path' src trg kend
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)
  (lift-get-return-edges get-return-edges valid-edge sourcenode
  targetnode kind) (Node m) es (Node Exit) by blast
with slp-edge have CFG.CFG.valid-path' src trg kend
  (lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit)

```

```

      (lift-get-return-edges get-return-edges valid-edge sourcenode
targetnode kind) (Node m) (es@[((Node Exit,(λs. True)✓,NewExit))]) NewExit
    by  $-(rule\ CFGExit.vp-slp-Append)$ 
    with  $\langle n = Node\ m \rangle$  show ?thesis by simp blast
qed
qed
next
fix n n'
assume method-exit1:CFGExit.CFGExit.method-exit src knd
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) NewExit n
and method-exit2:CFGExit.CFGExit.method-exit src knd
(lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit) NewExit n'
and lift-eq:lift-get-proc get-proc Main n = lift-get-proc get-proc Main n'
from method-exit1 show n = n'
proof(rule CFGExit.method-exit-cases)
  assume n = NewExit
  from method-exit2 show ?thesis
  proof(rule CFGExit.method-exit-cases)
    assume n' = NewExit
    with  $\langle n = NewExit \rangle$  show ?thesis by simp
  next
  fix a Q f p
  assume n' = src a
  and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
  and knd a =  $Q \leftrightarrow_p f$ 
  hence lift-get-proc get-proc Main (src a) = p
  by  $-(rule\ CFGExit.get-proc-return)$ 
  with CFGExit.get-proc-Exit lift-eq  $\langle n' = src\ a \rangle$   $\langle n = NewExit \rangle$ 
  have p = Main by simp
  with  $\langle knd\ a = Q \leftrightarrow_p f \rangle$  have knd a =  $Q \leftrightarrow_{Main} f$  by simp
  with  $\langle lift-valid-edge\ valid-edge\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a \rangle$ 
  have False by(rule CFGExit.Main-no-return-source)
  thus ?thesis by simp
qed
next
fix a Q f p
assume n = src a
and lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
and knd a =  $Q \leftrightarrow_p f$ 
then obtain x where valid-edge x and src a = Node (sourcenode x)
and kind x =  $Q \leftrightarrow_p f$ 
by(fastforce elim:lift-valid-edge.cases)
hence method-exit (sourcenode x) by(fastforce simp:method-exit-def)
from method-exit2 show ?thesis
proof(rule CFGExit.method-exit-cases)
  assume n' = NewExit
  from  $\langle lift-valid-edge\ valid-edge\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a \rangle$ 
   $\langle knd\ a = Q \leftrightarrow_p f \rangle$ 
  have lift-get-proc get-proc Main (src a) = p

```

```

    by  $-(rule\ CFGExit.get-proc-return)$ 
  with  $CFGExit.get-proc-Exit\ lift-eq\ \langle n = src\ a \rangle\ \langle n' = NewExit \rangle$ 
  have  $p = Main$  by simp
  with  $\langle knid\ a = Q \leftrightarrow_p f \rangle$  have  $knid\ a = Q \leftrightarrow_{Main} f$  by simp
  with  $\langle lift-valid-edge\ valid-edge\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a \rangle$ 
  have False by  $(rule\ CFGExit.Main-no-return-source)$ 
  thus ?thesis by simp
next
fix  $a'\ Q'\ f'\ p'$ 
assume  $n' = src\ a'$ 
  and  $lift-valid-edge\ valid-edge\ sourcenode\ targetnode\ kind\ Entry\ Exit\ a'$ 
  and  $knid\ a' = Q' \leftrightarrow_{p'} f'$ 
then obtain  $x'$  where  $valid-edge\ x'$  and  $src\ a' = Node\ (sourcenode\ x')$ 
  and  $kind\ x' = Q' \leftrightarrow_{p'} f'$ 
  by  $(fastforce\ elim:lift-valid-edge.cases)$ 
hence  $method-exit\ (sourcenode\ x')$  by  $(fastforce\ simp:method-exit-def)$ 
with  $\langle method-exit\ (sourcenode\ x) \rangle\ lift-eq\ \langle n = src\ a \rangle\ \langle n' = src\ a' \rangle$ 
   $\langle src\ a = Node\ (sourcenode\ x) \rangle\ \langle src\ a' = Node\ (sourcenode\ x') \rangle$ 
have  $sourcenode\ x = sourcenode\ x'$  by  $(fastforce\ intro:method-exit-unique)$ 
with  $\langle src\ a = Node\ (sourcenode\ x) \rangle\ \langle src\ a' = Node\ (sourcenode\ x') \rangle$ 
   $\langle n = src\ a \rangle\ \langle n' = src\ a' \rangle$ 
show ?thesis by simp
qed
qed
qed
qed

```

lemma *lift-SDG*:

```

assumes  $SDG:SDG\ sourcenode\ targetnode\ kind\ valid-edge\ Entry\ get-proc$ 
 $get-return-edges\ procs\ Main\ Exit\ Def\ Use\ ParamDefs\ ParamUses$ 
and  $inner:CFGExit.inner-node\ sourcenode\ targetnode\ valid-edge\ Entry\ Exit\ nx$ 
shows  $SDG\ src\ trg\ knid$ 
 $(lift-valid-edge\ valid-edge\ sourcenode\ targetnode\ kind\ Entry\ Exit)\ NewEntry$ 
 $(lift-get-proc\ get-proc\ Main)$ 
 $(lift-get-return-edges\ get-return-edges\ valid-edge\ sourcenode\ targetnode\ kind)$ 
 $procs\ Main\ NewExit\ (lift-Def\ Def\ Entry\ Exit\ H\ L)\ (lift-Use\ Use\ Entry\ Exit\ H\ L)$ 
 $(lift-ParamDefs\ ParamDefs)\ (lift-ParamUses\ ParamUses)$ 
proof  $-$ 
interpret  $SDG\ sourcenode\ targetnode\ kind\ valid-edge\ Entry\ get-proc$ 
 $get-return-edges\ procs\ Main\ Exit\ Def\ Use\ ParamDefs\ ParamUses$ 
  by  $(rule\ SDG)$ 
have  $wf:CFGExit-wf\ sourcenode\ targetnode\ kind\ valid-edge\ Entry\ get-proc$ 
 $get-return-edges\ procs\ Main\ Exit\ Def\ Use\ ParamDefs\ ParamUses$ 
  by  $(unfold-locales)$ 
have  $pd:Postdomination\ sourcenode\ targetnode\ kind\ valid-edge\ Entry\ get-proc$ 
 $get-return-edges\ procs\ Main\ Exit$ 
  by  $(unfold-locales)$ 
interpret  $wf':CFGExit-wf\ src\ trg\ knid$ 

```

```

lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit NewEntry
lift-get-proc get-proc Main
lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
procs Main NewExit lift-Def Def Entry Exit H L lift-Use Use Entry Exit H L
lift-ParamDefs ParamDefs lift-ParamUses ParamUses
by(fastforce intro:lift-CFGExit-wf wf pd)
interpret pd':Postdomination src trg kn
lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit NewEntry
lift-get-proc get-proc Main
lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
procs Main NewExit
by(fastforce intro:lift-Postdomination wf pd inner)
show ?thesis by(unfold-locales)
qed

```

3.2.3 Low-deterministic security via the lifted graph

lemma *Lift-NonInterferenceGraph*:

```

fixes valid-edge and sourcenode and targetnode and kind and Entry and Exit
and get-proc and get-return-edges and procs and Main
and Def and Use and ParamDefs and ParamUses and H and L
defines lve:lve ≡ lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit
and lget-proc:lget-proc ≡ lift-get-proc get-proc Main
and lget-return-edges:lget-return-edges ≡
lift-get-return-edges get-return-edges valid-edge sourcenode targetnode kind
and lDef:lDef ≡ lift-Def Def Entry Exit H L
and lUse:lUse ≡ lift-Use Use Entry Exit H L
and lParamDefs:lParamDefs ≡ lift-ParamDefs ParamDefs
and lParamUses:lParamUses ≡ lift-ParamUses ParamUses
assumes SDG:SDG sourcenode targetnode kind valid-edge Entry get-proc
get-return-edges procs Main Exit Def Use ParamDefs ParamUses
and inner:CFGExit.inner-node sourcenode targetnode valid-edge Entry Exit nx
and H ∩ L = {} and H ∪ L = UNIV
shows NonInterferenceInterGraph src trg kn lve NewEntry lget-proc
lget-return-edges procs Main NewExit lDef lUse lParamDefs lParamUses H L
(Node Entry) (Node Exit)

```

proof –

```

interpret SDG sourcenode targetnode kind valid-edge Entry get-proc
get-return-edges procs Main Exit Def Use ParamDefs ParamUses
by(rule SDG)

```

```

interpret SDG':SDG src trg kn lve NewEntry lget-proc lget-return-edges
procs Main NewExit lDef lUse lParamDefs lParamUses
by(fastforce intro:lift-SDG SDG inner simp:lve lget-proc lget-return-edges lDef
lUse lParamDefs lParamUses)

```

show ?thesis

proof

```

fix a assume lve a and src a = NewEntry
thus trg a = NewExit ∨ trg a = Node Entry
by(fastforce elim:lift-valid-edge.cases simp:lve)

```



```

next
  show  $\exists a. lve\ a \wedge src\ a = NewEntry \wedge trg\ a = Node\ Entry \wedge knd\ a = (\lambda s. True)$ 
  by(fastforce intro:lve-Entry-edge simp:lve)
next
  fix a assume lve a and trg a = Node Entry
  from  $\langle lve\ a \rangle$ 
  have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    by(simp add:lve)
  from this  $\langle trg\ a = Node\ Entry \rangle$ 
  show src a = NewEntry
  proof(induct rule:lift-valid-edge.induct)
    case (lve-edge a e)
    from  $\langle e = (Node\ (sourcenode\ a),\ kind\ a,\ Node\ (targetnode\ a)) \rangle$ 
       $\langle trg\ e = Node\ Entry \rangle$ 
    have targetnode a = Entry by simp
    with  $\langle valid\ edge\ a \rangle$  have False by(rule Entry-target)
    thus ?case by simp
  qed simp-all
next
  fix a assume lve a and trg a = NewExit
  thus src a = NewEntry  $\vee$  src a = Node Exit
    by(fastforce elim:lift-valid-edge.cases simp:lve)
next
  show  $\exists a. lve\ a \wedge src\ a = Node\ Exit \wedge trg\ a = NewExit \wedge knd\ a = (\lambda s. True)$ 
  by(fastforce intro:lve-Exit-edge simp:lve)
next
  fix a assume lve a and src a = Node Exit
  from  $\langle lve\ a \rangle$ 
  have lift-valid-edge valid-edge sourcenode targetnode kind Entry Exit a
    by(simp add:lve)
  from this  $\langle src\ a = Node\ Exit \rangle$ 
  show trg a = NewExit
  proof(induct rule:lift-valid-edge.induct)
    case (lve-edge a e)
    from  $\langle e = (Node\ (sourcenode\ a),\ kind\ a,\ Node\ (targetnode\ a)) \rangle$ 
       $\langle src\ e = Node\ Exit \rangle$ 
    have sourcenode a = Exit by simp
    with  $\langle valid\ edge\ a \rangle$  have False by(rule Exit-source)
    thus ?case by simp
  qed simp-all
next
  from lDef show lDef (Node Entry) = H
    by(fastforce elim:lift-Def-set.cases intro:lift-Def-High)
next
  from Entry-noteq-Exit lUse show lUse (Node Entry) = H
    by(fastforce elim:lift-Use-set.cases intro:lift-Use-High)
next
  from Entry-noteq-Exit lUse show lUse (Node Exit) = L

```

```

    by(fastforce elim:lift-Use-set.cases intro:lift-Use-Low)
next
  from  $\langle H \cap L = \{\} \rangle$  show  $H \cap L = \{\}$  .
next
  from  $\langle H \cup L = UNIV \rangle$  show  $H \cup L = UNIV$  .
qed
qed
end

```

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