

# State Spaces: The Locale Way

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## 1 Introduction

These theories introduce a new command called **statespace**. It's usage is similar to **records**. However, the command does not introduce a new type but an abstract specification based on the locale infrastructure. This leads to extra flexibility in composing state space components, in particular multiple inheritance and renaming of components.

The state space infrastructure basically manages the following things:

- distinctness of field names
- projections / injections from / to an abstract *value* type
- syntax translations for lookup and update, hiding the projections and injections
- simplification procedure for lookups / updates, similar to records

**Overview** In Section 2 we define distinctness of the nodes in a binary tree and provide the basic prover tools to support efficient distinctness reasoning for field names managed by state spaces. The state is represented as a function from (abstract) names to (abstract) values as introduced in Section 3. The basic setup for state spaces is in Section 4. Some syntax for lookup and updates is added in Section 5. Finally Section 6 explains the usage of state spaces by examples.

## 2 Distinctness of Names in a Binary Tree

```
theory DistinctTreeProver
imports Main
begin
```

A state space manages a set of (abstract) names and assumes that the names are distinct. The names are stored as parameters of a locale and distinctness as an assumption. The most common request is to proof distinctness of two given names. We maintain the names in a balanced binary tree and formulate a predicate that all nodes in the tree have distinct names. This setup leads to logarithmic certificates.

### 2.1 The Binary Tree

```
datatype 'a tree = Node 'a tree 'a bool 'a tree | Tip
```

The boolean flag in the node marks the content of the node as deleted, without having to build a new tree. We prefer the boolean flag to an option type, so that the ML-layer can still use the node content to facilitate binary search in the tree. The ML code keeps the nodes sorted using the term order. We do not have to push ordering to the HOL level.

### 2.2 Distinctness of Nodes

```
primrec set-of :: 'a tree  $\Rightarrow$  'a set
where
  set-of Tip = {}
| set-of (Node l x d r) = (if d then {} else {x})  $\cup$  set-of l  $\cup$  set-of r

primrec all-distinct :: 'a tree  $\Rightarrow$  bool
where
  all-distinct Tip = True
| all-distinct (Node l x d r) =
  ((d  $\vee$  (x  $\notin$  set-of l  $\wedge$  x  $\notin$  set-of r))  $\wedge$ 
   set-of l  $\cap$  set-of r = {}  $\wedge$ 
   all-distinct l  $\wedge$  all-distinct r)
```

Given a binary tree  $t$  for which *all-distinct* holds, given two different nodes contained in the tree, we want to write a ML function that generates a logarithmic certificate that the content of the nodes is distinct. We use the following lemmas to achieve this.

**lemma** *all-distinct-left*:  $\text{all-distinct } (\text{Node } l \ x \ b \ r) \implies \text{all-distinct } l$   
**by** *simp*

**lemma** *all-distinct-right*:  $\text{all-distinct } (\text{Node } l \ x \ b \ r) \implies \text{all-distinct } r$   
**by** *simp*

**lemma** *distinct-left*:  $\text{all-distinct } (\text{Node } l \ x \ \text{False} \ r) \implies y \in \text{set-of } l \implies x \neq y$   
**by** *auto*

**lemma** *distinct-right*:  $\text{all-distinct } (\text{Node } l \ x \ \text{False} \ r) \implies y \in \text{set-of } r \implies x \neq y$   
**by** *auto*

**lemma** *distinct-left-right*:  
 $\text{all-distinct } (\text{Node } l \ z \ b \ r) \implies x \in \text{set-of } l \implies y \in \text{set-of } r \implies x \neq y$   
**by** *auto*

**lemma** *in-set-root*:  $x \in \text{set-of } (\text{Node } l \ x \ \text{False} \ r)$   
**by** *simp*

**lemma** *in-set-left*:  $y \in \text{set-of } l \implies y \in \text{set-of } (\text{Node } l \ x \ \text{False} \ r)$   
**by** *simp*

**lemma** *in-set-right*:  $y \in \text{set-of } r \implies y \in \text{set-of } (\text{Node } l \ x \ \text{False} \ r)$   
**by** *simp*

**lemma** *swap-neq*:  $x \neq y \implies y \neq x$   
**by** *blast*

**lemma** *neq-to-eq-False*:  $x \neq y \implies (x=y) \equiv \text{False}$   
**by** *simp*

## 2.3 Containment of Trees

When deriving a state space from other ones, we create a new name tree which contains all the names of the parent state spaces and assume the predicate *all-distinct*. We then prove that the new locale interprets all parent locales. Hence we have to show that the new distinctness assumption on all names implies the distinctness assumptions of the parent locales. This proof is implemented in ML. We do this efficiently by defining a kind of containment check of trees by “subtraction”. We subtract the parent tree from the new tree. If this succeeds we know that *all-distinct* of the new tree implies *all-distinct* of the parent tree. The resulting certificate is of the order  $n * \log m$  where  $n$  is the size of the (smaller) parent tree and  $m$  the

size of the (bigger) new tree.

**primrec** *delete* :: 'a  $\Rightarrow$  'a tree  $\Rightarrow$  'a tree option

**where**

```

  delete x Tip = None
| delete x (Node l y d r) = (case delete x l of
    Some l'  $\Rightarrow$ 
      (case delete x r of
        Some r'  $\Rightarrow$  Some (Node l' y (d  $\vee$  (x=y)) r')
      | None  $\Rightarrow$  Some (Node l' y (d  $\vee$  (x=y)) r))
  | None  $\Rightarrow$ 
      (case delete x r of
        Some r'  $\Rightarrow$  Some (Node l y (d  $\vee$  (x=y)) r')
      | None  $\Rightarrow$  if x=y  $\wedge$   $\neg$ d then Some (Node l y True r)
                  else None))

```

**lemma** *delete-Some-set-of*: delete x t = Some t'  $\implies$  set-of t'  $\subseteq$  set-of t

**proof** (induct t arbitrary: t')

case Tip thus ?case **by** simp

**next**

case (Node l y d r)

**have** del: delete x (Node l y d r) = Some t' **by** fact

**show** ?case

**proof** (cases delete x l)

case (Some l')

**note** x-l-Some = this

**with** Node.hyps

**have** l'-l: set-of l'  $\subseteq$  set-of l

**by** simp

**show** ?thesis

**proof** (cases delete x r)

case (Some r')

**with** Node.hyps

**have** set-of r'  $\subseteq$  set-of r

**by** simp

**with** l'-l Some x-l-Some del

**show** ?thesis

**by** (auto split: if-split-asm)

**next**

case None

**with** l'-l Some x-l-Some del

**show** ?thesis

**by** (fastforce split: if-split-asm)

**qed**

**next**

case None

**note** x-l-None = this

**show** ?thesis

**proof** (cases delete x r)

```

    case (Some r')
    with Node.hyps
    have set-of r'  $\subseteq$  set-of r
      by simp
    with Some x-l-None del
    show ?thesis
      by (fastforce split: if-split-asm)
  next
    case None
    with x-l-None del
    show ?thesis
      by (fastforce split: if-split-asm)
  qed
qed
qed

lemma delete-Some-all-distinct:
  delete x t = Some t'  $\implies$  all-distinct t  $\implies$  all-distinct t'
proof (induct t arbitrary: t')
  case Tip thus ?case by simp
next
  case (Node l y d r)
  have del: delete x (Node l y d r) = Some t' by fact
  have all-distinct (Node l y d r) by fact
  then obtain
    dist-l: all-distinct l and
    dist-r: all-distinct r and
    d: d  $\vee$  (y  $\notin$  set-of l  $\wedge$  y  $\notin$  set-of r) and
    dist-l-r: set-of l  $\cap$  set-of r = {}
    by auto
  show ?case
proof (cases delete x l)
  case (Some l')
  note x-l-Some = this
  from Node.hyps (1) [OF Some dist-l]
  have dist-l': all-distinct l'
    by simp
  from delete-Some-set-of [OF x-l-Some]
  have l'-l: set-of l'  $\subseteq$  set-of l.
  show ?thesis
proof (cases delete x r)
  case (Some r')
  from Node.hyps (2) [OF Some dist-r]
  have dist-r': all-distinct r'
    by simp
  from delete-Some-set-of [OF Some]
  have set-of r'  $\subseteq$  set-of r.

  with dist-l' dist-r' l'-l Some x-l-Some del d dist-l-r

```

```

    show ?thesis
    by fastforce
next
case None
with l'-l dist-l' x-l-Some del d dist-l-r dist-r
show ?thesis
by fastforce
qed
next
case None
note x-l-None = this
show ?thesis
proof (cases delete x r)
case (Some r')
with Node.hyps (2) [OF Some dist-r]
have dist-r': all-distinct r'
by simp
from delete-Some-set-of [OF Some]
have set-of r'  $\subseteq$  set-of r.
with Some dist-r' x-l-None del dist-l d dist-l-r
show ?thesis
by fastforce
next
case None
with x-l-None del dist-l dist-r d dist-l-r
show ?thesis
by (fastforce split: if-split-asm)
qed
qed
qed

lemma delete-None-set-of-conv: delete x t = None = (x  $\notin$  set-of t)
proof (induct t)
case Tip thus ?case by simp
next
case (Node l y d r)
thus ?case
by (auto split: option.splits)
qed

lemma delete-Some-x-set-of:
delete x t = Some t'  $\implies$  x  $\in$  set-of t  $\wedge$  x  $\notin$  set-of t'
proof (induct t arbitrary: t')
case Tip thus ?case by simp
next
case (Node l y d r)
have del: delete x (Node l y d r) = Some t' by fact
show ?case
proof (cases delete x l)

```

```

case (Some l')
note x-l-Some = this
from Node.hyps (1) [OF Some]
obtain x-l:  $x \in \text{set-of } l \text{ } x \notin \text{set-of } l'$ 
  by simp
show ?thesis
proof (cases delete x r)
  case (Some r')
  from Node.hyps (2) [OF Some]
  obtain x-r:  $x \in \text{set-of } r \text{ } x \notin \text{set-of } r'$ 
    by simp
  from x-r x-l Some x-l-Some del
  show ?thesis
    by (clarsimp split: if-split-asm)
next
  case None
  then have  $x \notin \text{set-of } r$ 
    by (simp add: delete-None-set-of-conv)
  with x-l None x-l-Some del
  show ?thesis
    by (clarsimp split: if-split-asm)
qed
next
  case None
  note x-l-None = this
  then have x-notin-l:  $x \notin \text{set-of } l$ 
    by (simp add: delete-None-set-of-conv)
  show ?thesis
proof (cases delete x r)
  case (Some r')
  from Node.hyps (2) [OF Some]
  obtain x-r:  $x \in \text{set-of } r \text{ } x \notin \text{set-of } r'$ 
    by simp
  from x-r x-notin-l Some x-l-None del
  show ?thesis
    by (clarsimp split: if-split-asm)
next
  case None
  then have  $x \notin \text{set-of } r$ 
    by (simp add: delete-None-set-of-conv)
  with None x-l-None x-notin-l del
  show ?thesis
    by (clarsimp split: if-split-asm)
qed
qed
qed

```

**primrec** subtract :: 'a tree  $\Rightarrow$  'a tree  $\Rightarrow$  'a tree option

where

```

subtract Tip t = Some t
| subtract (Node l x b r) t =
  (case delete x t of
    Some t' => (case subtract l t' of
      Some t'' => subtract r t''
      | None => None)
    | None => None)

```

**lemma** *subtract-Some-set-of-res:*

*subtract t<sub>1</sub> t<sub>2</sub> = Some t  $\implies$  set-of t  $\subseteq$  set-of t<sub>2</sub>*

**proof** (*induct t<sub>1</sub> arbitrary: t<sub>2</sub> t*)

**case** *Tip thus ?case by simp*

**next**

**case** (*Node l x b r*)

**have** *sub: subtract (Node l x b r) t<sub>2</sub> = Some t by fact*

**show** *?case*

**proof** (*cases delete x t<sub>2</sub>*)

**case** (*Some t<sub>2</sub>'*)

**note** *del-x-Some = this*

**from** *delete-Some-set-of [OF Some]*

**have** *t<sub>2</sub>'-t<sub>2</sub>: set-of t<sub>2</sub>'  $\subseteq$  set-of t<sub>2</sub> .*

**show** *?thesis*

**proof** (*cases subtract l t<sub>2</sub>'*)

**case** (*Some t<sub>2</sub>''*)

**note** *sub-l-Some = this*

**from** *Node.hyps (1) [OF Some]*

**have** *t<sub>2</sub>''-t<sub>2</sub>': set-of t<sub>2</sub>''  $\subseteq$  set-of t<sub>2</sub>' .*

**show** *?thesis*

**proof** (*cases subtract r t<sub>2</sub>''*)

**case** (*Some t<sub>2</sub>'''*)

**from** *Node.hyps (2) [OF Some]*

**have** *set-of t<sub>2</sub>'''  $\subseteq$  set-of t<sub>2</sub>'' .*

**with** *Some sub-l-Some del-x-Some sub t<sub>2</sub>''-t<sub>2</sub>' t<sub>2</sub>'-t<sub>2</sub>*

**show** *?thesis*

**by** *simp*

**next**

**case** *None*

**with** *del-x-Some sub-l-Some sub*

**show** *?thesis*

**by** *simp*

**qed**

**next**

**case** *None*

**with** *del-x-Some sub*

**show** *?thesis*

**by** *simp*

**qed**

**next**



```

    case None
    with sub show ?thesis by simp
  qed
qed

lemma subtract-Some-set-of:
  subtract t1 t2 = Some t  $\implies$  set-of t1  $\subseteq$  set-of t2
proof (induct t1 arbitrary: t2 t)
  case Tip thus ?case by simp
next
  case (Node l x d r)
  have sub: subtract (Node l x d r) t2 = Some t by fact
  show ?case
  proof (cases delete x t2)
    case (Some t2')
    note del-x-Some = this
    from delete-Some-set-of [OF Some]
    have t2'-t2: set-of t2'  $\subseteq$  set-of t2 .
    from delete-None-set-of-conv [of x t2] Some
    have x-t2: x  $\in$  set-of t2
    by simp
    show ?thesis
  proof (cases subtract l t2')
    case (Some t2'')
    note sub-l-Some = this
    from Node.hyps (1) [OF Some]
    have l-t2': set-of l  $\subseteq$  set-of t2' .
    from subtract-Some-set-of-res [OF Some]
    have t2''-t2': set-of t2''  $\subseteq$  set-of t2' .
    show ?thesis
  proof (cases subtract r t2'')
    case (Some t2''')
    from Node.hyps (2) [OF Some]
    have r-t2': set-of r  $\subseteq$  set-of t2'' .
    from Some sub-l-Some del-x-Some sub r-t2'' l-t2' t2'-t2 t2''-t2' x-t2
    show ?thesis
    by auto
  next
    case None
    with del-x-Some sub-l-Some sub
    show ?thesis
    by simp
  qed
next
  case None
  with del-x-Some sub
  show ?thesis
  by simp
qed

```

```

next
  case None
  with sub show ?thesis by simp
qed
qed

lemma subtract-Some-all-distinct-res:
  subtract t1 t2 = Some t  $\implies$  all-distinct t2  $\implies$  all-distinct t
proof (induct t1 arbitrary: t2 t)
  case Tip thus ?case by simp
next
  case (Node l x d r)
  have sub: subtract (Node l x d r) t2 = Some t by fact
  have dist-t2: all-distinct t2 by fact
  show ?case
  proof (cases delete x t2)
    case (Some t2')
    note del-x-Some = this
    from delete-Some-all-distinct [OF Some dist-t2]
    have dist-t2': all-distinct t2'.
    show ?thesis
    proof (cases subtract l t2')
      case (Some t2'')
      note sub-l-Some = this
      from Node.hyps (1) [OF Some dist-t2']
      have dist-t2'': all-distinct t2''.
      show ?thesis
      proof (cases subtract r t2'')
        case (Some t2'')
        from Node.hyps (2) [OF Some dist-t2'']
        have dist-t2''': all-distinct t2''.
        from Some sub-l-Some del-x-Some sub
          dist-t2'''
        show ?thesis
        by simp
      next
        case None
        with del-x-Some sub-l-Some sub
        show ?thesis
        by simp
      qed
    next
      case None
      with del-x-Some sub
      show ?thesis
      by simp
    qed
  next
    case None
    with del-x-Some sub
    show ?thesis
    by simp
  qed
next
  case None
  with del-x-Some sub
  show ?thesis
  by simp
qed

```

```

    with sub show ?thesis by simp
qed
qed

lemma subtract-Some-dist-res:
  subtract  $t_1$   $t_2$  = Some  $t \implies \text{set-of } t_1 \cap \text{set-of } t = \{\}$ 
proof (induct  $t_1$  arbitrary:  $t_2$   $t$ )
  case Tip thus ?case by simp
next
  case (Node  $l$   $x$   $d$   $r$ )
  have sub: subtract (Node  $l$   $x$   $d$   $r$ )  $t_2$  = Some  $t$  by fact
  show ?case
  proof (cases delete  $x$   $t_2$ )
    case (Some  $t_2'$ )
    note del-x-Some = this
    from delete-Some-x-set-of [OF Some]
    obtain  $x$ - $t_2$ :  $x \in \text{set-of } t_2$  and  $x$ -not- $t_2'$ :  $x \notin \text{set-of } t_2'$ 
    by simp
    from delete-Some-set-of [OF Some]
    have  $t_2'$ - $t_2$ :  $\text{set-of } t_2' \subseteq \text{set-of } t_2$  .
    show ?thesis
    proof (cases subtract  $l$   $t_2'$ )
      case (Some  $t_2''$ )
      note sub-l-Some = this
      from Node.hyps (1) [OF Some]
      have dist-l- $t_2''$ :  $\text{set-of } l \cap \text{set-of } t_2'' = \{\}$ .
      from subtract-Some-set-of-res [OF Some]
      have  $t_2''$ - $t_2'$ :  $\text{set-of } t_2'' \subseteq \text{set-of } t_2'$  .
      show ?thesis
      proof (cases subtract  $r$   $t_2''$ )
        case (Some  $t_2'''$ )
        from Node.hyps (2) [OF Some]
        have dist-r- $t_2'''$ :  $\text{set-of } r \cap \text{set-of } t_2''' = \{\}$  .
        from subtract-Some-set-of-res [OF Some]
        have  $t_2'''$ - $t_2''$ :  $\text{set-of } t_2''' \subseteq \text{set-of } t_2''$ .

        from Some sub-l-Some del-x-Some sub  $t_2'''$ - $t_2''$  dist-l- $t_2''$  dist-r- $t_2'''$ 
           $t_2''$ - $t_2'$   $t_2'$ - $t_2$   $x$ -not- $t_2'$ 
        show ?thesis
        by auto
      next
        case None
      with del-x-Some sub-l-Some sub
      show ?thesis
      by simp
    qed
  next
    case None
  end
qed

```

```

    with del-x-Some sub
    show ?thesis
      by simp
    qed
  next
    case None
    with sub show ?thesis by simp
  qed
qed

lemma subtract-Some-all-distinct:
  subtract t1 t2 = Some t  $\implies$  all-distinct t2  $\implies$  all-distinct t1
proof (induct t1 arbitrary: t2 t)
  case Tip thus ?case by simp
next
  case (Node l x d r)
  have sub: subtract (Node l x d r) t2 = Some t by fact
  have dist-t2: all-distinct t2 by fact
  show ?case
  proof (cases delete x t2)
    case (Some t2')
    note del-x-Some = this
    from delete-Some-all-distinct [OF Some dist-t2]
    have dist-t2': all-distinct t2' .
    from delete-Some-set-of [OF Some]
    have t2'-t2: set-of t2'  $\subseteq$  set-of t2 .
    from delete-Some-x-set-of [OF Some]
    obtain x-t2: x  $\in$  set-of t2 and x-not-t2': x  $\notin$  set-of t2'
    by simp

    show ?thesis
    proof (cases subtract l t2')
      case (Some t2'')
      note sub-l-Some = this
      from Node.hyps (1) [OF Some dist-t2']
      have dist-l: all-distinct l .
      from subtract-Some-all-distinct-res [OF Some dist-t2']
      have dist-t2'': all-distinct t2'' .
      from subtract-Some-set-of [OF Some]
      have l-t2': set-of l  $\subseteq$  set-of t2' .
      from subtract-Some-set-of-res [OF Some]
      have t2''-t2': set-of t2''  $\subseteq$  set-of t2' .
      from subtract-Some-dist-res [OF Some]
      have dist-l-t2'': set-of l  $\cap$  set-of t2'' = {} .
      show ?thesis
      proof (cases subtract r t2'')
        case (Some t2''')
        from Node.hyps (2) [OF Some dist-t2'']
        have dist-r: all-distinct r .

```

```

from subtract-Some-set-of [OF Some]
have r-t2'': set-of r  $\subseteq$  set-of t2'' .
from subtract-Some-dist-res [OF Some]
have dist-r-t2''': set-of r  $\cap$  set-of t2''' = {}.

from dist-l dist-r Some sub-l-Some del-x-Some r-t2'' l-t2' x-t2 x-not-t2'
      t2''-t2' dist-l-t2'' dist-r-t2'''
show ?thesis
  by auto
next
  case None
  with del-x-Some sub-l-Some sub
  show ?thesis
    by simp
  qed
next
  case None
  with del-x-Some sub
  show ?thesis
    by simp
  qed
next
  case None
  with sub show ?thesis by simp
  qed
qed

```

```

lemma delete-left:
  assumes dist: all-distinct (Node l y d r)
  assumes del-l: delete x l = Some l'
  shows delete x (Node l y d r) = Some (Node l' y d r)
proof -
  from delete-Some-x-set-of [OF del-l]
  obtain x: x  $\in$  set-of l
    by simp
  with dist
  have delete x r = None
    by (cases delete x r) (auto dest:delete-Some-x-set-of)

  with x
  show ?thesis
    using del-l dist
    by (auto split: option.splits)
qed

```

```

lemma delete-right:
  assumes dist: all-distinct (Node l y d r)
  assumes del-r: delete x r = Some r'

```

```

    shows delete x (Node l y d r) = Some (Node l y d r')
  proof -
    from delete-Some-x-set-of [OF del-r]
    obtain x: x ∈ set-of r
      by simp
    with dist
    have delete x l = None
      by (cases delete x l) (auto dest:delete-Some-x-set-of)

    with x
    show ?thesis
      using del-r dist
      by (auto split: option.splits)
  qed

```

```

lemma delete-root:
  assumes dist: all-distinct (Node l x False r)
  shows delete x (Node l x False r) = Some (Node l x True r)
  proof -
    from dist have delete x r = None
      by (cases delete x r) (auto dest:delete-Some-x-set-of)
    moreover
    from dist have delete x l = None
      by (cases delete x l) (auto dest:delete-Some-x-set-of)
    ultimately show ?thesis
      using dist
      by (auto split: option.splits)
  qed

```

```

lemma subtract-Node:
  assumes del: delete x t = Some t'
  assumes sub-l: subtract l t' = Some t''
  assumes sub-r: subtract r t'' = Some t'''
  shows subtract (Node l x False r) t = Some t'''
  using del sub-l sub-r
  by simp

```

```

lemma subtract-Tip: subtract Tip t = Some t
  by simp

```

Now we have all the theorems in place that are needed for the certificate generating ML functions.

```

ML-file <distinct-tree-prover.ML>

```

```

end

```

### 3 State Space Representation as Function

```

theory StateFun imports DistinctTreeProver

```

**begin**

The state space is represented as a function from names to values. We neither fix the type of names nor the type of values. We define lookup and update functions and provide simprocs that simplify expressions containing these, similar to HOL-records.

The lookup and update function get constructor/destructor functions as parameters. These are used to embed various HOL-types into the abstract value type. Conceptually the abstract value type is a sum of all types that we attempt to store in the state space.

The update is actually generalized to a map function. The map supplies better compositionality, especially if you think of nested state spaces.

**definition**  $K\text{-statefun} :: 'a \Rightarrow 'b \Rightarrow 'a$  **where**  $K\text{-statefun } c \ x \equiv c$

**lemma**  $K\text{-statefun-apply}$  [simp]:  $K\text{-statefun } c \ x = c$   
**by** (simp add:  $K\text{-statefun-def}$ )

**lemma**  $K\text{-statefun-comp}$  [simp]:  $(K\text{-statefun } c \circ f) = K\text{-statefun } c$   
**by** (rule ext) (simp add: comp-def)

**lemma**  $K\text{-statefun-cong}$  [cong]:  $K\text{-statefun } c \ x = K\text{-statefun } c \ x$   
**by** (rule refl)

**definition**  $lookup :: ('v \Rightarrow 'a) \Rightarrow 'n \Rightarrow ('n \Rightarrow 'v) \Rightarrow 'a$   
**where**  $lookup \ destr \ n \ s = destr \ (s \ n)$

**definition**  $update ::$   
 $('v \Rightarrow 'a1) \Rightarrow ('a2 \Rightarrow 'v) \Rightarrow 'n \Rightarrow ('a1 \Rightarrow 'a2) \Rightarrow ('n \Rightarrow 'v) \Rightarrow ('n \Rightarrow 'v)$   
**where**  $update \ destr \ constr \ n \ f \ s = s(n := constr \ (f \ (destr \ (s \ n))))$

**lemma**  $lookup\text{-update-same}$ :  
 $(\bigwedge v. destr \ (constr \ v) = v) \implies lookup \ destr \ n \ (update \ destr \ constr \ n \ f \ s) =$   
 $f \ (destr \ (s \ n))$   
**by** (simp add: lookup-def update-def)

**lemma**  $lookup\text{-update-id-same}$ :  
 $lookup \ destr \ n \ (update \ destr' \ id \ n \ (K\text{-statefun} \ (lookup \ id \ n \ s')) \ s) =$   
 $lookup \ destr \ n \ s'$   
**by** (simp add: lookup-def update-def)

**lemma**  $lookup\text{-update-other}$ :  
 $n \neq m \implies lookup \ destr \ n \ (update \ destr' \ constr \ m \ f \ s) = lookup \ destr \ n \ s$   
**by** (simp add: lookup-def update-def)

**lemma**  $id\text{-id-cancel}$ :  $id \ (id \ x) = x$   
**by** (simp add: id-def)

**lemma** *destr-contstr-comp-id*:  $(\bigwedge v. \text{destr } (\text{constr } v) = v) \implies \text{destr} \circ \text{constr} = \text{id}$   
**by** (*rule ext*) *simp*

**lemma** *block-conj-cong*:  $(P \wedge Q) = (P \wedge Q)$   
**by** *simp*

**lemma** *conj1-False*:  $P \equiv \text{False} \implies (P \wedge Q) \equiv \text{False}$   
**by** *simp*

**lemma** *conj2-False*:  $Q \equiv \text{False} \implies (P \wedge Q) \equiv \text{False}$   
**by** *simp*

**lemma** *conj-True*:  $P \equiv \text{True} \implies Q \equiv \text{True} \implies (P \wedge Q) \equiv \text{True}$   
**by** *simp*

**lemma** *conj-cong*:  $P \equiv P' \implies Q \equiv Q' \implies (P \wedge Q) \equiv (P' \wedge Q')$   
**by** *simp*

**lemma** *update-apply*:  $(\text{update destr constr } n \text{ } f \text{ } s \text{ } x) =$   
 $(\text{if } x=n \text{ then } \text{constr } (f (\text{destr } (s \text{ } n))) \text{ else } s \text{ } x)$   
**by** (*simp add: update-def*)

**lemma** *ex-id*:  $\exists x. \text{id } x = y$   
**by** (*simp add: id-def*)

**lemma** *swap-ex-eq*:  
 $\exists s. f \text{ } s = x \equiv \text{True} \implies$   
 $\exists s. x = f \text{ } s \equiv \text{True}$   
**apply** (*rule eq-reflection*)  
**apply** *auto*  
**done**

**lemmas** *meta-ext* = *eq-reflection* [*OF ext*]

**lemma** *update d c n* (*K-statespace* (*lookup d n s*))  $s = s$   
**apply** (*simp add: update-def lookup-def*)  
**apply** (*rule ext*)  
**apply** *simp*  
**oops**

**end**

## 4 Setup for State Space Locales

**theory** *StateSpaceLocale* **imports** *StateFun*



```

keywords statespace :: thy-defn
begin

```

```

ML-file ⟨state-space.ML⟩
ML-file ⟨state-fun.ML⟩

```

For every type that is to be stored in a state space, an instance of this locale is imported in order convert the abstract and concrete values.

```

locale project-inject =
  fixes project :: 'value  $\Rightarrow$  'a
  and inject :: 'a  $\Rightarrow$  'value
  assumes project-inject-cancel [statefun-simp]: project (inject x) = x
begin

```

```

lemma ex-project [statefun-simp]:  $\exists v. \text{project } v = x$ 
proof
  show project (inject x) = x
  by (rule project-inject-cancel)
qed

```

```

lemma project-inject-comp-id [statefun-simp]: project  $\circ$  inject = id
  by (rule ext) (simp add: project-inject-cancel)

```

```

lemma project-inject-comp-cancel [statefun-simp]: f  $\circ$  project  $\circ$  inject = f
  by (rule ext) (simp add: project-inject-cancel)

```

```

end

```

```

end

```

## 5 Syntax for State Space Lookup and Update

```

theory StateSpaceSyntax
imports StateSpaceLocale
begin

```

The state space syntax is kept in an extra theory so that you can choose if you want to use it or not.

```

syntax
  -statespace-lookup :: ('a  $\Rightarrow$  'b)  $\Rightarrow$  'a  $\Rightarrow$  'c ( $\langle \dots \rangle$  [60, 60] 60)
  -statespace-update :: ('a  $\Rightarrow$  'b)  $\Rightarrow$  'a  $\Rightarrow$  'c  $\Rightarrow$  ('a  $\Rightarrow$  'b)
  -statespace-updates :: ('a  $\Rightarrow$  'b)  $\Rightarrow$  updbinds  $\Rightarrow$  ('a  $\Rightarrow$  'b) ( $\langle \dots \rangle$  [900, 0] 900)

```

```

translations
  -statespace-updates f (-updbinds b bs) ==
    -statespace-updates (-statespace-updates f b) bs
  s <x := y> == -statespace-update s x y

```

```

parse-translation
<
  [(syntax-const <-statespace-lookup>, StateSpace.lookup-tr),
   (syntax-const <-statespace-update>, StateSpace.update-tr)]
>

print-translation
<
  [(const-syntax <lookup>, StateSpace.lookup-tr'),
   (const-syntax <update>, StateSpace.update-tr')]
>

end

```

## 6 Examples

```

theory StateSpaceEx
imports StateSpaceLocale StateSpaceSyntax
begin

```

Did you ever dream about records with multiple inheritance? Then you should definitely have a look at statespaces. They may be what you are dreaming of. Or at least almost ...

Isabelle allows to add new top-level commands to the system. Building on the locale infrastructure, we provide a command **statespace** like this:

```

statespace vars =
  n::nat
  b::bool

print-locale vars-namespace
print-locale vars-valuetypes
print-locale vars

```

This resembles a **record** definition, but introduces sophisticated locale infrastructure instead of HOL type schemes. The resulting context postulates two distinct names *n* and *b* and projection / injection functions that convert from abstract values to *nat* and *bool*. The logical content of the locale is:

```

locale vars' =
  fixes n::'name and b::'name
  assumes distinct [n, b]

  fixes project-nat::'value  $\Rightarrow$  nat and inject-nat::nat  $\Rightarrow$  'value
  assumes  $\bigwedge n. \text{project-nat } (\text{inject-nat } n) = n$ 

```

**fixes** *project-bool*::'value  $\Rightarrow$  bool **and** *inject-bool*::bool  $\Rightarrow$  'value  
**assumes**  $\bigwedge b. \text{project-bool } (\text{inject-bool } b) = b$

The HOL predicate *distinct* describes distinctness of all names in the context. Locale *vars*' defines the raw logical content that is defined in the state space locale. We also maintain non-logical context information to support the user:

- Syntax for state lookup and updates that automatically inserts the corresponding projection and injection functions.
- Setup for the proof tools that exploit the distinctness information and the cancellation of projections and injections in deductions and simplifications.

This extra-logical information is added to the locale in form of declarations, which associate the name of a variable to the corresponding projection and injection functions to handle the syntax transformations, and a link from the variable name to the corresponding distinctness theorem. As state spaces are merged or extended there are multiple distinctness theorems in the context. Our declarations take care that the link always points to the strongest distinctness assumption. With these declarations in place, a lookup can be written as  $s \cdot n$ , which is translated to  $\text{project-nat } (s \ n)$ , and an update as  $s \langle n := 2 \rangle$ , which is translated to  $s(n := \text{inject-nat } 2)$ . We can now establish the following lemma:

**lemma** (**in** *vars*) *foo*:  $s \langle n := 2 \rangle \cdot b = s \cdot b$  **by** *simp*

Here the simplifier was able to refer to distinctness of  $b$  and  $n$  to solve the equation. The resulting lemma is also recorded in locale *vars* for later use and is automatically propagated to all its interpretations. Here is another example:

**statespace** 'a *varsX* = NB: *vars* [ $n=N$ ,  $b=B$ ] + *vars* +  $x::'a$

The state space *varsX* imports two copies of the state space *vars*, where one has the variables renamed to upper-case letters, and adds another variable  $x$  of type 'a. This type is fixed inside the state space but may get instantiated later on, analogous to type parameters of an ML-functor. The distinctness assumption is now *distinct* [ $N$ ,  $B$ ,  $n$ ,  $b$ ,  $x$ ], from this we can derive both *distinct* [ $N$ ,  $B$ ] and *distinct* [ $n$ ,  $b$ ], the distinction assumptions for the two versions of locale *vars* above. Moreover we have all necessary projection and injection assumptions available. These assumptions together allow us to establish state space *varsX* as an interpretation of both instances of locale *vars*. Hence we inherit both variants of theorem *foo*:  $s \langle N := 2 \rangle \cdot B = s \cdot B$  as

well as  $s\langle n := 2 \rangle \cdot b = s \cdot b$ . These are immediate consequences of the locale interpretation action.

The declarations for syntax and the distinctness theorems also observe the morphisms generated by the locale package due to the renaming  $n = N$ :

**lemma** (in *varsX*) *foo*:  $s\langle N := 2 \rangle \cdot x = s \cdot x$  **by** *simp*

To assure scalability towards many distinct names, the distinctness predicate is refined to operate on balanced trees. Thus we get logarithmic certificates for the distinctness of two names by the distinctness of the paths in the tree. Asked for the distinctness of two names, our tool produces the paths of the variables in the tree (this is implemented in Isabelle/ML, outside the logic) and returns a certificate corresponding to the different paths. Merging state spaces requires to prove that the combined distinctness assumption implies the distinctness assumptions of the components. Such a proof is of the order  $m \cdot \log n$ , where  $n$  and  $m$  are the number of nodes in the larger and smaller tree, respectively.

We continue with more examples.

**statespace** *'a foo* =  
 $f :: nat \Rightarrow nat$   
 $a :: int$   
 $b :: nat$   
 $c :: 'a$

**lemma** (in *foo*) *foo1*:  
**shows**  $s\langle a := i \rangle \cdot a = i$   
**by** *simp*

**lemma** (in *foo*) *foo2*:  
**shows**  $(s\langle a := i \rangle) \cdot a = i$   
**by** *simp*

**lemma** (in *foo*) *foo3*:  
**shows**  $(s\langle a := i \rangle) \cdot b = s \cdot b$   
**by** *simp*

**lemma** (in *foo*) *foo4*:  
**shows**  $(s\langle a := i, b := j, c := k, a := x \rangle) = (s\langle b := j, c := k, a := x \rangle)$   
**by** *simp*

**statespace** *bar* =  
 $b :: bool$   
 $c :: string$

**lemma** (in *bar*) *bar1*:

```

shows ( $s\langle b := \text{True} \rangle$ )· $c = s\cdot c$ 
by simp

```

You can define a derived state space by inheriting existing state spaces, renaming of components if you like, and by declaring new components.

```

statespace ('a,'b) loo = 'a foo + bar [ $b=B, c=C$ ] +
  X::'b

```

```

lemma (in loo) loo1:
  shows  $s\langle a := i \rangle\cdot B = s\cdot B$ 
proof –
  thm foo1

```

The Lemma *foo1* from the parent state space is also available here:

$$?s\langle a := ?i \rangle\cdot a = ?i$$

```

have  $s\langle a := i \rangle\cdot a = i$ 
  by (rule foo1)
thm bar1

```

Note the renaming of the parameters in Lemma *bar1*:

$$?s\langle B := \text{True} \rangle\cdot C = ?s\cdot C$$

```

have  $s\langle B := \text{True} \rangle\cdot C = s\cdot C$ 
  by (rule bar1)
show ?thesis
  by simp
qed

```

```

statespace 'a dup = FA: 'a foo [ $f=F, a=A$ ] + 'a foo +
  x::int

```

```

lemma (in dup)
shows  $s\langle a := i \rangle\cdot x = s\cdot x$ 
by simp

```

```

lemma (in dup)
shows  $s\langle A := i \rangle\cdot a = s\cdot a$ 
by simp

```

```

lemma (in dup)
shows  $s\langle A := i \rangle\cdot x = s\cdot x$ 
by simp

```

There were known problems with syntax-declarations. They only worked when the context is already completely built. This is now overcome. e.g.:

**locale**  $fooX = foo +$   
**assumes**  $s<a:=i>\cdot b = k$

We can also put statespaces side-by-side by using ordinary **locale** expressions (instead of the **statespace**).

**locale**  $side-by-side = foo + bar$  **where**  $b=B::'a$  **and**  $c=C$  **for**  $B\ C$

**context**  $side-by-side$   
**begin**

Simplification within one of the statespaces works as expected.

**lemma**  $s<B := i>\cdot C = s\cdot C$   
**by**  $simp$

**lemma**  $s<a := i>\cdot b = s\cdot b$   
**by**  $simp$

In contrast to the statespace  $loo$  there is no 'inter' statespace distinctness between the names of  $foo$  and  $bar$ .

**end**

Sharing of names in side-by-side statespaces is also possible as long as they are mapped to the same type.

**statespace**  $vars1 = n::nat\ m::nat$   
**statespace**  $vars2 = n::nat\ k::nat$

**locale**  $vars1-vars2 = vars1 + vars2$

**context**  $vars1-vars2$   
**begin**

Note that the distinctness theorem for  $vars1$  is selected here to do the proof.

**lemma**  $s<n := i>\cdot m = s\cdot m$   
**by**  $simp$

Note that the distinctness theorem for  $vars2$  is selected here to do the proof.

**lemma**  $s<n := i>\cdot k = s\cdot k$   
**by**  $simp$

Still there is no inter-statespace distinctness.

**lemma**  $s<k := i>\cdot m = s\cdot m$

**oops**  
**end**

**statespace**  $merge-vars1-vars2 = vars1 + vars2$

```
context merge-vars1-vars2
begin
```

When defining a statespace instead of a side-by-side locale we get the distinctness of all variables.

```
lemma  $s < k := i > \cdot m = s \cdot m$ 
  by simp
end
```

## 6.1 Benchmarks

Here are some bigger examples for benchmarking.

```
ML <
  fun make-benchmark n =
    writeln (Active.sendback-markup-command
      (statespace benchmark ^ string-of-int n ^ "\n ^
        (cat-lines (map (fn i => A ^ string-of-int i ^ "::nat) (1 upto n)))));
  >
```

0.2s

```
statespace benchmark100 = A1::nat A2::nat A3::nat A4::nat A5::nat
A6::nat A7::nat A8::nat A9::nat A10::nat A11::nat A12::nat A13::nat
A14::nat A15::nat A16::nat A17::nat A18::nat A19::nat A20::nat
A21::nat A22::nat A23::nat A24::nat A25::nat A26::nat A27::nat
A28::nat A29::nat A30::nat A31::nat A32::nat A33::nat A34::nat
A35::nat A36::nat A37::nat A38::nat A39::nat A40::nat A41::nat
A42::nat A43::nat A44::nat A45::nat A46::nat A47::nat A48::nat
A49::nat A50::nat A51::nat A52::nat A53::nat A54::nat A55::nat
A56::nat A57::nat A58::nat A59::nat A60::nat A61::nat A62::nat
A63::nat A64::nat A65::nat A66::nat A67::nat A68::nat A69::nat
A70::nat A71::nat A72::nat A73::nat A74::nat A75::nat A76::nat
A77::nat A78::nat A79::nat A80::nat A81::nat A82::nat A83::nat
A84::nat A85::nat A86::nat A87::nat A88::nat A89::nat A90::nat
A91::nat A92::nat A93::nat A94::nat A95::nat A96::nat A97::nat
A98::nat A99::nat A100::nat
```

2.4s

```
statespace benchmark500 = A1::nat A2::nat A3::nat A4::nat A5::nat
A6::nat A7::nat A8::nat A9::nat A10::nat A11::nat A12::nat A13::nat
A14::nat A15::nat A16::nat A17::nat A18::nat A19::nat A20::nat
A21::nat A22::nat A23::nat A24::nat A25::nat A26::nat A27::nat
A28::nat A29::nat A30::nat A31::nat A32::nat A33::nat A34::nat
A35::nat A36::nat A37::nat A38::nat A39::nat A40::nat A41::nat
A42::nat A43::nat A44::nat A45::nat A46::nat A47::nat A48::nat
A49::nat A50::nat A51::nat A52::nat A53::nat A54::nat A55::nat
A56::nat A57::nat A58::nat A59::nat A60::nat A61::nat A62::nat
A63::nat A64::nat A65::nat A66::nat A67::nat A68::nat A69::nat
A70::nat A71::nat A72::nat A73::nat A74::nat A75::nat A76::nat
```

[illegible]



*A420::nat A421::nat A422::nat A423::nat A424::nat A425::nat A426::nat  
A427::nat A428::nat A429::nat A430::nat A431::nat A432::nat A433::nat  
A434::nat A435::nat A436::nat A437::nat A438::nat A439::nat A440::nat  
A441::nat A442::nat A443::nat A444::nat A445::nat A446::nat A447::nat  
A448::nat A449::nat A450::nat A451::nat A452::nat A453::nat A454::nat  
A455::nat A456::nat A457::nat A458::nat A459::nat A460::nat A461::nat  
A462::nat A463::nat A464::nat A465::nat A466::nat A467::nat A468::nat  
A469::nat A470::nat A471::nat A472::nat A473::nat A474::nat A475::nat  
A476::nat A477::nat A478::nat A479::nat A480::nat A481::nat A482::nat  
A483::nat A484::nat A485::nat A486::nat A487::nat A488::nat A489::nat  
A490::nat A491::nat A492::nat A493::nat A494::nat A495::nat A496::nat  
A497::nat A498::nat A499::nat A500::nat*

9.0s

**statespace** *benchmark1000 = A1::nat A2::nat A3::nat A4::nat A5::nat  
A6::nat A7::nat A8::nat A9::nat A10::nat A11::nat A12::nat A13::nat  
A14::nat A15::nat A16::nat A17::nat A18::nat A19::nat A20::nat  
A21::nat A22::nat A23::nat A24::nat A25::nat A26::nat A27::nat  
A28::nat A29::nat A30::nat A31::nat A32::nat A33::nat A34::nat  
A35::nat A36::nat A37::nat A38::nat A39::nat A40::nat A41::nat  
A42::nat A43::nat A44::nat A45::nat A46::nat A47::nat A48::nat  
A49::nat A50::nat A51::nat A52::nat A53::nat A54::nat A55::nat  
A56::nat A57::nat A58::nat A59::nat A60::nat A61::nat A62::nat  
A63::nat A64::nat A65::nat A66::nat A67::nat A68::nat A69::nat  
A70::nat A71::nat A72::nat A73::nat A74::nat A75::nat A76::nat  
A77::nat A78::nat A79::nat A80::nat A81::nat A82::nat A83::nat  
A84::nat A85::nat A86::nat A87::nat A88::nat A89::nat A90::nat  
A91::nat A92::nat A93::nat A94::nat A95::nat A96::nat A97::nat  
A98::nat A99::nat A100::nat A101::nat A102::nat A103::nat A104::nat  
A105::nat A106::nat A107::nat A108::nat A109::nat A110::nat A111::nat  
A112::nat A113::nat A114::nat A115::nat A116::nat A117::nat A118::nat  
A119::nat A120::nat A121::nat A122::nat A123::nat A124::nat A125::nat  
A126::nat A127::nat A128::nat A129::nat A130::nat A131::nat A132::nat  
A133::nat A134::nat A135::nat A136::nat A137::nat A138::nat A139::nat  
A140::nat A141::nat A142::nat A143::nat A144::nat A145::nat A146::nat  
A147::nat A148::nat A149::nat A150::nat A151::nat A152::nat A153::nat  
A154::nat A155::nat A156::nat A157::nat A158::nat A159::nat A160::nat  
A161::nat A162::nat A163::nat A164::nat A165::nat A166::nat A167::nat  
A168::nat A169::nat A170::nat A171::nat A172::nat A173::nat A174::nat  
A175::nat A176::nat A177::nat A178::nat A179::nat A180::nat A181::nat  
A182::nat A183::nat A184::nat A185::nat A186::nat A187::nat A188::nat  
A189::nat A190::nat A191::nat A192::nat A193::nat A194::nat A195::nat  
A196::nat A197::nat A198::nat A199::nat A200::nat A201::nat A202::nat  
A203::nat A204::nat A205::nat A206::nat A207::nat A208::nat A209::nat  
A210::nat A211::nat A212::nat A213::nat A214::nat A215::nat A216::nat  
A217::nat A218::nat A219::nat A220::nat A221::nat A222::nat A223::nat  
A224::nat A225::nat A226::nat A227::nat A228::nat A229::nat A230::nat  
A231::nat A232::nat A233::nat A234::nat A235::nat A236::nat A237::nat  
A238::nat A239::nat A240::nat A241::nat A242::nat A243::nat A244::nat*

[illegible]

[illegible]

*A931::nat A932::nat A933::nat A934::nat A935::nat A936::nat A937::nat*  
*A938::nat A939::nat A940::nat A941::nat A942::nat A943::nat A944::nat*  
*A945::nat A946::nat A947::nat A948::nat A949::nat A950::nat A951::nat*  
*A952::nat A953::nat A954::nat A955::nat A956::nat A957::nat A958::nat*  
*A959::nat A960::nat A961::nat A962::nat A963::nat A964::nat A965::nat*  
*A966::nat A967::nat A968::nat A969::nat A970::nat A971::nat A972::nat*  
*A973::nat A974::nat A975::nat A976::nat A977::nat A978::nat A979::nat*  
*A980::nat A981::nat A982::nat A983::nat A984::nat A985::nat A986::nat*  
*A987::nat A988::nat A989::nat A990::nat A991::nat A992::nat A993::nat*  
*A994::nat A995::nat A996::nat A997::nat A998::nat A999::nat A1000::nat*

**lemma** (in benchmark100) test:  $s \langle A1 := a \rangle \cdot A100 = s \cdot A100$  **by** simp  
**lemma** (in benchmark500) test:  $s \langle A1 := a \rangle \cdot A100 = s \cdot A100$  **by** simp  
**lemma** (in benchmark1000) test:  $s \langle A1 := a \rangle \cdot A100 = s \cdot A100$  **by** simp

**end**