

The Unified Policy Framework (UPF)

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Abstract

We present the *Unified Policy Framework* (UPF), a generic framework for modelling security (access-control) policies; in Isabelle/HOL. UPF emphasizes the view that a policy is a policy decision function that grants or denies access to resources, permissions, etc. In other words, instead of modelling the relations of permitted or prohibited requests directly, we model the concrete function that implements the policy decision point in a system, seen as an “aspect” of “wrapper” around the business logic of a system. In more detail, UPF is based on the following four principles: 1. Functional representation of policies, 2. No conflicts are possible, 3. Three-valued decision type (allow, deny, undefined), 4. Output type not containing the decision only.

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1 Introduction

Access control, i. e., restricting the access to information or resources, is an important pillar of today’s information security portfolio. Thus the large number of access control models (e. g., [1, 5, 6, 15–17, 19, 21]) and variants thereof (e. g., [2, 2, 4, 7, 14, 18, 22]) is not surprising. On the one hand, this variety of specialized access control models allows concise representation of access control policies. On the other hand, the lack of a common foundations makes it difficult to compare and analyze different access control models formally.

We present formalization of the Unified Policy Framework (UPF) [13] that provides a formal semantics for the core concepts of access control policies. It can serve as a meta-model for a large set of well-known access control policies and moreover, serve as a framework for analysis and test generation tools addressing common ground in policy models. Thus, UPF for comparing different access control models, including a formal correctness proof of a specific embedding, for example, implementing a role-based access control policy in terms of a discretionary access enforcement architecture. Moreover, defining well-known access control models by instantiating a unified policy framework allows to re-use tools, such as test-case generators, that are already provided for the unified policy framework. As the instantiation of a unified policy framework may also define a domain-specific (i. e., access control model specific) set of policy combinators (syntax), such an approach still provides the usual notations and thus a concise representation of access control policies.

UPF was already successful used as a basis for large scale access control policies in the health care domain [10] as well as in the domain of firewall and router policies [12]. In both domains, the formal policy specifications served as basis for the generation, using HOL-TestGen [9], of test cases that can be used for validating the compliance of an implementation to the formal model. UPF is based on the following four principles:

1. policies are represented as *functions* (rather than relations),
2. policy combination avoids conflicts by construction,
3. the decision type is three-valued (allow, deny, undefined),
4. the output type does not only contain the decision but also a ‘slot’ for arbitrary result data.

UPF is related to the state-exception monad modeling failing computations; in some cases our UPF model makes explicit use of this connection, although it is not central. The used theory for state-exception monads can be found in the appendix.

2 The Unified Policy Framework (UPF)

2.1 The Core of the Unified Policy Framework (UPF)

```
theory  
  UPFCore  
  imports  
    Monads  
begin
```

2.1.1 Foundation

The purpose of this theory is to formalize a somewhat non-standard view on the fundamental concept of a security policy which is worth outlining. This view has arisen from prior experience in the modelling of network (firewall) policies. Instead of regarding policies as relations on resources, sets of permissions, etc., we emphasise the view that a policy is a policy decision function that grants or denies access to resources, permissions, etc. In other words, we model the concrete function that implements the policy decision point in a system, and which represents a "wrapper" around the business logic. An advantage of this view is that it is compatible with many different policy models, enabling a uniform modelling framework to be defined. Furthermore, this function is typically a large cascade of nested conditionals, using conditions referring to an internal state and security contexts of the system or a user. This cascade of conditionals can easily be decomposed into a set of test cases similar to transformations used for binary decision diagrams (BDD), and motivate equivalence class testing for unit test and sequence test scenarios. From the modelling perspective, using HOL as its input language, we will consequently use the expressive power of its underlying functional programming language, including the possibility to define higher-order combinators.

In more detail, we model policies as partial functions based on input data α (arguments, system state, security context, ...) to output data β :

```
datatype 'a decision = allow 'a | deny 'a
```

```
type-synonym ('a,'b) policy = 'a  $\rightarrow$  'b decision (infixr  $|-\>$  0)
```

In the following, we introduce a number of shortcuts and alternative notations. The type of policies is represented as:

```
translations (type) 'a  $|-\>$  'b  $\leq$  (type) 'a  $\rightarrow$  'b decision  
type-notation policy (infixr  $\mapsto$  0)
```

... allowing the notation $'\alpha \mapsto '\beta$ for the policy type and the alternative notations for *None* and *Some* of the HOLlibrary $'\alpha$ *option* type:

notation *None* (\perp)

notation *Some* ($[-]$ *80*)

Thus, the range of a policy may consist of $[accept\ x]$ data, of $[deny\ x]$ data, as well as \perp modeling the undefinedness of a policy, i.e. a policy is considered as a partial function. Partial functions are used since we describe elementary policies by partial system behaviour, which are glued together by operators such as function override and functional composition.

We define the two fundamental sets, the allow-set *Allow* and the deny-set *Deny* (written *A* and *D* set for short), to characterize these two main sets of the range of a policy.

definition *Allow* :: ($'\alpha$ *decision*) *set*

where *Allow* = *range allow*

definition *Deny* :: ($'\alpha$ *decision*) *set*

where *Deny* = *range deny*

2.1.2 Policy Constructors

Most elementary policy constructors are based on the update operation *Fun.fun-upd-def* $?f(?a := ?b) = (\lambda x. \text{if } x = ?a \text{ then } ?b \text{ else } ?f\ x)$ and the maplet-notation $a(x \mapsto y)$ used for $a(x \mapsto y)$.

Furthermore, we add notation adopted to our problem domain:

nonterminal *policylets* and *policylet*

syntax

-policylet1 :: [$'a, 'a$] => *policylet* ($- / \mapsto_+ / -$)

-policylet2 :: [$'a, 'a$] => *policylet* ($- / \mapsto_- / -$)

:: *policylet* => *policylets* ($-$)

-Maplets :: [*policylet*, *policylets*] => *policylets* ($- / -$)

-Maplets :: [*policylet*, *policylets*] => *policylets* ($- / -$)

-MapUpd :: [$'a \mid \rightarrow 'b$, *policylets*] => $'a \mid \rightarrow 'b$ ($- / (-)$ [900,0]900)

-emptypolicy :: $'a \mid \rightarrow 'b$ (\emptyset)

translations

-MapUpd m (-Maplets xy ms) \equiv *-MapUpd (-MapUpd m xy) ms*

-MapUpd m (-policylet1 x y) \equiv $m(x := \text{CONST Some (CONST allow y)})$

-MapUpd m (-policylet2 x y) \equiv $m(x := \text{CONST Some (CONST deny y)})$

\emptyset \equiv *CONST Map.empty*

Here are some lemmas essentially showing syntactic equivalences:

lemma test: $\emptyset(x \mapsto_+ a, y \mapsto_- b) = \emptyset(x \mapsto_+ a, y \mapsto_- b)$ **by simp**

lemma test2: $p(x \mapsto_+ a, x \mapsto_- b) = p(x \mapsto_- b)$ **by** *simp*

We inherit a fairly rich theory on policy updates from Map here. Some examples are:

lemma pol-upd-triv1: $t\ k = \lfloor \text{allow } x \rfloor \implies t(k \mapsto_+ x) = t$
by (*rule ext*) *simp*

lemma pol-upd-triv2: $t\ k = \lfloor \text{deny } x \rfloor \implies t(k \mapsto_- x) = t$
by (*rule ext*) *simp*

lemma pol-upd-allow-nonempty: $t(k \mapsto_+ x) \neq \emptyset$
by *simp*

lemma pol-upd-deny-nonempty: $t(k \mapsto_- x) \neq \emptyset$
by *simp*

lemma pol-upd-eqD1 : $m(a \mapsto_+ x) = n(a \mapsto_+ y) \implies x = y$
by(*auto dest: map-upd-eqD1*)

lemma pol-upd-eqD2 : $m(a \mapsto_- x) = n(a \mapsto_- y) \implies x = y$
by(*auto dest: map-upd-eqD1*)

lemma pol-upd-neq1 [*simp*]: $m(a \mapsto_+ x) \neq n(a \mapsto_- y)$
by(*auto dest: map-upd-eqD1*)

2.1.3 Override Operators

Key operators for constructing policies are the override operators. There are four different versions of them, with one of them being the override operator from the Map theory. As it is common to compose policy rules in a “left-to-right-first-fit”-manner, that one is taken as default, defined by a syntax translation from the provided override operator from the Map theory (which does it in reverse order).

syntax

-policyoverride $:: ['a \mapsto 'b, 'a \mapsto 'b] \Rightarrow 'a \mapsto 'b$ (**infixl** \oplus 100)

translations

$p \oplus q \equiv q ++ p$

Some elementary facts inherited from Map are:

lemma override-empty: $p \oplus \emptyset = p$
by *simp*

lemma empty-override: $\emptyset \oplus p = p$
by *simp*

lemma *override-assoc*: $p1 \oplus (p2 \oplus p3) = (p1 \oplus p2) \oplus p3$
by *simp*

The following two operators are variants of the standard override. For *override_A*, an allow of wins over a deny. For *override_D*, the situation is dual.

definition *override-A* :: $['\alpha \mapsto '\beta, '\alpha \mapsto '\beta] \Rightarrow '\alpha \mapsto '\beta$ (**infixl** $++$ -A 100)
where $m2 ++\text{-}A m1 =$
 $(\lambda x. (\text{case } m1 \text{ } x \text{ of}$
 $\quad [allow \ a] \Rightarrow [allow \ a]$
 $\quad | [deny \ a] \Rightarrow (\text{case } m2 \text{ } x \text{ of } [allow \ b] \Rightarrow [allow \ b]$
 $\quad \quad \quad | - \Rightarrow [deny \ a])$
 $\quad | \perp \Rightarrow m2 \ x)$
 $)$

syntax

-policyoverride-A :: $['a \mapsto 'b, 'a \mapsto 'b] \Rightarrow 'a \mapsto 'b$ (**infixl** \oplus_A 100)

translations

$p \oplus_A q \Rightarrow p ++\text{-}A q$

lemma *override-A-empty[simp]*: $p \oplus_A \emptyset = p$
by (*simp add: override-A-def*)

lemma *empty-override-A[simp]*: $\emptyset \oplus_A p = p$
apply (*rule ext*)
apply (*simp add: override-A-def*)
subgoal for x
apply (*case-tac p x*)
apply (*simp-all*)
subgoal for a
apply (*case-tac a*)
apply (*simp-all*)
done
done
done

lemma *override-A-assoc*: $p1 \oplus_A (p2 \oplus_A p3) = (p1 \oplus_A p2) \oplus_A p3$
by (*rule ext, simp add: override-A-def split: decision.splits option.splits*)

definition *override-D* :: $['\alpha \mapsto '\beta, '\alpha \mapsto '\beta] \Rightarrow '\alpha \mapsto '\beta$ (**infixl** $++$ -D 100)
where $m1 ++\text{-}D m2 =$
 $(\lambda x. \text{case } m2 \text{ } x \text{ of}$
 $\quad [deny \ a] \Rightarrow [deny \ a]$
 $\quad | [allow \ a] \Rightarrow (\text{case } m1 \text{ } x \text{ of } [deny \ b] \Rightarrow [deny \ b]$
 $\quad \quad \quad | - \Rightarrow [allow \ a])$
 $)$

```

    | - ⇒ [allow a])
  | ⊥ ⇒ m1 x
)

```

syntax

```
-policyoverride-D :: ['a ↦ 'b, 'a ↦ 'b] ⇒ 'a ↦ 'b (infixl ⊕D 100)
```

translations

```
p ⊕D q ⇒ p ++-D q
```

lemma *override-D-empty*[simp]: $p \oplus_D \emptyset = p$
by(simp add:override-D-def)

lemma *empty-override-D*[simp]: $\emptyset \oplus_D p = p$

apply (rule ext)

apply (simp add:override-D-def)

subgoal for x

apply (case-tac p x, simp-all)

subgoal for a

apply (case-tac a, simp-all)

done

done

done

lemma *override-D-assoc*: $p1 \oplus_D (p2 \oplus_D p3) = (p1 \oplus_D p2) \oplus_D p3$

apply (rule ext)

apply (simp add: override-D-def split: decision.splits option.splits)

done

2.1.4 Coercion Operators

Often, especially when combining policies of different type, it is necessary to adapt the input or output domain of a policy to a more refined context.

An analogous for the range of a policy is defined as follows:

definition *policy-range-comp* :: $['\beta \Rightarrow '\gamma, '\alpha \mapsto '\beta] \Rightarrow '\alpha \mapsto '\gamma$ (infixl *o'-f* 55)

where

```
f o-f p = (λx. case p x of
  [allow y] ⇒ [allow (f y)]
| [deny y] ⇒ [deny (f y)]
| ⊥ ⇒ ⊥)

```

syntax

```
-policy-range-comp :: ['β ⇒ 'γ, 'α ↦ 'β] ⇒ 'α ↦ 'γ (infixl of 55)
```

translations

$$p \text{ o}_f q \Rightarrow p \text{ o-f } q$$

lemma *policy-range-comp-strict* : $f \text{ o}_f \emptyset = \emptyset$
apply (*rule ext*)
apply (*simp add: policy-range-comp-def*)
done

A generalized version is, where separate coercion functions are applied to the result depending on the decision of the policy is as follows:

definition *range-split* :: $[('\beta \Rightarrow '\gamma) \times ('\beta \Rightarrow '\gamma), '\alpha \mapsto '\beta] \Rightarrow '\alpha \mapsto '\gamma$
(infixr ∇ *100*)

where $(P) \nabla p = (\lambda x. \text{ case } p \text{ x of}$
 $\quad [allow \ y] \Rightarrow [allow \ ((fst \ P) \ y)]$
 $\quad | [deny \ y] \Rightarrow [deny \ ((snd \ P) \ y)]$
 $\quad | \perp \quad \quad \Rightarrow \perp)$

lemma *range-split-strict*[*simp*]: $P \nabla \emptyset = \emptyset$
apply (*rule ext*)
apply (*simp add: range-split-def*)
done

lemma *range-split-charn*:

$(f, g) \nabla p = (\lambda x. \text{ case } p \text{ x of}$
 $\quad [allow \ x] \Rightarrow [allow \ (f \ x)]$
 $\quad | [deny \ x] \Rightarrow [deny \ (g \ x)]$
 $\quad | \perp \quad \quad \Rightarrow \perp)$

apply (*simp add: range-split-def*)
apply (*rule ext*)
subgoal for x
apply (*case-tac p x*)
apply (*simp-all*)
subgoal for a
apply (*case-tac a*)
apply (*simp-all*)
done
done
done

The connection between these two becomes apparent if considering the following lemma:

lemma *range-split-vs-range-compose*: $(f, f) \nabla p = f \text{ o}_f p$
by(*simp add: range-split-charn policy-range-comp-def*)

```

lemma range-split-id [simp]: (id, id)  $\nabla$  p = p
  apply (rule ext)
  apply (simp add: range-split-charn id-def)
  subgoal for x
    apply (case-tac p x)
    apply (simp-all)
  subgoal for a
    apply (case-tac a)
    apply (simp-all)
  done
done
done

```

```

lemma range-split-bi-compose [simp]: (f1, f2)  $\nabla$  (g1, g2)  $\nabla$  p = (f1 o g1, f2 o g2)  $\nabla$  p
  apply (rule ext)
  apply (simp add: range-split-charn comp-def)
  subgoal for x
    apply (case-tac p x)
    apply (simp-all)
  subgoal for a
    apply (case-tac a)
    apply (simp-all)
  done
done
done

```

The next three operators are rather exotic and in most cases not used.

The following is a variant of `range_split`, where the change in the decision depends on the input instead of the output.

definition *dom-split2a* :: [$'\alpha \rightarrow '\gamma$] \times [$'\alpha \rightarrow '\gamma$], $'\alpha \mapsto '\beta$] \Rightarrow $'\alpha \mapsto '\gamma$ (**infixr** Δa 100)

where $P \Delta a p = (\lambda x. \text{case } p \text{ } x \text{ of}$
 $\quad [allow \ y] \Rightarrow [allow \ (the \ ((fst \ P) \ x))]$
 $\quad | [deny \ y] \Rightarrow [deny \ (the \ ((snd \ P) \ x))]$
 $\quad | \perp \quad \quad \Rightarrow \perp)$

definition *dom-split2* :: [$'\alpha \Rightarrow '\gamma$] \times [$'\alpha \Rightarrow '\gamma$], $'\alpha \mapsto '\beta$] \Rightarrow $'\alpha \mapsto '\gamma$ (**infixr** Δ 100)

where $P \Delta p = (\lambda x. \text{case } p \text{ } x \text{ of}$
 $\quad [allow \ y] \Rightarrow [allow \ ((fst \ P) \ x)]$
 $\quad | [deny \ y] \Rightarrow [deny \ ((snd \ P) \ x)]$
 $\quad | \perp \quad \quad \Rightarrow \perp)$

definition *range-split2* :: [$'\alpha \Rightarrow '\gamma$] \times [$'\alpha \Rightarrow '\gamma$], $'\alpha \mapsto '\beta$] \Rightarrow $'\alpha \mapsto (' \beta \times '\gamma)$ (**infixr** $\nabla 2$)

100)

where $P \nabla 2 p = (\lambda x. \text{case } p \text{ } x \text{ of}$
 $\quad \lfloor \text{allow } y \rfloor \Rightarrow \lfloor \text{allow } (y, (\text{fst } P) \ x) \rfloor$
 $\quad \mid \lfloor \text{deny } y \rfloor \Rightarrow \lfloor \text{deny } (y, (\text{snd } P) \ x) \rfloor$
 $\quad \mid \perp \quad \quad \Rightarrow \perp)$

The following operator is used for transition policies only: a transition policy is transformed into a state-exception monad. Such a monad can for example be used for test case generation using HOL-Testgen [9].

definition $\text{policy2MON} :: ('i \times 'o \rightarrow 'o \times 'o) \Rightarrow ('i \Rightarrow ('o \text{ decision}, 'o) \text{ MON}_{SE})$

where $\text{policy2MON } p = (\lambda \iota \sigma. \text{case } p \ (\iota, \sigma) \text{ of}$
 $\quad \lfloor (\text{allow } (\text{outs}, \sigma')) \rfloor \Rightarrow \lfloor (\text{allow } \text{outs}, \sigma') \rfloor$
 $\quad \mid \lfloor (\text{deny } (\text{outs}, \sigma')) \rfloor \Rightarrow \lfloor (\text{deny } \text{outs}, \sigma') \rfloor$
 $\quad \mid \perp \quad \quad \quad \Rightarrow \perp)$

lemmas $\text{UPFCoreDefs} = \text{Allow-def } \text{Deny-def } \text{override-A-def } \text{override-D-def } \text{policy-range-comp-def}$

$\text{range-split-def } \text{dom-split2-def } \text{map-add-def } \text{restrict-map-def}$

end

2.2 Elementary Policies

theory

ElementaryPolicies

imports

UPFCore

begin

In this theory, we introduce the elementary policies of UPF that build the basis for more complex policies. These complex policies, respectively, embedding of well-known access control or security models, are build by composing the elementary policies defined in this theory.

2.2.1 The Core Policy Combinators: Allow and Deny Everything

definition

$\text{deny-pfun} \quad :: ('o \rightarrow 'o) \Rightarrow ('o \rightarrow 'o) \ (\text{AllD})$

where

$\text{deny-pfun } pf \equiv (\lambda x. \text{case } pf \ x \text{ of}$
 $\quad \lfloor y \rfloor \Rightarrow \lfloor \text{deny } (y) \rfloor$
 $\quad \mid \perp \Rightarrow \perp)$

definition

$\text{allow-pfun} \quad :: ('o \rightarrow 'o) \Rightarrow ('o \rightarrow 'o) \ (\text{AllA})$

where

$allow\text{-}pfun\ pf \equiv (\lambda\ x.\ case\ pf\ x\ of$
 $\ [y] \Rightarrow [allow\ (y)]$
 $|\perp \Rightarrow \perp)$

syntax

$\text{-}allow\text{-}pfun\ :: ('\alpha \multimap '\beta) \Rightarrow ('\alpha \mapsto '\beta)\ (A_p)$

translations

$A_p\ f \equiv AllA\ f$

syntax

$\text{-}deny\text{-}pfun\ :: ('\alpha \multimap '\beta) \Rightarrow ('\alpha \mapsto '\beta)\ (D_p)$

translations

$D_p\ f \equiv AllD\ f$

notation

$deny\text{-}pfun$ (**binder** $\forall D\ 10$) **and**
 $allow\text{-}pfun$ (**binder** $\forall A\ 10$)

lemma $AllD\text{-}norm[simp]$: $deny\text{-}pfun\ (id\ o\ (\lambda x.\ [x])) = (\forall Dx.\ [x])$
by($simp\ add:id\text{-}def\ comp\text{-}def$)

lemma $AllD\text{-}norm2[simp]$: $deny\text{-}pfun\ (Some\ o\ id) = (\forall Dx.\ [x])$
by($simp\ add:id\text{-}def\ comp\text{-}def$)

lemma $AllA\text{-}norm[simp]$: $allow\text{-}pfun\ (id\ o\ Some) = (\forall Ax.\ [x])$
by($simp\ add:id\text{-}def\ comp\text{-}def$)

lemma $AllA\text{-}norm2[simp]$: $allow\text{-}pfun\ (Some\ o\ id) = (\forall Ax.\ [x])$
by($simp\ add:id\text{-}def\ comp\text{-}def$)

lemma $AllA\text{-}apply[simp]$: $(\forall Ax.\ Some\ (P\ x))\ x = [allow\ (P\ x)]$
by($simp\ add:allow\text{-}pfun\text{-}def$)

lemma $AllD\text{-}apply[simp]$: $(\forall Dx.\ Some\ (P\ x))\ x = [deny\ (P\ x)]$
by($simp\ add:deny\text{-}pfun\text{-}def$)

lemma $neg\text{-}Allow\text{-}Deny$: $pf \neq \emptyset \implies (deny\text{-}pfun\ pf) \neq (allow\text{-}pfun\ pf)$

apply ($erule\ contrapos\text{-}nn$)

apply ($rule\ ext$)

subgoal for x

apply ($drule\text{-}tac\ x=x\ in\ fun\text{-}cong$)

apply ($auto\ simp: deny\text{-}pfun\text{-}def\ allow\text{-}pfun\text{-}def$)

apply ($case\text{-}tac\ pf\ x = \perp$)

```

    apply (auto)
  done
done

```

2.2.2 Common Instances

definition *allow-all-fun* :: ($'\alpha \Rightarrow '\beta$) \Rightarrow ($'\alpha \mapsto '\beta$) (A_f)
where *allow-all-fun* $f = \text{allow-pfun } (\text{Some } o f)$

definition *deny-all-fun* :: ($'\alpha \Rightarrow '\beta$) \Rightarrow ($'\alpha \mapsto '\beta$) (D_f)
where *deny-all-fun* $f \equiv \text{deny-pfun } (\text{Some } o f)$

definition
deny-all-id :: $'\alpha \mapsto '\alpha$ (D_I) **where**
deny-all-id $\equiv \text{deny-pfun } (\text{id } o \text{Some})$

definition
allow-all-id :: $'\alpha \mapsto '\alpha$ (A_I) **where**
allow-all-id $\equiv \text{allow-pfun } (\text{id } o \text{Some})$

definition
allow-all :: ($'\alpha \mapsto \text{unit}$) (A_U) **where**
allow-all $p = \lfloor \text{allow } () \rfloor$

definition
deny-all :: ($'\alpha \mapsto \text{unit}$) (D_U) **where**
deny-all $p = \lfloor \text{deny } () \rfloor$

... and resulting properties:

lemma $A_I \oplus \text{Map.empty} = A_I$
by *simp*

lemma $A_f f \oplus \text{Map.empty} = A_f f$
by *simp*

lemma $\text{allow-pfun } \text{Map.empty} = \text{Map.empty}$
apply (*rule ext*)
apply (*simp add: allow-pfun-def*)
done

lemma $\text{allow-left-cancel} : \text{dom } pf = \text{UNIV} \implies (\text{allow-pfun } pf) \oplus x = (\text{allow-pfun } pf)$

```

    apply (rule ext)+
    apply (auto simp: allow-pfun-def option.splits)

```


done

lemma *deny-left-cancel* : $dom\ pf = UNIV \implies (deny\text{-}pfun\ pf) \oplus x = (deny\text{-}pfun\ pf)$
 apply (*rule ext*)
 by (*auto simp: deny-pfun-def option.splits*)

2.2.3 Domain, Range, and Restrictions

Since policies are essentially maps, we inherit the basic definitions for domain and range on Maps:

`Map.dom_def` : $dom\ ?m = \{a. ?m\ a \neq \perp\}$

whereas `range` is just an abbreviation for image:

```
abbreviation range :: "('a => 'b) => 'b set"
  where -- "of function"  "range f == f ` UNIV"
```

As a consequence, we inherit the following properties on policies:

- `Map.domD` $?a \in dom\ ?m \implies \exists b. ?m\ ?a = [b]$
- `Map.domI` $?m\ ?a = [?b] \implies ?a \in dom\ ?m$
- `Map.domIff` $(?a \in dom\ ?m) = (?m\ ?a \neq \perp)$
- `Map.dom_const` $dom\ (\lambda x. [?f\ x]) = UNIV$
- `Map.dom_def` $dom\ ?m = \{a. ?m\ a \neq \perp\}$
- `Map.dom_empty` $dom\ (\lambda x. \perp) = \{\}$
- `Map.dom_eq_empty_conv` $(dom\ ?f = \{\}) = (?f = (\lambda x. \perp))$
- `Map.dom_eq_singleton_conv` $(dom\ ?f = \{?x\}) = (\exists v. ?f = [?x \mapsto v])$
- `Map.dom_fun_upd` $dom\ (?f(?x := ?y)) = (if\ ?y = \perp\ then\ dom\ ?f - \{?x\}\ else\ insert\ ?x\ (dom\ ?f))$
- `Map.dom_if` $dom\ (\lambda x. if\ ?P\ x\ then\ ?f\ x\ else\ ?g\ x) = dom\ ?f \cap \{x. ?P\ x\} \cup dom\ ?g \cap \{x. \neg\ ?P\ x\}$
- `Map.dom_map_add` $dom\ (?n \oplus ?m) = dom\ ?n \cup dom\ ?m$

However, some properties are specific to policy concepts:

lemma *sub-ran* : $ran\ p \subseteq Allow \cup Deny$

apply (*auto simp: Allow-def Deny-def ran-def full-SetCompr-eq[symmetric]*)[1]

subgoal for $x\ a$

```

  apply (case-tac x)
  apply (simp-all)
done
done

```

```

lemma dom-allow-pfun [simp]: dom(allow-pfun f) = dom f
  apply (auto simp: allow-pfun-def)
  subgoal for x y
    apply (case-tac f x, simp-all)
    done
  done

```

```

lemma dom-allow-all: dom(Af f) = UNIV
  by(auto simp: allow-all-fun-def o-def)

```

```

lemma dom-deny-pfun [simp]: dom(deny-pfun f) = dom f
  apply (auto simp: deny-pfun-def)[1]
  apply (case-tac f x)
  apply (simp-all)
done

```

```

lemma dom-deny-all: dom(Df f) = UNIV
  by(auto simp: deny-all-fun-def o-def)

```

```

lemma ran-allow-pfun [simp]: ran(allow-pfun f) = allow (ran f)
  apply (simp add: allow-pfun-def ran-def)
  apply (rule set-eqI)
  apply (auto)[1]
  subgoal for x a
    apply (case-tac f a)
    apply (auto simp: image-def)[1]
    apply (auto simp: image-def)[1]
    done
  subgoal for xa a
    apply (rule-tac x=a in exI)
    apply (simp)
    done
  done

```

```

lemma ran-allow-all: ran(Af id) = Allow
  apply (simp add: allow-all-fun-def Allow-def o-def)
  apply (rule set-eqI)
  apply (auto simp: image-def ran-def)
done

```

```

lemma ran-deny-pfun[simp]: ran(deny-pfun f) = deny ` (ran f)
  apply (simp add: deny-pfun-def ran-def)
  apply (rule set-eqI)
  apply (auto)[1]
  subgoal for x a
    apply (case-tac f a)
    apply (auto simp: image-def)[1]
    apply (auto simp: image-def)[1]
    done
  subgoal for xa a
    apply (rule-tac x=a in exI)
    apply (simp)
    done
  done

```

```

lemma ran-deny-all: ran(Df id) = Deny
  apply (simp add: deny-all-fun-def Deny-def o-def)
  apply (rule set-eqI)
  apply (auto simp: image-def ran-def)
  done

```

Reasoning over `dom` is most crucial since it paves the way for simplification and reordering of policies composed by `override` (i.e. by the normal left-to-right rule composition method).

- $\text{Map.dom_map_add } \text{dom } (?n \oplus ?m) = \text{dom } ?n \cup \text{dom } ?m$
- $\text{Map.inj_on_map_add_dom } \text{inj-on } (?m' \oplus ?m) (\text{dom } ?m') = \text{inj-on } ?m' (\text{dom } ?m')$
- $\text{Map.map_add_comm } \text{dom } ?m1.0 \cap \text{dom } ?m2.0 = \{\} \implies ?m2.0 \oplus ?m1.0 = ?m1.0 \oplus ?m2.0$
- $\text{Map.map_add_dom_app_simps}(1) ?m \in \text{dom } ?l2.0 \implies (?l2.0 \oplus ?l1.0) ?m = ?l2.0 ?m$
- $\text{Map.map_add_dom_app_simps}(2) ?m \notin \text{dom } ?l1.0 \implies (?l2.0 \oplus ?l1.0) ?m = ?l2.0 ?m$
- $\text{Map.map_add_dom_app_simps}(3) ?m \notin \text{dom } ?l2.0 \implies (?l2.0 \oplus ?l1.0) ?m = ?l1.0 ?m$
- $\text{Map.map_add_upd_left } ?m \notin \text{dom } ?e2.0 \implies ?e2.0 \oplus ?e1.0(?m \mapsto ?u1.0) = (?e2.0 \oplus ?e1.0)(?m \mapsto ?u1.0)$

The latter rule also applies to `allow-` and `deny-override`.

definition *dom-restrict* :: [$'\alpha$ set, $'\alpha \mapsto '\beta$] \Rightarrow $'\alpha \mapsto '\beta$ (**infixr** \triangleleft 55)
where $S \triangleleft p \equiv (\lambda x. \text{if } x \in S \text{ then } p \ x \text{ else } \perp)$

lemma *dom-dom-restrict*[*simp*] : $\text{dom}(S \triangleleft p) = S \cap \text{dom } p$
apply (*auto simp: dom-restrict-def*)
subgoal for $x \ y$
apply (*case-tac* $x \in S$)
apply (*simp-all*)
done
subgoal for $x \ y$
apply (*case-tac* $x \in S$)
apply (*simp-all*)
done
done

lemma *dom-restrict-idem*[*simp*] : $(\text{dom } p) \triangleleft p = p$
apply (*rule ext*)
apply (*auto simp: dom-restrict-def*
dest: neq-commute[THEN iffD1, THEN not-None-eq [THEN iffD1]])
done

lemma *dom-restrict-inter*[*simp*] : $T \triangleleft S \triangleleft p = T \cap S \triangleleft p$
apply (*rule ext*)
apply (*auto simp: dom-restrict-def*
dest: neq-commute[THEN iffD1, THEN not-None-eq [THEN iffD1]])
done

definition *ran-restrict* :: [$'\alpha \mapsto '\beta, '\beta$ decision set] \Rightarrow $'\alpha \mapsto '\beta$ (**infixr** \triangleright 55)
where $p \triangleright S \equiv (\lambda x. \text{if } p \ x \in (\text{Some } S) \text{ then } p \ x \text{ else } \perp)$

definition *ran-restrict2* :: [$'\alpha \mapsto '\beta, '\beta$ decision set] \Rightarrow $'\alpha \mapsto '\beta$ (**infixr** $\triangleright 2$ 55)
where $p \triangleright 2 \ S \equiv (\lambda x. \text{if } (\text{the } (p \ x)) \in (S) \text{ then } p \ x \text{ else } \perp)$

lemma *ran-restrict = ran-restrict2*
apply (*rule ext*)
apply (*simp add: ran-restrict-def ran-restrict2-def*)
subgoal for $x \ x_a \ x_b$
apply (*case-tac* $x \ x_b$)
apply *simp-all*
apply (*metis inj-Some inj-image-mem-iff*)
done
done

```

lemma ran-ran-restrict[simp] :  $\text{ran}(p \triangleright S) = S \cap \text{ran } p$ 
  by(auto simp: ran-restrict-def image-def ran-def)

lemma ran-restrict-idem[simp] :  $p \triangleright (\text{ran } p) = p$ 
  apply (rule ext)
  apply (auto simp: ran-restrict-def image-def Ball-def ran-def)
  apply (erule contrapos-pp)
  apply (auto dest!: neq-commute[THEN iffD1, THEN not-None-eq [THEN iffD1]])
  done

lemma ran-restrict-inter[simp] :  $(p \triangleright S) \triangleright T = p \triangleright T \cap S$ 
  apply (rule ext)
  apply (auto simp: ran-restrict-def)
  dest: neq-commute[THEN iffD1, THEN not-None-eq [THEN iffD1]]
  done

lemma ran-gen-A[simp] :  $(\forall Ax. [P x]) \triangleright \text{Allow} = (\forall Ax. [P x])$ 
  apply (rule ext)
  apply (auto simp: Allow-def ran-restrict-def)
  done

lemma ran-gen-D[simp] :  $(\forall Dx. [P x]) \triangleright \text{Deny} = (\forall Dx. [P x])$ 
  apply (rule ext)
  apply (auto simp: Deny-def ran-restrict-def)
  done

lemmas ElementaryPoliciesDefs = deny-pfun-def allow-pfun-def allow-all-fun-def
deny-all-fun-def
allow-all-id-def deny-all-id-def allow-all-def deny-all-def
dom-restrict-def ran-restrict-def

end

```

2.3 Sequential Composition

```

theory
  SeqComposition
  imports
    ElementaryPolicies
begin

```

Sequential composition is based on the idea that two policies are to be combined by applying the second policy to the output of the first one. Again, there are four possibilities how the decisions can be combined.

2.3.1 Flattening

A key concept of sequential policy composition is the flattening of nested decisions. There are four possibilities, and these possibilities will give the various flavours of policy composition.

```
fun flat-orA :: ('α decision) decision ⇒ ('α decision)
where flat-orA(allow(allow y)) = allow y
      |flat-orA(allow(deny y)) = allow y
      |flat-orA(deny(allow y)) = allow y
      |flat-orA(deny(deny y)) = deny y
```

```
lemma flat-orA-deny[dest]: flat-orA x = deny y ⇒ x = deny(deny y)
apply (case-tac x)
apply (rename-tac α)
apply (case-tac α, simp-all)[1]
apply (rename-tac α)
apply (case-tac α, simp-all)[1]
done
```

```
lemma flat-orA-allow[dest]: flat-orA x = allow y ⇒ x = allow(allow y)
      ∨ x = allow(deny y)
      ∨ x = deny(allow y)

apply (case-tac x)
apply (rename-tac α)
apply (case-tac α, simp-all)[1]
apply (rename-tac α)
apply (case-tac α, simp-all)[1]
done
```

```
fun flat-orD :: ('α decision) decision ⇒ ('α decision)
where flat-orD(allow(allow y)) = allow y
      |flat-orD(allow(deny y)) = deny y
      |flat-orD(deny(allow y)) = deny y
      |flat-orD(deny(deny y)) = deny y
```

```
lemma flat-orD-allow[dest]: flat-orD x = allow y ⇒ x = allow(allow y)
apply (case-tac x)
apply (rename-tac α)
apply (case-tac α, simp-all)[1]
apply (rename-tac α)
apply (case-tac α, simp-all)[1]
done
```

```
lemma flat-orD-deny[dest]: flat-orD x = deny y ⇒ x = deny(deny y)
```

$\vee x = \text{allow}(\text{deny } y)$
 $\vee x = \text{deny}(\text{allow } y)$

```

apply (case-tac x)
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
done

```

```

fun flat-1 :: (' $\alpha$  decision) decision  $\Rightarrow$  (' $\alpha$  decision)
where flat-1 (allow (allow y)) = allow y
      |flat-1 (allow (deny y)) = allow y
      |flat-1 (deny (allow y)) = deny y
      |flat-1 (deny (deny y)) = deny y

```

lemma flat-1-allow[dest]: flat-1 $x = \text{allow } y \implies x = \text{allow}(\text{allow } y) \vee x = \text{allow}(\text{deny } y)$

```

apply (case-tac x)
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
done

```

lemma flat-1-deny[dest]: flat-1 $x = \text{deny } y \implies x = \text{deny}(\text{deny } y) \vee x = \text{deny}(\text{allow } y)$

```

apply (case-tac x)
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
done

```

```

fun flat-2 :: (' $\alpha$  decision) decision  $\Rightarrow$  (' $\alpha$  decision)
where flat-2 (allow (allow y)) = allow y
      |flat-2 (allow (deny y)) = deny y
      |flat-2 (deny (allow y)) = allow y
      |flat-2 (deny (deny y)) = deny y

```

lemma flat-2-allow[dest]: flat-2 $x = \text{allow } y \implies x = \text{allow}(\text{allow } y) \vee x = \text{deny}(\text{allow } y)$

```

apply (case-tac x)
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]

```

```

apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
done

```

lemma *flat-2-deny*[*dest*]: $\text{flat-2 } x = \text{deny } y \implies x = \text{deny}(\text{deny } y) \vee x = \text{allow}(\text{deny } y)$

```

apply (case-tac  $x$ )
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
apply (rename-tac  $\alpha$ )
apply (case-tac  $\alpha$ , simp-all)[1]
done

```

2.3.2 Policy Composition

The following definition allows to compose two policies. Denies and allows are transferred.

```

fun lift :: (' $\alpha$   $\mapsto$  ' $\beta$ )  $\Rightarrow$  (' $\alpha$  decision  $\mapsto$  ' $\beta$  decision)
where lift f (deny  $s$ ) = (case f s of
  |  $y$   $\Rightarrow$  [deny  $y$ ]
  |  $\perp$   $\Rightarrow$   $\perp$ )
  | lift f (allow  $s$ ) = (case f s of
  |  $y$   $\Rightarrow$  [allow  $y$ ]
  |  $\perp$   $\Rightarrow$   $\perp$ )

```

```

lemma lift-mt [simp]: lift  $\emptyset = \emptyset$ 
apply (rule ext)
subgoal for  $x$ 
apply (case-tac  $x$ )
apply (simp-all)
done
done

```

Since policies are maps, we inherit a composition on them. However, this results in nestings of decisions—which must be flattened. As we now that there are four different forms of flattening, we have four different forms of policy composition:

definition

```

comp-orA :: [' $\beta$   $\mapsto$  ' $\gamma$ , ' $\alpha$   $\mapsto$  ' $\beta$ ]  $\Rightarrow$  ' $\alpha$   $\mapsto$  ' $\gamma$  (infixl o'-orA 55) where
p2 o-orA p1  $\equiv$  (map-option flat-orA) o (lift p2  $\circ_m$  p1)

```

notation

```

comp-orA (infixl  $\circ_{VA}$  55)

```

lemma *comp-orA-mt*[*simp*]: $p \circ_{VA} \emptyset = \emptyset$

by(*simp add: comp-orA-def*)

lemma *mt-comp-orA[simp]:* $\emptyset \circ_{\vee A} p = \emptyset$

by(*simp add: comp-orA-def*)

definition

comp-orD :: [$'\beta \mapsto '\gamma$, $'\alpha \mapsto '\beta$] \Rightarrow $'\alpha \mapsto '\gamma$ (**infixl** *o'-orD* 55) **where**
p2 o-orD p1 \equiv (*map-option flat-orD*) *o* (*lift p2* \circ_m *p1*)

notation

comp-orD (**infixl** *o_orD* 55)

lemma *comp-orD-mt[simp]:* $p \text{ o-orD } \emptyset = \emptyset$

by(*simp add: comp-orD-def*)

lemma *mt-comp-orD[simp]:* $\emptyset \text{ o-orD } p = \emptyset$

by(*simp add: comp-orD-def*)

definition

comp-1 :: [$'\beta \mapsto '\gamma$, $'\alpha \mapsto '\beta$] \Rightarrow $'\alpha \mapsto '\gamma$ (**infixl** *o'-1* 55) **where**
p2 o-1 p1 \equiv (*map-option flat-1*) *o* (*lift p2* \circ_m *p1*)

notation

comp-1 (**infixl** *o_1* 55)

lemma *comp-1-mt[simp]:* $p \circ_1 \emptyset = \emptyset$

by(*simp add: comp-1-def*)

lemma *mt-comp-1[simp]:* $\emptyset \circ_1 p = \emptyset$

by(*simp add: comp-1-def*)

definition

comp-2 :: [$'\beta \mapsto '\gamma$, $'\alpha \mapsto '\beta$] \Rightarrow $'\alpha \mapsto '\gamma$ (**infixl** *o'-2* 55) **where**
p2 o-2 p1 \equiv (*map-option flat-2*) *o* (*lift p2* \circ_m *p1*)

notation

comp-2 (**infixl** *o_2* 55)

lemma *comp-2-mt[simp]:* $p \circ_2 \emptyset = \emptyset$

by(*simp add: comp-2-def*)

lemma *mt-comp-2[simp]:* $\emptyset \circ_2 p = \emptyset$

by(*simp add: comp-2-def*)

end

2.4 Parallel Composition

theory

ParallelComposition

imports

ElementaryPolicies

begin

The following combinators are based on the idea that two policies are executed in parallel. Since both input and the output can differ, we chose to pair them.

The new input pair will often contain repetitions, which can be reduced using the domain-restriction and domain-reduction operators. Using additional range-modifying operators such as ∇ , decide which result argument is chosen; this might be the first or the latter or, in case that $\beta = \gamma$, and β underlies a lattice structure, the supremum or infimum of both, or, an arbitrary combination of them.

In any case, although we have strictly speaking a pairing of decisions and not a nesting of them, we will apply the same notational conventions as for the latter, i.e. as for flattening.

2.4.1 Parallel Combinators: Foundations

There are four possible semantics how the decision can be combined, thus there are four parallel composition operators. For each of them, we prove several properties.

definition *prod-orA* :: [$'\alpha \mapsto '\beta$, $'\gamma \mapsto '\delta$] \Rightarrow ($'\alpha \times '\gamma \mapsto '\beta \times '\delta$) (**infixr** $\otimes_{\vee A}$ 55)

where $p1 \otimes_{\vee A} p2 =$

$$(\lambda(x,y). (\text{case } p1 \text{ of } x \text{ of } \\ \quad [allow \ d1] \Rightarrow (\text{case } p2 \text{ of } y \text{ of } \\ \quad \quad [allow \ d2] \Rightarrow [allow(d1,d2)] \\ \quad \quad | [deny \ d2] \Rightarrow [allow(d1,d2)] \\ \quad \quad | \perp \Rightarrow \perp) \\ \quad | [deny \ d1] \Rightarrow (\text{case } p2 \text{ of } y \text{ of } \\ \quad \quad [allow \ d2] \Rightarrow [allow(d1,d2)] \\ \quad \quad | [deny \ d2] \Rightarrow [deny \ (d1,d2)] \\ \quad \quad | \perp \Rightarrow \perp) \\ \quad | \perp \Rightarrow \perp))$$

lemma *prod-orA-mt[simp]:p* $\otimes_{\vee A} \emptyset = \emptyset$

apply (*rule ext*)

apply (*simp add: prod-orA-def*)

apply (*auto*)

apply (*simp split: option.splits decision.splits*)

done

lemma *mt-prod-orA*[simp]: $\emptyset \otimes_{\vee A} p = \emptyset$

apply (*rule ext*)
apply (*simp add: prod-orA-def*)
done

lemma *prod-orA-quasi-commute*: $p2 \otimes_{\vee A} p1 = (((\lambda(x,y). (y,x)) \text{ o-f } (p1 \otimes_{\vee A} p2)))$
o ($\lambda(a,b).(b,a)$)

apply (*rule ext*)
apply (*simp add: prod-orA-def policy-range-comp-def o-def*)
apply (*auto*)[1]
apply (*simp split: option.splits decision.splits*)
done

definition *prod-orD* :: [$'\alpha \mapsto '\beta, '\gamma \mapsto '\delta$] $\Rightarrow ('\alpha \times '\gamma \mapsto '\beta \times '\delta)$ (**infixr** $\otimes_{\vee D}$ 55)

where $p1 \otimes_{\vee D} p2 =$

$(\lambda(x,y). (case\ p1\ x\ of$
 $[allow\ d1] \Rightarrow (case\ p2\ y\ of$
 $[allow\ d2] \Rightarrow [allow(d1,d2)]$
 $| [deny\ d2] \Rightarrow [deny(d1,d2)]$
 $| \perp \Rightarrow \perp$
 $| [deny\ d1] \Rightarrow (case\ p2\ y\ of$
 $[allow\ d2] \Rightarrow [deny(d1,d2)]$
 $| [deny\ d2] \Rightarrow [deny(d1,d2)]$
 $| \perp \Rightarrow \perp$
 $| \perp \Rightarrow \perp))$

lemma *prod-orD-mt*[simp]: $p \otimes_{\vee D} \emptyset = \emptyset$

apply (*rule ext*)
apply (*simp add: prod-orD-def*)
apply (*auto*)[1]
apply (*simp split: option.splits decision.splits*)
done

lemma *mt-prod-orD*[simp]: $\emptyset \otimes_{\vee D} p = \emptyset$

apply (*rule ext*)
apply (*simp add: prod-orD-def*)
done

lemma *prod-orD-quasi-commute*: $p2 \otimes_{\vee D} p1 = (((\lambda(x,y). (y,x)) \text{ o-f } (p1 \otimes_{\vee D} p2)))$
o ($\lambda(a,b).(b,a)$)

apply (*rule ext*)
apply (*simp add: prod-orD-def policy-range-comp-def o-def*)

```

apply (auto)[1]
apply (simp split: option.splits decision.splits)
done

```

The following two combinators are by definition non-commutative, but still strict.

```

definition prod-1 :: [' $\alpha \mapsto \beta$ , ' $\gamma \mapsto \delta$ ]  $\Rightarrow$  (' $\alpha \times \gamma \mapsto \beta \times \delta$ ) (infixr  $\otimes_1$  55)
where p1  $\otimes_1$  p2  $\equiv$ 
  ( $\lambda(x,y).$  (case p1 x of
    [allow d1]  $\Rightarrow$  (case p2 y of
      [allow d2]  $\Rightarrow$  [allow(d1,d2)]
      | [deny d2]  $\Rightarrow$  [allow(d1,d2)]
      |  $\perp \Rightarrow \perp$ )
    | [deny d1]  $\Rightarrow$  (case p2 y of
      [allow d2]  $\Rightarrow$  [deny(d1,d2)]
      | [deny d2]  $\Rightarrow$  [deny(d1,d2)]
      |  $\perp \Rightarrow \perp$ )
    |  $\perp \Rightarrow \perp$ ))

```

```

lemma prod-1-mt[simp]:p  $\otimes_1 \emptyset = \emptyset$ 
apply (rule ext)
apply (simp add: prod-1-def)
apply (auto)[1]
apply (simp split: option.splits decision.splits)
done

```

```

lemma mt-prod-1[simp]: $\emptyset \otimes_1 p = \emptyset$ 
apply (rule ext)
apply (simp add: prod-1-def)
done

```

```

definition prod-2 :: [' $\alpha \mapsto \beta$ , ' $\gamma \mapsto \delta$ ]  $\Rightarrow$  (' $\alpha \times \gamma \mapsto \beta \times \delta$ ) (infixr  $\otimes_2$  55)
where p1  $\otimes_2$  p2  $\equiv$ 
  ( $\lambda(x,y).$  (case p1 x of
    [allow d1]  $\Rightarrow$  (case p2 y of
      [allow d2]  $\Rightarrow$  [allow(d1,d2)]
      | [deny d2]  $\Rightarrow$  [deny (d1,d2)]
      |  $\perp \Rightarrow \perp$ )
    | [deny d1]  $\Rightarrow$  (case p2 y of
      [allow d2]  $\Rightarrow$  [allow(d1,d2)]
      | [deny d2]  $\Rightarrow$  [deny (d1,d2)]
      |  $\perp \Rightarrow \perp$ )
    |  $\perp \Rightarrow \perp$ ))

```

```

lemma prod-2-mt[simp]:p  $\otimes_2 \emptyset = \emptyset$ 

```

```

apply (rule ext)
apply (simp add: prod-2-def)
apply (auto)[1]
apply (simp split: option.splits decision.splits)
done

```

```

lemma mt-prod-2[simp]:  $\emptyset \otimes_2 p = \emptyset$ 
apply (rule ext)
apply (simp add: prod-2-def)
done

```

```

definition prod-1-id :: [ $'\alpha \mapsto '\beta, '\alpha \mapsto '\gamma$ ]  $\Rightarrow (' \alpha \mapsto '\beta \times '\gamma)$  (infixr  $\otimes_{1I}$  55)
where  $p \otimes_{1I} q = (p \otimes_1 q) \circ (\lambda x. (x, x))$ 

```

```

lemma prod-1-id-mt[simp]:  $p \otimes_{1I} \emptyset = \emptyset$ 
apply (rule ext)
apply (simp add: prod-1-id-def)
done

```

```

lemma mt-prod-1-id[simp]:  $\emptyset \otimes_{1I} p = \emptyset$ 
apply (rule ext)
apply (simp add: prod-1-id-def prod-1-def)
done

```

```

definition prod-2-id :: [ $'\alpha \mapsto '\beta, '\alpha \mapsto '\gamma$ ]  $\Rightarrow (' \alpha \mapsto '\beta \times '\gamma)$  (infixr  $\otimes_{2I}$  55)
where  $p \otimes_{2I} q = (p \otimes_2 q) \circ (\lambda x. (x, x))$ 

```

```

lemma prod-2-id-mt[simp]:  $p \otimes_{2I} \emptyset = \emptyset$ 
apply (rule ext)
apply (simp add: prod-2-id-def)
done

```

```

lemma mt-prod-2-id[simp]:  $\emptyset \otimes_{2I} p = \emptyset$ 
apply (rule ext)
apply (simp add: prod-2-id-def prod-2-def)
done

```

2.4.2 Combinators for Transition Policies

For constructing transition policies, two additional combinators are required: one combines state transitions by pairing the states, the other works equivalently on general maps.

```

definition parallel-map :: ( $'\alpha \rightarrow '\beta$ )  $\Rightarrow (' \delta \rightarrow '\gamma) \Rightarrow$ 
 $('\alpha \times '\delta \rightarrow '\beta \times '\gamma)$  (infixr  $\otimes_M$  60)

```

where $p1 \otimes_M p2 = (\lambda (x,y). \text{case } p1 \text{ of } [d1] \Rightarrow$
 $(\text{case } p2 \text{ of } [d2] \Rightarrow [(d1,d2)]$
 $\quad | \perp \Rightarrow \perp)$
 $\quad | \perp \Rightarrow \perp)$

definition $parallel\text{-}st :: ('i \times 's \rightarrow 's) \Rightarrow ('i \times 's' \rightarrow 's') \Rightarrow$
 $('i \times 's \times 's' \rightarrow 's \times 's') \text{ (infixr } \otimes_S 60)$

where

$p1 \otimes_S p2 = (p1 \otimes_M p2) \circ (\lambda (a,b,c). ((a,b),a,c))$

2.4.3 Range Splitting

The following combinator is a special case of both a parallel composition operator and a range splitting operator. Its primary use case is when combining a policy with state transitions.

definition $comp\text{-}ran\text{-}split :: [('\alpha \rightarrow '\gamma) \times ('\alpha \rightarrow '\gamma), 'd \mapsto '\beta] \Rightarrow ('d \times '\alpha) \mapsto ('s \times '\gamma)$
 $\text{ (infixr } \otimes_{\nabla} 100)$

where $P \otimes_{\nabla} p \equiv \lambda x. \text{case } p \text{ (fst } x) \text{ of}$

$\quad [allow \ y] \Rightarrow (\text{case } ((fst \ P) \ (snd \ x)) \text{ of } \perp \Rightarrow \perp \mid [z] \Rightarrow [allow$
 $\quad (y,z)])$
 $\quad \mid [deny \ y] \Rightarrow (\text{case } ((snd \ P) \ (snd \ x)) \text{ of } \perp \Rightarrow \perp \mid [z] \Rightarrow [deny$
 $\quad (y,z)])$
 $\quad \mid \perp \Rightarrow \perp$

An alternative characterisation of the operator is as follows:

lemma $comp\text{-}ran\text{-}split\text{-}charn:$

$(f, g) \otimes_{\nabla} p = ($
 $((p \triangleright Allow) \otimes_{\vee A} (A_p \ f)) \oplus$
 $((p \triangleright Deny) \otimes_{\vee A} (D_p \ g)))$

apply $(rule \ ext)$

apply $(simp \ add: \ comp\text{-}ran\text{-}split\text{-}def \ map\text{-}add\text{-}def \ o\text{-}def \ ran\text{-}restrict\text{-}def \ image\text{-}def$
 $\quad Allow\text{-}def \ Deny\text{-}def \ dom\text{-}restrict\text{-}def \ prod\text{-}orA\text{-}def$
 $\quad allow\text{-}pfun\text{-}def \ deny\text{-}pfun\text{-}def$
 $\quad split:option.splits \ decision.splits)$

apply $(auto)$

done

2.4.4 Distributivity of the parallel combinators

lemma $distr\text{-}or1\text{-}a: (F = F1 \oplus F2) \Longrightarrow (((N \otimes_1 F) \circ f) =$
 $((N \otimes_1 F1) \circ f) \oplus ((N \otimes_1 F2) \circ f))$

apply $(rule \ ext)$

apply $(simp \ add: \ prod\text{-}1\text{-}def \ map\text{-}add\text{-}def$
 $\quad split: \ decision.splits \ option.splits)$

subgoal for x
apply (*case-tac f x*)
apply (*simp-all add: prod-1-def map-add-def*
split: decision.splits option.splits)
done
done

lemma *distr-or1*: $(F = F1 \oplus F2) \implies ((g \circ f ((N \otimes_1 F) \circ f)) =$
 $((g \circ f ((N \otimes_1 F1) \circ f)) \oplus (g \circ f ((N \otimes_1 F2) \circ f))))$
apply (*rule ext*)
apply (*simp add: prod-1-def map-add-def policy-range-comp-def*
split: decision.splits option.splits)
subgoal for x
apply (*case-tac f x*)
apply (*simp-all add: prod-1-def map-add-def*
split: decision.splits option.splits)
done
done

lemma *distr-or2-a*: $(F = F1 \oplus F2) \implies (((N \otimes_2 F) \circ f) =$
 $((N \otimes_2 F1) \circ f) \oplus ((N \otimes_2 F2) \circ f)))$
apply (*rule ext*)
apply (*simp add: prod-2-id-def prod-2-def map-add-def*
split: decision.splits option.splits)
subgoal for x
apply (*case-tac f x*)
apply (*simp-all add: prod-2-def map-add-def*
split: decision.splits option.splits)
done
done

lemma *distr-or2*: $(F = F1 \oplus F2) \implies ((r \circ f ((N \otimes_2 F) \circ f)) =$
 $((r \circ f ((N \otimes_2 F1) \circ f)) \oplus (r \circ f ((N \otimes_2 F2) \circ f))))$
apply (*rule ext*)
apply (*simp add: prod-2-id-def prod-2-def map-add-def policy-range-comp-def*
split: decision.splits option.splits)
subgoal for x
apply (*case-tac f x*)
apply (*simp-all add: prod-2-def map-add-def*
split: decision.splits option.splits)
done
done

lemma *distr-orA*: $(F = F1 \oplus F2) \implies ((g \circ f ((N \otimes_{\vee A} F) \circ f)) =$

```

      ((g o-f ((N ⊗VA F1) o f)) ⊕ (g o-f ((N ⊗VA F2) o f))))
apply (rule ext)+
apply (simp add: prod-orA-def map-add-def policy-range-comp-def
      split: decision.splits option.splits)
subgoal for x
  apply (case-tac f x)
  apply (simp-all add: map-add-def
      split: decision.splits option.splits)
  done
done

lemma distr-orD: (F = F1 ⊕ F2) ⇒ ((g o-f ((N ⊗VD F) o f)) =
      ((g o-f ((N ⊗VD F1) o f)) ⊕ (g o-f ((N ⊗VD F2) o f))))
apply (rule ext)+
apply (simp add: prod-orD-def map-add-def policy-range-comp-def
      split: decision.splits option.splits)
subgoal for x
  apply (case-tac f x)
  apply (simp-all add: map-add-def
      split: decision.splits option.splits)
  done
done

lemma coerc-assoc: (r o-f P) o d = r o-f (P o d)
  apply (simp add: policy-range-comp-def)
  apply (rule ext)
  apply (simp split: option.splits decision.splits)
  done

lemmas ParallelDefs = prod-orA-def prod-orD-def prod-1-def prod-2-def paral-
  lel-map-def
      parallel-st-def comp-ran-split-def
end

```

2.5 Properties on Policies

```

theory
  Analysis
  imports
    ParallelComposition
    SeqComposition
begin

```

In this theory, several standard policy properties are paraphrased in UPF terms.

2.5.1 Basic Properties

A Policy Has no Gaps

definition *gap-free* :: ('a \mapsto 'b) \Rightarrow bool
where *gap-free* p = (dom p = UNIV)

Comparing Policies

Policy p is more defined than q:

definition *more-defined* :: ('a \mapsto 'b) \Rightarrow ('a \mapsto 'b) \Rightarrow bool
where *more-defined* p q = (dom q \subseteq dom p)

definition *strictly-more-defined* :: ('a \mapsto 'b) \Rightarrow ('a \mapsto 'b) \Rightarrow bool
where *strictly-more-defined* p q = (dom q \subset dom p)

lemma *strictly-more-vs-more*: *strictly-more-defined* p q \Longrightarrow *more-defined* p q
unfolding *more-defined-def* *strictly-more-defined-def*
by *auto*

Policy p is more permissive than q:

definition *more-permissive* :: ('a \mapsto 'b) \Rightarrow ('a \mapsto 'b) \Rightarrow bool (**infixl** \sqsubseteq_A 60)
where p \sqsubseteq_A q = (\forall x. (case q x of [allow y] \Rightarrow (\exists z. (p x = [allow z]))
| [deny y] \Rightarrow True
| \perp \Rightarrow True))

lemma *more-permissive-refl* : p \sqsubseteq_A p
unfolding *more-permissive-def*
by(*auto split : option.split decision.split*)

lemma *more-permissive-trans* : p \sqsubseteq_A p' \Longrightarrow p' \sqsubseteq_A p'' \Longrightarrow p \sqsubseteq_A p''
unfolding *more-permissive-def*
apply(*auto split : option.split decision.split*)
subgoal for x y
apply(*erule-tac* x = x **and**
P = λ x. case p'' x of \perp \Rightarrow True
| [allow y] \Rightarrow \exists z. p' x = [allow z]
| [deny y] \Rightarrow True **in** *allE*)
apply(*simp, elim exE*)
by(*erule-tac* x = x **in** *allE, simp*)
done

Policy p is more rejective than q:

definition *more-rejective* :: ('a \mapsto 'b) \Rightarrow ('a \mapsto 'b) \Rightarrow bool (**infixl** \sqsubseteq_D 60)
where $p \sqsubseteq_D q = (\forall x. (case\ q\ x\ of\ [deny\ y] \Rightarrow (\exists z. (p\ x = [deny\ z]))$
 $\quad \quad \quad | [allow\ y] \Rightarrow True$
 $\quad \quad \quad | \perp \quad \quad \Rightarrow True))$

lemma *more-rejective-trans* : $p \sqsubseteq_D p' \Longrightarrow p' \sqsubseteq_D p'' \Longrightarrow p \sqsubseteq_D p''$
unfolding *more-rejective-def*
apply(*auto split : option.split decision.split*)
subgoal for $x\ y$
apply(*erule-tac x = x and*
 $P = \lambda x. case\ p''\ x\ of\ \perp \Rightarrow True$
 $\quad \quad \quad | [allow\ y] \Rightarrow True$
 $\quad \quad \quad | [deny\ y] \Rightarrow \exists z. p'\ x = [deny\ z]$ **in** *allE*)
apply(*simp, elim exE*)
by(*erule-tac x = x in allE, simp*)
done

lemma *more-rejective-refl* : $p \sqsubseteq_D p$
unfolding *more-rejective-def*
by(*auto split : option.split decision.split*)

lemma $A_f\ f \sqsubseteq_A p$
unfolding *more-permissive-def allow-all-fun-def allow-pfun-def*
by(*auto split: option.split decision.split*)

lemma $A_I \sqsubseteq_A p$
unfolding *more-permissive-def allow-all-fun-def allow-pfun-def allow-all-id-def*
by(*auto split: option.split decision.split*)

2.5.2 Combined Data-Policy Refinement

definition *policy-refinement* ::
('a \mapsto 'b) \Rightarrow ('a' \Rightarrow 'a) \Rightarrow ('b' \Rightarrow 'b) \Rightarrow ('a' \mapsto 'b') \Rightarrow bool
 $(-\ \sqsubseteq_{-, -} - [50, 50, 50, 50] 50)$
where $p \sqsubseteq_{abs_a, abs_b} q \equiv$
 $(\forall a. case\ p\ a\ of$
 $\quad \perp \Rightarrow True$
 $\quad | [allow\ y] \Rightarrow (\forall a' \in \{x. abs_a\ x = a\}.$
 $\quad \quad \quad \exists b'. q\ a' = [allow\ b']$
 $\quad \quad \quad \wedge\ abs_b\ b' = y)$
 $\quad | [deny\ y] \Rightarrow (\forall a' \in \{x. abs_a\ x = a\}.$

$$\exists b'. q a' = [\text{deny } b'] \\ \wedge \text{abs}_b b' = y))$$

theorem *polref-refl*: $p \sqsubseteq_{id, id} p$
unfolding *policy-refinement-def*
by(*auto split: option.split decision.split*)

theorem *polref-trans*:
assumes $A: p \sqsubseteq_{f, g} p'$
and $B: p' \sqsubseteq_{f', g'} p''$
shows $p \sqsubseteq_{f \circ f', g \circ g'} p''$
apply(*insert A B*)
unfolding *policy-refinement-def*
apply(*auto split: option.split decision.split simp: o-def*)[1]
subgoal for $a a'$
apply(*erule-tac x=f (f' a') in allE, simp*)[1]
apply(*erule-tac x=f' a' in allE, auto*)[1]
apply(*erule-tac x=(f' a') in allE, auto*)[1]
done
subgoal for $a a'$
apply(*erule-tac x=f (f' a') in allE, simp*)[1]
apply(*erule-tac x=f' a' in allE, auto*)[1]
apply(*erule-tac x=(f' a') in allE, auto*)[1]
done
done

2.5.3 Equivalence of Policies

Equivalence over domain D

definition *p-eq-dom* :: $('a \mapsto 'b) \Rightarrow 'a \text{ set} \Rightarrow ('a \mapsto 'b) \Rightarrow \text{bool}$ ($- \approx_D -$ [60,60,60]60)
where $p \approx_D q = (\forall x \in D. p x = q x)$

p and q have no conflicts

definition *no-conflicts* :: $('a \mapsto 'b) \Rightarrow ('a \mapsto 'b) \Rightarrow \text{bool}$ **where**
no-conflicts $p q = (\text{dom } p = \text{dom } q \wedge (\forall x \in (\text{dom } p). \\ (\text{case } p x \text{ of } [\text{allow } y] \Rightarrow (\exists z. q x = [\text{allow } z]) \\ | [\text{deny } y] \Rightarrow (\exists z. q x = [\text{deny } z])))$)

lemma *policy-eq*:

assumes *p-over-qA*: $p \sqsubseteq_A q$
and *q-over-pA*: $q \sqsubseteq_A p$
and *p-over-qD*: $q \sqsubseteq_D p$
and *q-over-pD*: $p \sqsubseteq_D q$
and *dom-eq*: $\text{dom } p = \text{dom } q$

```

shows                no-conflicts p q
apply (insert p-over-qA q-over-pA p-over-qD q-over-pD dom-eq)
apply (simp add: no-conflicts-def more-permissive-def more-rejective-def
        split: option.splits decision.splits)
apply (safe)
        apply (metis domI domIff dom-eq)
        apply (metis)+
done

```

Miscellaneous

```

lemma dom-inter:  $\llbracket \text{dom } p \cap \text{dom } q = \{\}; p \ x = \lfloor y \rfloor \rrbracket \implies q \ x = \perp$ 
by (auto)

```

```

lemma dom-eq:  $\text{dom } p \cap \text{dom } q = \{\} \implies p \oplus_A q = p \oplus_D q$ 
unfolding override-A-def override-D-def
by (rule ext, auto simp: dom-def split: prod.splits option.splits decision.splits )

```

```

lemma dom-split-alt-def :  $(f, g) \Delta p = (\text{dom}(p \triangleright \text{Allow}) \triangleleft (A_f f)) \oplus (\text{dom}(p \triangleright \text{Deny})$ 
 $\triangleleft (D_f g))$ 
apply (rule ext)
apply (simp add: dom-split2-def Allow-def Deny-def dom-restrict-def
        deny-all-fun-def allow-all-fun-def map-add-def)
apply (simp split: option.splits decision.splits)
apply (auto simp: map-add-def o-def deny-pfun-def ran-restrict-def image-def)
done

```

end

2.6 Policy Transformations

```

theory
  Normalisation
imports
  SeqComposition
  ParallelComposition
begin

```

This theory provides the formalisations required for the transformation of UPF policies. A typical usage scenario can be observed in the firewall case study [12].

2.6.1 Elementary Operators

We start by providing several operators and theorems useful when reasoning about a list of rules which should eventually be interpreted as combined using the standard override operator.

The following definition takes as argument a list of rules and returns a policy where the rules are combined using the standard override operator.

definition *list2policy*::('a \mapsto 'b) list \Rightarrow ('a \mapsto 'b) **where**
list2policy l = foldr (λ x y. (x \oplus y)) l \emptyset

Determine the position of element of a list.

fun *position* :: 'a \Rightarrow 'a list \Rightarrow nat **where**
position a [] = 0
|(*position* a (x#xs)) = (if a = x then 1 else (Suc (*position* a xs)))

Provides the first applied rule of a policy given as a list of rules.

fun *applied-rule* **where**
applied-rule C a (x#xs) = (if a \in dom (C x) then (Some x)
else (*applied-rule* C a xs))
|*applied-rule* C a [] = None

The following is used if the list is constructed backwards.

definition *applied-rule-rev* **where**
applied-rule-rev C a x = *applied-rule* C a (rev x)

The following is a typical policy transformation. It can be applied to any type of policy and removes all the rules from a policy with an empty domain. It takes two arguments: a semantic interpretation function and a list of rules.

fun *rm-MT-rules* **where**
rm-MT-rules C (x#xs) = (if dom (C x) = {}
then *rm-MT-rules* C xs
else x#(*rm-MT-rules* C xs))
|*rm-MT-rules* C [] = []

The following invariant establishes that there are no rules with an empty domain in a list of rules.

fun *none-MT-rules* **where**
none-MT-rules C (x#xs) = (dom (C x) \neq {}) \wedge (*none-MT-rules* C xs)
|*none-MT-rules* C [] = True

The following related invariant establishes that the policy has not a completely empty domain.

fun *not-MT* **where**
not-MT C (x#xs) = (if (dom (C x) = {}) then (*not-MT* C xs) else True)

|not-MT C [] = False

Next, a few theorems about the two invariants and the transformation:

lemma none-MT-rules-vs-notMT: none-MT-rules C p \implies p \neq [] \implies not-MT C p
 apply (induct p)
 apply (simp-all)
 done

lemma rmnMT: none-MT-rules C (rm-MT-rules C p)
 apply (induct p)
 apply (simp-all)
 done

lemma rmnMT2: none-MT-rules C p \implies (rm-MT-rules C p) = p
 apply (induct p)
 apply (simp-all)
 done

lemma nMTcharn: none-MT-rules C p = (\forall r \in set p. dom (C r) \neq {})
 apply (induct p)
 apply (simp-all)
 done

lemma nMTeqSet: set p = set s \implies none-MT-rules C p = none-MT-rules C s
 apply (simp add: nMTcharn)
 done

lemma notMTnMT: [a \in set p; none-MT-rules C p] \implies dom (C a) \neq {}
 apply (simp add: nMTcharn)
 done

lemma none-MT-rulesconc: none-MT-rules C (a@[b]) \implies none-MT-rules C a
 apply (induct a)
 apply (simp-all)
 done

lemma nMTtail: none-MT-rules C p \implies none-MT-rules C (tl p)
 apply (induct p)
 apply (simp-all)
 done

lemma not-MTimpnotMT[simp]: not-MT C p \implies p \neq []
 apply (auto)
 done

lemma *SR3nMT*: $\neg \text{not-MT } C \ p \implies \text{rm-MT-rules } C \ p = []$
apply (*induct p*)
apply (*auto simp: if-splits*)
done

lemma *NMPcharn*: $\llbracket a \in \text{set } p; \text{dom } (C \ a) \neq \{\} \rrbracket \implies \text{not-MT } C \ p$
apply (*induct p*)
apply (*auto simp: if-splits*)
done

lemma *NMPrm*: $\text{not-MT } C \ p \implies \text{not-MT } C \ (\text{rm-MT-rules } C \ p)$
apply (*induct p*)
apply (*simp-all*)
done

Next, a few theorems about `applied_rule`:

lemma *mrconc*: $\text{applied-rule-rev } C \ x \ p = \text{Some } a \implies \text{applied-rule-rev } C \ x \ (b\#p) = \text{Some } a$

proof (*induct p rule: rev-induct*)
case Nil show ?case using Nil
by (*simp add: applied-rule-rev-def*)
next
case (snoc xs x) show ?case using snoc
apply (*simp add: applied-rule-rev-def if-splits*)
by (*metis option.inject*)
qed

lemma *mreq-end*: $\llbracket \text{applied-rule-rev } C \ x \ b = \text{Some } r; \text{applied-rule-rev } C \ x \ c = \text{Some } r \rrbracket \implies$
 $\text{applied-rule-rev } C \ x \ (a\#b) = \text{applied-rule-rev } C \ x \ (a\#c)$
by (*simp add: mrconc*)

lemma *mrconcNone*: $\text{applied-rule-rev } C \ x \ p = \text{None} \implies$
 $\text{applied-rule-rev } C \ x \ (b\#p) = \text{applied-rule-rev } C \ x \ [b]$

proof (*induct p rule: rev-induct*)
case Nil show ?case
by (*simp add: applied-rule-rev-def*)
next
case (snoc ys y) show ?case using snoc
proof (*cases x \in dom (C ys)*)
case True show ?thesis using True snoc
by (*auto simp: applied-rule-rev-def*)
next

```

    case False show ?thesis using False snoc
      by (auto simp: applied-rule-rev-def)
  qed
qed

lemma mreq-endNone:  $\llbracket \text{applied-rule-rev } C \ x \ b = \text{None}; \text{applied-rule-rev } C \ x \ c = \text{None} \rrbracket$ 
 $\implies$ 
  applied-rule-rev  $C \ x \ (a\#b) = \text{applied-rule-rev } C \ x \ (a\#c)$ 
  by (metis mrconcNone)

lemma mreq-end2: applied-rule-rev  $C \ x \ b = \text{applied-rule-rev } C \ x \ c \implies$ 
  applied-rule-rev  $C \ x \ (a\#b) = \text{applied-rule-rev } C \ x \ (a\#c)$ 
  apply (case-tac applied-rule-rev  $C \ x \ b = \text{None}$ )
  apply (auto intro: mreq-end mreq-endNone)
  done

lemma mreq-end3: applied-rule-rev  $C \ x \ p \neq \text{None} \implies$ 
  applied-rule-rev  $C \ x \ (b \# p) = \text{applied-rule-rev } C \ x \ (p)$ 
  by (auto simp: mrconc)

lemma mrNoneMT:  $\llbracket r \in \text{set } p; \text{applied-rule-rev } C \ x \ p = \text{None} \rrbracket \implies$ 
   $x \notin \text{dom } (C \ r)$ 
proof (induct p rule: rev-induct)
  case Nil show ?case using Nil
    by (simp add: applied-rule-rev-def)
next
  case (snoc y ys) show ?case using snoc
  proof (cases r  $\in \text{set } ys$ )
    case True show ?thesis using snoc True
      by (simp add: applied-rule-rev-def split: if-split-asm)
  next
    case False show ?thesis using snoc False
      by (simp add: applied-rule-rev-def split: if-split-asm)
  qed
qed
qed

```

2.6.2 Distributivity of the Transformation.

The scenario is the following (can be applied iteratively):

- Two policies are combined using one of the parallel combinators
- (e.g. $P = P1 \ P2$) (At least) one of the constituent policies has
- a normalisation procedures, which as output produces a list of

- policies that are semantically equivalent to the original policy if
- combined from left to right using the override operator.

The following function is crucial for the distribution. Its arguments are a policy, a list of policies, a parallel combinator, and a range and a domain coercion function.

```
fun prod-list :: ('α ↦ 'β) ⇒ (('γ ↦ 'δ) list) ⇒
  (('α ↦ 'β) ⇒ ('γ ↦ 'δ) ⇒ (('α × 'γ) ↦ ('β × 'δ))) ⇒
  (('β × 'δ) ⇒ 'y) ⇒ ('x ⇒ ('α × 'γ)) ⇒
  (('x ↦ 'y) list) (infixr ⊗L 54) where
  prod-list x (y#ys) par-comb ran-adapt dom-adapt =
    ((ran-adapt o-f ((par-comb x y) o dom-adapt))#(prod-list x ys par-comb ran-adapt
    dom-adapt))
| prod-list x [] par-comb ran-adapt dom-adapt = []
```

An instance, as usual there are four of them.

```
definition prod-2-list :: [('α ↦ 'β), (('γ ↦ 'δ) list)] ⇒
  (('β × 'δ) ⇒ 'y) ⇒ ('x ⇒ ('α × 'γ)) ⇒
  (('x ↦ 'y) list) (infixr ⊗2L 55) where
  x ⊗2L y = (λ d r. (x ⊗L y) (⊗2) d r)
```

```
lemma list2listNMT: x ≠ [] ⇒ map sem x ≠ []
apply (case-tac x)
apply (simp-all)
done
```

```
lemma two-conc: (prod-list x (y#ys) p r d) = ((r o-f ((p x y) o d))#(prod-list x ys p
r d))
by simp
```

The following two invariants establish if the law of distributivity holds for a combinator and if an operator is strict regarding undefinedness.

```
definition is-distr where
  is-distr p = (λ g f. (∀ N P1 P2. ((g o-f ((p N (P1 ⊕ P2)) o f)) =
    ((g o-f ((p N P1) o f)) ⊕ (g o-f ((p N P2) o f)))))
```

```
definition is-strict where
  is-strict p = (λ r d. ∀ P1. (r o-f (p P1 ∅ o d)) = ∅)
```

```
lemma is-distr-orD: is-distr (⊗∨D) d r
apply (simp add: is-distr-def)
apply (rule allI)+
apply (rule distr-orD)
apply (simp)
```

done

lemma *is-strict-orD*: *is-strict* ($\otimes_{\vee D}$) *d r*
apply (*simp add: is-strict-def*)
apply (*simp add: policy-range-comp-def*)
done

lemma *is-distr-2*: *is-distr* (\otimes_2) *d r*
apply (*simp add: is-distr-def*)
apply (*rule allI*)
apply (*rule distr-or2*)
by simp

lemma *is-strict-2*: *is-strict* (\otimes_2) *d r*
apply (*simp only: is-strict-def*)
apply *simp*
apply (*simp add: policy-range-comp-def*)
done

lemma *domStart*: $t \in \text{dom } p1 \implies (p1 \oplus p2) t = p1 t$
apply (*simp add: map-add-dom-app-simps*)
done

lemma *notDom*: $x \in \text{dom } A \implies \neg A x = \text{None}$
apply *auto*
done

The following theorems are crucial: they establish the correctness of the distribution.

lemma *Norm-Distr-1*: $((r \text{ o-f } (((\otimes_1) P1 (\text{list2policy } P2)) \text{ o } d)) x =$
 $((\text{list2policy } ((P1 \otimes_L P2) (\otimes_1 r d)) x))$

proof (*induct P2*)
case Nil **show** *?case*
by (*simp add: policy-range-comp-def list2policy-def*)
next
case (*Cons p ps*) **show** *?case* **using** *Cons*
proof (*cases x \in \text{dom } (r \text{ o-f } ((P1 \otimes_1 p) \text{ o } d))*)
case True **show** *?thesis* **using** *True*
by (*auto simp: list2policy-def policy-range-comp-def prod-1-def*
split: option.splits decision.splits prod.splits)
next
case False **show** *?thesis* **using** *Cons False*
by (*auto simp: list2policy-def policy-range-comp-def map-add-dom-app-simps(3)*
prod-1-def
split: option.splits decision.splits prod.splits)

qed
 qed

lemma *Norm-Distr-2*: $((r \text{ o-f } (((\otimes_2) P1 \text{ (list2policy } P2)) \text{ o } d)) \text{ x} =$
 $((\text{list2policy } ((P1 \otimes_L P2) (\otimes_2) r \text{ d})) \text{ x}))$ **proof** (*induct* $P2$)

case *Nil* **show** $?case$
 by (*simp add: policy-range-comp-def list2policy-def*)

next

case (*Cons* $p \text{ ps}$) **show** $?case$ **using** *Cons*
proof (*cases* $x \in \text{dom } (r \text{ o-f } ((P1 \otimes_2 p) \text{ o } d))$)

case *True* **show** $?thesis$ **using** *True*
 by (*auto simp: list2policy-def prod-2-def policy-range-comp-def*
split: option.splits decision.splits prod.splits)

next

case *False* **show** $?thesis$ **using** *Cons False*
 by (*auto simp: policy-range-comp-def list2policy-def map-add-dom-app-simps(3)*
prod-2-def
split: option.splits decision.splits prod.splits)

 qed
 qed

lemma *Norm-Distr-A*: $((r \text{ o-f } (((\otimes_{\vee A}) P1 \text{ (list2policy } P2)) \text{ o } d)) \text{ x} =$
 $((\text{list2policy } ((P1 \otimes_L P2) (\otimes_{\vee A}) r \text{ d})) \text{ x}))$

proof (*induct* $P2$)

case *Nil* **show** $?case$
 by (*simp add: policy-range-comp-def list2policy-def*)

next

case (*Cons* $p \text{ ps}$) **show** $?case$ **using** *Cons*
proof (*cases* $x \in \text{dom } (r \text{ o-f } ((P1 \otimes_{\vee A} p) \text{ o } d))$)

case *True* **show** $?thesis$ **using** *True*
 by (*auto simp: policy-range-comp-def list2policy-def prod-orA-def*
split: option.splits decision.splits prod.splits)

next

case *False* **show** $?thesis$ **using** *Cons False*
 by (*auto simp: policy-range-comp-def list2policy-def map-add-dom-app-simps(3)*
prod-orA-def
split: option.splits decision.splits prod.splits)

 qed
 qed

lemma *Norm-Distr-D*: $((r \text{ o-f } (((\otimes_{\vee D}) P1 \text{ (list2policy } P2)) \text{ o } d)) \text{ x} =$
 $((\text{list2policy } ((P1 \otimes_L P2) (\otimes_{\vee D}) r \text{ d})) \text{ x}))$

proof (*induct* $P2$)

```

case Nil show ?case
  by (simp add: policy-range-comp-def list2policy-def)
next
case (Cons p ps) show ?case using Cons
proof (cases x ∈ dom (r o-f ((P1 ⊗VD p) ∘ d)))
  case True show ?thesis using True
    by (auto simp: policy-range-comp-def list2policy-def prod-orD-def
      split: option.splits decision.splits prod.splits)
  next
    case False show ?thesis using Cons False
      by (auto simp: policy-range-comp-def list2policy-def map-add-dom-app-simps(3)
        prod-orD-def
          split: option.splits decision.splits prod.splits)
qed
qed

```

Some domain reasoning

```

lemma domSubsetDistr1: dom A = UNIV ⇒ dom ((λ(x, y). x) o-f (A ⊗1 B) o (λ
x. (x,x))) = dom B
apply (rule set-eqI)
apply (rule iffI)
apply (auto simp: prod-1-def policy-range-comp-def dom-def
  split: decision.splits option.splits prod.splits)
done

```

```

lemma domSubsetDistr2: dom A = UNIV ⇒ dom ((λ(x, y). x) o-f (A ⊗2 B) o (λ
x. (x,x))) = dom B
apply (rule set-eqI)
apply (rule iffI)
apply (auto simp: prod-2-def policy-range-comp-def dom-def
  split: decision.splits option.splits prod.splits)
done

```

```

lemma domSubsetDistrA: dom A = UNIV ⇒ dom ((λ(x, y). x) o-f (A ⊗VA B) o
(λ x. (x,x))) = dom B
apply (rule set-eqI)
apply (rule iffI)
apply (auto simp: prod-orA-def policy-range-comp-def dom-def
  split: decision.splits option.splits prod.splits)
done

```

```

lemma domSubsetDistrD: dom A = UNIV ⇒ dom ((λ(x, y). x) o-f (A ⊗VD B) o
(λ x. (x,x))) = dom B
apply (rule set-eqI)

```

```

apply (rule iffI)
apply (auto simp: prod-orD-def policy-range-comp-def dom-def
  split: decision.splits option.splits prod.splits)
done
end

```

2.7 Policy Transformation for Testing

```

theory
  NormalisationTestSpecification
imports
  Normalisation
begin

```

This theory provides functions and theorems which are useful if one wants to test policy which are transformed. Most exist in two versions: one where the domains of the rules of the list (which is the result of a transformation) are pairwise disjoint, and one where this applies not for the last rule in a list (which is usually a default rules).

The examples in the firewall case study provide a good documentation how these theories can be applied.

This invariant establishes that the domains of a list of rules are pairwise disjoint.

```

fun disjDom where
  disjDom (x#xs) = (( $\forall y \in (\text{set } xs). \text{dom } x \cap \text{dom } y = \{\}$ )  $\wedge$  disjDom xs)
|disjDom [] = True

```

```

fun PUTList :: ('a  $\mapsto$  'b)  $\Rightarrow$  'a  $\Rightarrow$  ('a  $\mapsto$  'b) list  $\Rightarrow$  bool
where
  PUTList PUT x (p#ps) = ((x  $\in$  dom p  $\longrightarrow$  (PUT x = p x))  $\wedge$  (PUTList PUT x ps))
|PUTList PUT x [] = True

```

```

lemma distrPUTL1: x  $\in$  dom P  $\Longrightarrow$  (list2policy PL) x = P x
   $\Longrightarrow$  (PUTList PUT x PL  $\Longrightarrow$  (PUT x = P x))

```

```

apply (induct PL)
apply (auto simp: list2policy-def dom-def)
done

```

```

lemma PUTList-None: x  $\notin$  dom (list2policy list)  $\Longrightarrow$  PUTList PUT x list
apply (induct list)
apply (auto simp: list2policy-def dom-def)
done

```

```

lemma PUTList-DomMT:
  ( $\forall y \in \text{set } list. \text{dom } a \cap \text{dom } y = \{\}$ )  $\Longrightarrow$  x  $\in$  (dom a)  $\Longrightarrow$  x  $\notin$  dom (list2policy list)

```

```

apply (induct list)
apply (auto simp: dom-def list2policy-def)
done

```

lemma *distrPUTL2*:

```

 $x \in \text{dom } P \implies (\text{list2policy } PL) x = P x \implies \text{disjDom } PL \implies (PUT x = P x) \implies$ 
 $PUTList\ PUT\ x\ PL$ 
apply (induct PL)
apply (simp-all add: list2policy-def)
apply (auto)[1]
subgoal for a PL p
apply (case-tac x \in dom a)
apply (case-tac list2policy PL x = P x)
apply (simp add: list2policy-def)
apply (rule PUTList-None)
apply (rule-tac a = a in PUTList-DomMT)
apply (simp-all add: list2policy-def dom-def)
done
done

```

lemma *distrPUTL*:

```

 $\llbracket x \in \text{dom } P; (\text{list2policy } PL) x = P x; \text{disjDom } PL \rrbracket \implies (PUT x = P x) = PUTList$ 
 $PUT\ x\ PL$ 
apply (rule iffI)
apply (rule distrPUTL2)
apply (simp-all)
apply (rule-tac PL = PL in distrPUTL1)
apply (auto)
done

```

It makes sense to cater for the common special case where the normalisation returns a list where the last element is a default-catch-all rule. It seems easier to cater for this globally, rather than to require the normalisation procedures to do this.

fun *gatherDomain-aux* **where**

```

gatherDomain-aux (x#xs) = (dom x  $\cup$  (gatherDomain-aux xs))
gatherDomain-aux [] = {}

```

definition *gatherDomain* **where** *gatherDomain p* = (*gatherDomain-aux* (*butlast p*))

definition *PUTListGD* **where** *PUTListGD PUT x p* =

```

(((x  $\notin$  (gatherDomain p)  $\wedge$  x  $\in$  dom (last p))  $\longrightarrow$  PUT x = (last p) x)  $\wedge$ 
(PUTList PUT x (butlast p)))

```

definition *disjDomGD* **where** $disjDomGD\ p = disjDom\ (butlast\ p)$

lemma *distrPUTLG1*: $\llbracket x \in dom\ P; (list2policy\ PL)\ x = P\ x; PUTListGD\ PUT\ x\ PL \rrbracket \implies PUT\ x = P\ x$

apply (*induct PL*)

apply (*simp-all add: domIff PUTListGD-def disjDomGD-def gatherDomain-def list2policy-def*)

apply (*auto simp: dom-def domIff split: if-split-asm*)

done

lemma *distrPUTLG2*:

$PL \neq [] \implies x \in dom\ P \implies (list2policy\ (PL))\ x = P\ x \implies disjDomGD\ PL \implies (PUT\ x = P\ x) \implies PUTListGD\ PUT\ x\ (PL)$

apply (*simp add: PUTListGD-def disjDomGD-def gatherDomain-def list2policy-def*)

apply (*induct PL*)

apply (*auto*)

apply (*metis PUTList-DomMT PUTList-None domI*)

done

lemma *distrPUTLG*:

$\llbracket x \in dom\ P; (list2policy\ PL)\ x = P\ x; disjDomGD\ PL; PL \neq [] \rrbracket \implies (PUT\ x = P\ x) = PUTListGD\ PUT\ x\ PL$

apply (*rule iffI*)

apply (*rule distrPUTLG2*)

apply (*simp-all*)

apply (*rule-tac PL = PL in distrPUTLG1*)

apply (*auto*)

done

end

2.8 Putting Everything Together: UPF

theory

UPF

imports

Normalisation

NormalisationTestSpecification

Analysis

begin

This is the top-level theory for the Unified Policy Framework (UPF) and, thus, builds the base theory for using UPF. For the moment, we only define a set of lemmas for all core UPF definitions that is useful for using UPF:

```
lemmas UPFDefs = UPFCoreDefs ParallelDefs ElementaryPoliciesDefs  
end
```


3 Example

In this chapter, we present a small example application of UPF for modeling access control for a Web service that might be used in a hospital. This scenario is motivated by our formalization of the NHS system [10, 13].

UPF was also successfully used for modeling network security policies such as the ones enforced by firewalls [12, 13]. These models were also used for generating test cases using HOL-TestGen [9].

3.1 Secure Service Specification

```
theory  
  Service  
  imports  
    UPF  
begin
```

In this section, we model a simple Web service and its access control model that allows the staff in a hospital to access health care records of patients.

3.1.1 Datatypes for Modelling Users and Roles

Users

First, we introduce a type for users that we use to model that each staff member has a unique id:

```
type-synonym user = int
```

Similarly, each patient has a unique id:

```
type-synonym patient = int
```

Roles and Relationships

In our example, we assume three different roles for members of the clinical staff:

```
datatype role = ClinicalPractitioner | Nurse | Clerical
```

We model treatment relationships (legitimate relationships) between staff and patients (respectively, their health records. This access control model is inspired by our detailed NHS model.

type-synonym $lr-id = int$
type-synonym $LR = lr-id \rightarrow (user\ set)$

The security context stores all the existing LRs.

type-synonym $\Sigma = patient \rightarrow LR$

The user context stores the roles the users are in.

type-synonym $v = user \rightarrow role$

3.1.2 Modelling Health Records and the Web Service API

Health Records

The content and the status of the entries of a health record

datatype $data = dummyContent$
datatype $status = Open \mid Closed$
type-synonym $entry-id = int$
type-synonym $entry = status \times user \times data$
type-synonym $SCR = (entry-id \rightarrow entry)$
type-synonym $DB = patient \rightarrow SCR$

The Web Service API

The operations provided by the service:

datatype $Operation = createSCR\ user\ role\ patient$
| $appendEntry\ user\ role\ patient\ entry-id\ entry$
| $deleteEntry\ user\ role\ patient\ entry-id$
| $readEntry\ user\ role\ patient\ entry-id$
| $readSCR\ user\ role\ patient$
| $addLR\ user\ role\ patient\ lr-id\ (user\ set)$
| $removeLR\ user\ role\ patient\ lr-id$
| $changeStatus\ user\ role\ patient\ entry-id\ status$
| $deleteSCR\ user\ role\ patient$
| $editEntry\ user\ role\ patient\ entry-id\ entry$

fun $is-createSCR$ **where**
| $is-createSCR\ (createSCR\ u\ r\ p) = True$
| $is-createSCR\ x = False$

fun $is-appendEntry$ **where**
| $is-appendEntry\ (appendEntry\ u\ r\ p\ e\ ei) = True$
| $is-appendEntry\ x = False$

fun $is-deleteEntry$ **where**

is-deleteEntry (*deleteEntry* *u r p e-id*) = *True*
| *is-deleteEntry* *x* = *False*

fun *is-readEntry* **where**
is-readEntry (*readEntry* *u r p e*) = *True*
| *is-readEntry* *x* = *False*

fun *is-readSCR* **where**
is-readSCR (*readSCR* *u r p*) = *True*
| *is-readSCR* *x* = *False*

fun *is-changeStatus* **where**
is-changeStatus (*changeStatus* *u r p s ei*) = *True*
| *is-changeStatus* *x* = *False*

fun *is-deleteSCR* **where**
is-deleteSCR (*deleteSCR* *u r p*) = *True*
| *is-deleteSCR* *x* = *False*

fun *is-addLR* **where**
is-addLR (*addLR* *u r lrid lr us*) = *True*
| *is-addLR* *x* = *False*

fun *is-removeLR* **where**
is-removeLR (*removeLR* *u r p lr*) = *True*
| *is-removeLR* *x* = *False*

fun *is-editEntry* **where**
is-editEntry (*editEntry* *u r p e-id s*) = *True*
| *is-editEntry* *x* = *False*

fun *SCROp* :: (*Operation* × *DB*) → *SCR* **where**
SCROp ((*createSCR* *u r p*), *S*) = *S p*
| *SCROp* ((*appendEntry* *u r p ei e*), *S*) = *S p*
| *SCROp* ((*deleteEntry* *u r p e-id*), *S*) = *S p*
| *SCROp* ((*readEntry* *u r p e*), *S*) = *S p*
| *SCROp* ((*readSCR* *u r p*), *S*) = *S p*
| *SCROp* ((*changeStatus* *u r p s ei*), *S*) = *S p*
| *SCROp* ((*deleteSCR* *u r p*), *S*) = *S p*
| *SCROp* ((*editEntry* *u r p e-id s*), *S*) = *S p*
| *SCROp* *x* = ⊥

fun *patientOfOp* :: *Operation* ⇒ *patient* **where**
patientOfOp (*createSCR* *u r p*) = *p*

```

|patientOfOp (appendEntry u r p e ei) = p
|patientOfOp (deleteEntry u r p e-id) = p
|patientOfOp (readEntry u r p e) = p
|patientOfOp (readSCR u r p) = p
|patientOfOp (changeStatus u r p s ei) = p
|patientOfOp (deleteSCR u r p) = p
|patientOfOp (addLR u r p lr ei) = p
|patientOfOp (removeLR u r p lr) = p
|patientOfOp (editEntry u r p e-id s) = p

```

```

fun userOfOp :: Operation ⇒ user where
  userOfOp (createSCR u r p) = u
|userOfOp (appendEntry u r p e ei) = u
|userOfOp (deleteEntry u r p e-id) = u
|userOfOp (readEntry u r p e) = u
|userOfOp (readSCR u r p) = u
|userOfOp (changeStatus u r p s ei) = u
|userOfOp (deleteSCR u r p) = u
|userOfOp (editEntry u r p e-id s) = u
|userOfOp (addLR u r p lr ei) = u
|userOfOp (removeLR u r p lr) = u

```

```

fun roleOfOp :: Operation ⇒ role where
  roleOfOp (createSCR u r p) = r
|roleOfOp (appendEntry u r p e ei) = r
|roleOfOp (deleteEntry u r p e-id) = r
|roleOfOp (readEntry u r p e) = r
|roleOfOp (readSCR u r p) = r
|roleOfOp (changeStatus u r p s ei) = r
|roleOfOp (deleteSCR u r p) = r
|roleOfOp (editEntry u r p e-id s) = r
|roleOfOp (addLR u r p lr ei) = r
|roleOfOp (removeLR u r p lr) = r

```

```

fun contentOfOp :: Operation ⇒ data where
  contentOfOp (appendEntry u r p ei e) = (snd (snd e))
|contentOfOp (editEntry u r p ei e) = (snd (snd e))

```

```

fun contentStatic :: Operation ⇒ bool where
  contentStatic (appendEntry u r p ei e) = ((snd (snd e)) = dummyContent)
|contentStatic (editEntry u r p ei e) = ((snd (snd e)) = dummyContent)
|contentStatic x = True

```

```

fun allContentStatic where

```

$$\begin{aligned} allContentStatic (x\#xs) &= (contentStatic x \wedge allContentStatic xs) \\ allContentStatic [] &= True \end{aligned}$$

3.1.3 Modelling Access Control

In the following, we define a rather complex access control model for our scenario that extends traditional role-based access control (RBAC) [20] with treatment relationships and sealed envelopes. Sealed envelopes (see [13] for details) are a variant of break-the-glass access control (see [8] for a general motivation and explanation of break-the-glass access control).

Sealed Envelopes

type-synonym $SEPolicy = (Operation \times DB \mapsto unit)$

definition $getEntry :: DB \Rightarrow patient \Rightarrow entry-id \Rightarrow entry\ option\ \mathbf{where}$
 $getEntry\ S\ p\ e-id = (case\ S\ p\ of\ \perp \Rightarrow \perp$
 $\quad | [Scr] \Rightarrow Scr\ e-id)$

definition $userHasAccess :: user \Rightarrow entry \Rightarrow bool\ \mathbf{where}$
 $userHasAccess\ u\ e = ((fst\ e) = Open \vee (fst\ (snd\ e) = u))$

definition $readEntrySE :: SEPolicy\ \mathbf{where}$
 $readEntrySE\ x = (case\ x\ of\ (readEntry\ u\ r\ p\ e-id,\ S) \Rightarrow (case\ getEntry\ S\ p\ e-id\ of$
 $\quad \perp \Rightarrow \perp$
 $\quad | [e] \Rightarrow (if\ (userHasAccess\ u\ e)$
 $\quad \quad then\ [allow\ ()]$
 $\quad \quad else\ [deny\ ()]))$
 $\quad | x \Rightarrow \perp)$

definition $deleteEntrySE :: SEPolicy\ \mathbf{where}$
 $deleteEntrySE\ x = (case\ x\ of\ (deleteEntry\ u\ r\ p\ e-id,\ S) \Rightarrow (case\ getEntry\ S\ p\ e-id\ of$
 $\quad \perp \Rightarrow \perp$
 $\quad | [e] \Rightarrow (if\ (userHasAccess\ u\ e)$
 $\quad \quad then\ [allow\ ()]$
 $\quad \quad else\ [deny\ ()]))$
 $\quad | x \Rightarrow \perp)$

definition $editEntrySE :: SEPolicy\ \mathbf{where}$
 $editEntrySE\ x = (case\ x\ of\ (editEntry\ u\ r\ p\ e-id\ s,\ S) \Rightarrow (case\ getEntry\ S\ p\ e-id\ of$
 $\quad \perp \Rightarrow \perp$
 $\quad | [e] \Rightarrow (if\ (userHasAccess\ u\ e)$
 $\quad \quad then\ [allow\ ()]$
 $\quad \quad else\ [deny\ ()]))$

| $x \Rightarrow \perp$)

definition *SEPolicy* :: *SEPolicy* **where**

SEPolicy = *editEntrySE* \oplus *deleteEntrySE* \oplus *readEntrySE* \oplus *A_U*

lemmas *SEsimps* = *SEPolicy-def* *get-entry-def* *userHasAccess-def*
editEntrySE-def *deleteEntrySE-def* *readEntrySE-def*

Legitimate Relationships

type-synonym *LRPolicy* = (*Operation* \times Σ , *unit*) *policy*

fun *hasLR*:: *user* \Rightarrow *patient* \Rightarrow Σ \Rightarrow *bool* **where**

hasLR *u p* Σ = (*case* Σ *p* *of* $\perp \Rightarrow$ *False*
| [*lrs*] \Rightarrow (\exists *lr*. *lr* \in (*ran* *lrs*) \wedge *u* \in *lr*))

definition *LRPolicy* :: *LRPolicy* **where**

LRPolicy = ($\lambda(x,y)$. (*if* *hasLR* (*userOfOp* *x*) (*patientOfOp* *x*) *y*
then [*allow* ()]
else [*deny* ()]))

definition *createSCRPolicy* :: *LRPolicy* **where**

createSCRPolicy *x* = (*if* (*is-createSCR* (*fst* *x*))
then [*allow* ()]
else \perp)

definition *addLRPolicy* :: *LRPolicy* **where**

addLRPolicy *x* = (*if* (*is-addLR* (*fst* *x*))
then [*allow* ()]
else \perp)

definition *LR-Policy* **where** *LR-Policy* = *createSCRPolicy* \oplus *addLRPolicy* \oplus *LR-Policy* \oplus *A_U*

lemmas *LRsimps* = *LR-Policy-def* *createSCRPolicy-def* *addLRPolicy-def* *LRPolicy-def*

type-synonym *FunPolicy* = (*Operation* \times *DB* \times Σ , *unit*) *policy*

fun *createFunPolicy* :: *FunPolicy* **where**

createFunPolicy ((*createSCR* *u r p*), (*D*, *S*)) = (*if* *p* \in *dom* *D*
then [*deny* ()]
else [*allow* ()])

| *createFunPolicy* *x* = \perp

```

fun addLRFunPolicy :: FunPolicy where
    addLRFunPolicy ((addLR u r p l us),(D,S)) = (if l ∈ dom S
                                                then [deny ()]
                                                else [allow ()])

|addLRFunPolicy x = ⊥

fun removeLRFunPolicy :: FunPolicy where
    removeLRFunPolicy ((removeLR u r p l),(D,S)) = (if l ∈ dom S
                                                then [allow ()]
                                                else [deny ()])

|removeLRFunPolicy x = ⊥

fun readSCRFunPolicy :: FunPolicy where
    readSCRFunPolicy ((readSCR u r p),(D,S)) = (if p ∈ dom D
                                                then [allow ()]
                                                else [deny ()])

|readSCRFunPolicy x = ⊥

fun deleteSCRFunPolicy :: FunPolicy where
    deleteSCRFunPolicy ((deleteSCR u r p),(D,S)) = (if p ∈ dom D
                                                then [allow ()]
                                                else [deny ()])

|deleteSCRFunPolicy x = ⊥

fun changeStatusFunPolicy :: FunPolicy where
    changeStatusFunPolicy (changeStatus u r p e s,(d,S)) =
        (case d p of [x] ⇒ (if e ∈ dom x
                            then [allow ()]
                            else [deny ()])
         | - ⇒ [deny ()])

|changeStatusFunPolicy x = ⊥

fun deleteEntryFunPolicy :: FunPolicy where
    deleteEntryFunPolicy (deleteEntry u r p e,(d,S)) =
        (case d p of [x] ⇒ (if e ∈ dom x
                            then [allow ()]
                            else [deny ()])
         | - ⇒ [deny ()])

|deleteEntryFunPolicy x = ⊥

fun readEntryFunPolicy :: FunPolicy where
    readEntryFunPolicy (readEntry u r p e,(d,S)) =
        (case d p of [x] ⇒ (if e ∈ dom x

```

$$\begin{aligned}
& \text{then } \lfloor \text{allow } () \rfloor \\
& \text{else } \lfloor \text{deny } () \rfloor \\
& | - \Rightarrow \lfloor \text{deny } () \rfloor \\
\text{readEntryFunPolicy } x = \perp
\end{aligned}$$

fun *appendEntryFunPolicy* :: *FunPolicy* **where**
appendEntryFunPolicy (*appendEntry u r p e ed*,(*d,S*)) =
 (case *d p of* [*x*] \Rightarrow (if $e \in \text{dom } x$
 then $\lfloor \text{deny } () \rfloor$
 else $\lfloor \text{allow } () \rfloor$)
 | - \Rightarrow $\lfloor \text{deny } () \rfloor$)
appendEntryFunPolicy *x* = \perp

fun *editEntryFunPolicy* :: *FunPolicy* **where**
editEntryFunPolicy (*editEntry u r p ei e*,(*d,S*)) =
 (case *d p of* [*x*] \Rightarrow (if $ei \in \text{dom } x$
 then $\lfloor \text{allow } () \rfloor$
 else $\lfloor \text{deny } () \rfloor$)
 | - \Rightarrow $\lfloor \text{deny } () \rfloor$)
editEntryFunPolicy *x* = \perp

definition *FunPolicy* **where**

$$\begin{aligned}
\text{FunPolicy} = & \text{editEntryFunPolicy} \oplus \text{appendEntryFunPolicy} \oplus \\
& \text{readEntryFunPolicy} \oplus \text{deleteEntryFunPolicy} \oplus \\
& \text{changeStatusFunPolicy} \oplus \text{deleteSCRFunPolicy} \oplus \\
& \text{removeLRFunPolicy} \oplus \text{readSCRFunPolicy} \oplus \\
& \text{addLRFunPolicy} \oplus \text{createFunPolicy} \oplus A_U
\end{aligned}$$

Modelling Core RBAC

type-synonym *RBACPolicy* = *Operation* $\times v \mapsto \text{unit}$

definition *RBAC* :: (*role* \times *Operation*) *set* **where**

$$\begin{aligned}
\text{RBAC} = & \{(r,f). r = \text{Nurse} \wedge \text{is-readEntry } f\} \cup \\
& \{(r,f). r = \text{Nurse} \wedge \text{is-readSCR } f\} \cup \\
& \{(r,f). r = \text{ClinicalPractitioner} \wedge \text{is-appendEntry } f\} \cup \\
& \{(r,f). r = \text{ClinicalPractitioner} \wedge \text{is-deleteEntry } f\} \cup \\
& \{(r,f). r = \text{ClinicalPractitioner} \wedge \text{is-readEntry } f\} \cup \\
& \{(r,f). r = \text{ClinicalPractitioner} \wedge \text{is-readSCR } f\} \cup \\
& \{(r,f). r = \text{ClinicalPractitioner} \wedge \text{is-changeStatus } f\} \cup \\
& \{(r,f). r = \text{ClinicalPractitioner} \wedge \text{is-editEntry } f\} \cup \\
& \{(r,f). r = \text{Clerical} \wedge \text{is-createSCR } f\} \cup \\
& \{(r,f). r = \text{Clerical} \wedge \text{is-deleteSCR } f\} \cup \\
& \{(r,f). r = \text{Clerical} \wedge \text{is-addLR } f\} \cup
\end{aligned}$$

$$\{(r,f). r = \text{Clerical} \wedge \text{is-removeLR } f\}$$

definition *RBACPolicy* :: *RBACPolicy* **where**

RBACPolicy = $(\lambda (f,uc).$

 if $((\text{roleOfOp } f,f) \in \text{RBAC} \wedge [\text{roleOfOp } f] = uc (\text{userOfOp } f))$

 then $[\text{allow } ()]$

 else $[\text{deny } ()]$)

3.1.4 The State Transitions and Output Function

State Transition

fun *OpSuccessDB* :: $(\text{Operation} \times \text{DB}) \rightarrow \text{DB}$ **where**

OpSuccessDB (*createSCR* *u r p*,*S*) = $(\text{case } S \text{ p of } \perp \Rightarrow [S(p \mapsto \emptyset)]$
 $| [x] \Rightarrow [S])$

$| \text{OpSuccessDB } ((\text{appendEntry } u \text{ r p } ei \text{ e}),S) =$
 $(\text{case } S \text{ p of } \perp \Rightarrow [S]$
 $| [x] \Rightarrow ((\text{if } ei \in (\text{dom } x)$
 $\quad \text{then } [S]$
 $\quad \text{else } [S(p \mapsto x(ei \mapsto e))]))))$

$| \text{OpSuccessDB } ((\text{deleteSCR } u \text{ r p}),S) = (\text{Some } (S(p := \perp)))$

$| \text{OpSuccessDB } ((\text{deleteEntry } u \text{ r p } ei),S) =$
 $(\text{case } S \text{ p of } \perp \Rightarrow [S]$
 $| [x] \Rightarrow \text{Some } (S(p \mapsto (x(ei := \perp))))))$

$| \text{OpSuccessDB } ((\text{changeStatus } u \text{ r p } ei \text{ s}),S) =$
 $(\text{case } S \text{ p of } \perp \Rightarrow [S]$
 $| [x] \Rightarrow (\text{case } x \text{ ei of}$
 $\quad [e] \Rightarrow [S(p \mapsto x(ei \mapsto (s, \text{snd } e)))]$
 $\quad | \perp \Rightarrow [S]))$

$| \text{OpSuccessDB } ((\text{editEntry } u \text{ r p } ei \text{ e}),S) =$
 $(\text{case } S \text{ p of } \perp \Rightarrow [S]$
 $| [x] \Rightarrow (\text{case } x \text{ ei of}$
 $\quad [e] \Rightarrow [S(p \mapsto (x(ei \mapsto (e))))]$
 $\quad | \perp \Rightarrow [S]))$

$| \text{OpSuccessDB } (x,S) = [S]$

fun *OpSuccessSigma* :: $(\text{Operation} \times \Sigma) \rightarrow \Sigma$ **where**

OpSuccessSigma (*addLR* *u r p lr-id us*,*S*) =
 $(\text{case } S \text{ p of } [lrs] \Rightarrow (\text{case } (lrs \text{ lr-id}) \text{ of}$
 $\quad \perp \Rightarrow [S(p \mapsto (lrs(\text{lr-id} \mapsto us)))]$
 $\quad | [x] \Rightarrow [S])$
 $| \perp \Rightarrow [S(p \mapsto (\text{Map.empty}(\text{lr-id} \mapsto us)))]))$

$| \text{OpSuccessSigma } (\text{removeLR } u \text{ r p } lr\text{-id},S) =$

$$\begin{aligned} & (\text{case } S \text{ p of Some lrs} \Rightarrow \lfloor S(p \mapsto (\text{lrs}(lr\text{-id} := \perp))) \rfloor \\ & \quad \mid \perp \Rightarrow \lfloor S \rfloor) \\ \text{OpSuccessSigma } (x, S) &= \lfloor S \rfloor \end{aligned}$$

fun *OpSuccessUC* :: (*Operation* × *v*) → *v* **where**
OpSuccessUC (*f*, *u*) = $\lfloor u \rfloor$

Output

type-synonym *Output* = *unit*

fun *OpSuccessOutput* :: (*Operation*) → *Output* **where**
OpSuccessOutput *x* = $\lfloor () \rfloor$

fun *OpFailOutput* :: *Operation* → *Output* **where**
OpFailOutput *x* = $\lfloor () \rfloor$

3.1.5 Combine All Parts

definition *SE-LR-Policy* :: (*Operation* × *DB* × Σ , *unit*) *policy* **where**
SE-LR-Policy = $(\lambda(x, x). x) \circ_f (\text{SEPolicy} \otimes_{\vee D} \text{LR-Policy}) \circ (\lambda(a, b, c). ((a, b), a, c))$

definition *SE-LR-FUN-Policy* :: (*Operation* × *DB* × Σ , *unit*) *policy* **where**
SE-LR-FUN-Policy = $((\lambda(x, x). x) \circ_f (\text{FunPolicy} \otimes_{\vee D} \text{SE-LR-Policy}) \circ (\lambda a. (a, a)))$

definition *SE-LR-RBAC-Policy* :: (*Operation* × *DB* × Σ × *v*, *unit*) *policy* **where**
SE-LR-RBAC-Policy = $(\lambda(x, x). x) \circ_f (\text{RBACPolicy} \otimes_{\vee D} \text{SE-LR-FUN-Policy}) \circ (\lambda(a, b, c, d). ((a, d), (a, b, c)))$

definition *ST-Allow* :: *Operation* × *DB* × Σ × *v* → *Output* × *DB* × Σ × *v*
where *ST-Allow* = $((\text{OpSuccessOutput} \otimes_M (\text{OpSuccessDB} \otimes_S \text{OpSuccessSigma} \otimes_S \text{OpSuccessUC})) \circ ((\lambda(a, b, c). ((a), (a, b, c))))$

definition *ST-Deny* :: *Operation* × *DB* × Σ × *v* → *Output* × *DB* × Σ × *v*
where *ST-Deny* = $(\lambda(\text{ope}, \text{sp}, \text{si}, \text{uc}). \text{Some } ((\text{ope}, \text{sp}, \text{si}, \text{uc})))$

definition *SE-LR-RBAC-ST-Policy* :: *Operation* × *DB* × Σ × *v* → *Output* × *DB* ×

$\Sigma \times v$
where $SE\text{-LR-RBAC-ST-Policy} = ((\lambda (x,y).y)$
 $o_f ((ST\text{-Allow},ST\text{-Deny}) \otimes_{\nabla} SE\text{-LR-RBAC-Policy})$
 $o (\lambda x.(x,x)))$

definition $PolMon :: Operation \Rightarrow (Output\ decision, DB \times \Sigma \times v) MON_{SE}$
where $PolMon = (policy2MON\ SE\text{-LR-RBAC-ST-Policy})$

end

3.2 Instantiating Our Secure Service Example

theory

ServiceExample

imports

Service

begin

In the following, we briefly present an instantiations of our secure service example from the last section. We assume three different members of the health care staff and two patients:

3.2.1 Access Control Configuration

definition $alice :: user$ **where** $alice = 1$

definition $bob :: user$ **where** $bob = 2$

definition $charlie :: user$ **where** $charlie = 3$

definition $patient1 :: patient$ **where** $patient1 = 5$

definition $patient2 :: patient$ **where** $patient2 = 6$

definition $UC0 :: v$ **where**

$UC0 = Map.empty(alice \mapsto Nurse, bob \mapsto ClinicalPractitioner, charlie \mapsto Clerical)$

definition $entry1 :: entry$ **where**

$entry1 = (Open,alice, dummyContent)$

definition $entry2 :: entry$ **where**

$entry2 = (Closed,bob, dummyContent)$

definition $entry3 :: entry$ **where**

$entry3 = (Closed,alice, dummyContent)$

definition $SCR1 :: SCR$ **where**

$SCR1 = (Map.empty(1 \mapsto entry1))$

definition *SCR2* :: *SCR* **where**

SCR2 = (*Map.empty*)

definition *Spine0* :: *DB* **where**

Spine0 = *Map.empty*(*patient1* ↦ *SCR1*, *patient2* ↦ *SCR2*)

definition *LR1* :: *LR* **where**

LR1 = (*Map.empty*(1 ↦ {*alice*}))

definition $\Sigma 0$:: Σ **where**

$\Sigma 0$ = (*Map.empty*(*patient1* ↦ *LR1*))

3.2.2 The Initial System State

definition $\sigma 0$:: *DB* × Σ × *v* **where**

$\sigma 0$ = (*Spine0*, $\Sigma 0$, *UC0*)

3.2.3 Basic Properties

lemma [*simp*]: (*case a of allow d* ⇒ [*X*] | *deny d2* ⇒ [*Y*]) = ⊥ ⇒ *False*

by (*case-tac a, simp-all*)

lemma [*cong, simp*]:

((*if hasLR urp1-alice 1* $\Sigma 0$ then [*allow* ()] else [*deny* ()]) = ⊥) = *False*

by (*simp*)

lemmas *MonSimps* = *valid-SE-def unit-SE-def bind-SE-def*

lemmas *Psplits* = *option.splits unit.splits prod.splits decision.splits*

lemmas *PolSimps* = *valid-SE-def unit-SE-def bind-SE-def if-splits policy2MON-def*
SE-LR-RBAC-ST-Policy-def map-add-def id-def LRsimps prod-2-def
RBACPolicy-def

SE-LR-Policy-def SEPpolicy-def RBAC-def deleteEntrySE-def editEntrySE-def

readEntrySE-def $\sigma 0$ -*def* $\Sigma 0$ -*def* *UC0-def patient1-def patient2-def LR1-def*

alice-def bob-def charlie-def get-entry-def SE-LR-RBAC-Policy-def Allow-def

Deny-def dom-restrict-def policy-range-comp-def prod-orA-def prod-orD-def

ST-Allow-def ST-Deny-def Spine0-def SCR1-def SCR2-def entry1-def
entry2-def

entry3-def FunPolicy-def SE-LR-FUN-Policy-def o-def image-def UPFDefs

lemma *SE-LR-RBAC-Policy* ((*createSCR* *alice Clerical patient1*), $\sigma\theta$)= *Some* (*deny* ())
by (*simp* *add: PolSimps*)

lemma *exBool*[*simp*]: $\exists a::\text{bool}. a$
by *auto*

lemma *deny-allow*[*simp*]: [*deny* ()] \notin *Some* ‘*range allow*
by *auto*

lemma *allow-deny*[*simp*]: [*allow* ()] \notin *Some* ‘*range deny*
by *auto*

Policy as monad. Alice using her first urp can read the SCR of patient1.

lemma
 $(\sigma\theta \models (os \leftarrow \text{mbind } [(createSCR \text{ alice Clerical patient1})] (PolMon);$
 $(return (os = [(deny (Out)]))))))$
by (*simp* *add: PolMon-def MonSimps PolSimps*)

Presenting her other urp, she is not allowed to read it.

lemma *SE-LR-RBAC-Policy* ((*appendEntry* *alice Clerical patient1 ei d*), $\sigma\theta$)= [*deny* ()]
by (*simp* *add: PolSimps*)

end

4 Conclusion and Related Work

4.1 Related Work

With Barker [3], our UPF shares the observation that a broad range of access control models can be reduced to a surprisingly small number of primitives together with a set of combinators or relations to build more complex policies. We also share the vision that the semantics of access control models should be formally defined. In contrast to [3], UPF uses higher-order constructs and, more importantly, is geared towards machine support for (formally) transforming policies and supporting model-based test case generation approaches.

4.2 Conclusion Future Work

We have presented a uniform framework for modelling security policies. This might be regarded as merely an interesting academic exercise in the art of abstraction, especially given the fact that underlying core concepts are logically equivalent, but presented remarkably different from—apparently simple—security textbook formalisations. However, we have successfully used the framework to model fully the large and complex information governance policy of a national health-care record system as described in the official documents [10] as well as network policies [12]. Thus, we have shown the framework being able to accommodate relatively conventional RBAC [20] mechanisms alongside less common ones such as Legitimate Relationships. These security concepts are modelled separately and combined into one global access control mechanism. Moreover, we have shown the practical relevance of our model by using it in our test generation system HOL-TestGen [9], translating informal security requirements into formal test specifications to be processed to test sequences for a distributed system consisting of applications accessing a central record storage system.

Besides applying our framework to other access control models, we plan to develop specific test case generation algorithms. Such domain-specific algorithms allow, by exploiting knowledge about the structure of access control models, respectively the UPF, for a deeper exploration of the test space. Finally, this results in an improved test coverage.

5 Appendix

5.1 Basic Monad Theory for Sequential Computations

```
theory
  Monads
  imports
    Main
begin
```

5.1.1 General Framework for Monad-based Sequence-Test

As such, Higher-order Logic as a purely functional specification formalism has no built-in mechanism for state and state-transitions. Forms of testing involving state require therefore explicit mechanisms for their treatment inside the logic; a well-known technique to model states inside purely functional languages are *monads* made popular by Wadler and Moggi and extensively used in Haskell. HOL is powerful enough to represent the most important standard monads; however, it is not possible to represent monads as such due to well-known limitations of the Hindley-Milner type-system.

Here is a variant for state-exception monads, that models precisely transition functions with preconditions. Next, we declare the state-backtrack-monad. In all of them, our concept of i/o-stepping functions can be formulated; these are functions mapping input to a given monad. Later on, we will build the usual concepts of:

1. deterministic i/o automata,
2. non-deterministic i/o automata, and
3. labelled transition systems (LTS)

State Exception Monads

type-synonym $(\prime o, \prime \sigma) \text{MON}_{SE} = \prime \sigma \rightarrow (\prime o \times \prime \sigma)$

definition $\text{bind-SE} :: (\prime o, \prime \sigma) \text{MON}_{SE} \Rightarrow (\prime o \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SE}) \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SE}$

where $\text{bind-SE } f g = (\lambda \sigma. \text{case } f \sigma \text{ of } \text{None} \Rightarrow \text{None}$
 $\quad \quad \quad | \text{Some } (out, \sigma') \Rightarrow g \text{ out } \sigma')$

notation $\text{bind-SE } (\text{bind}_{SE})$

syntax

$-bind-SE :: [pttrn, ('o, 'σ)MON_{SE}, ('o', 'σ)MON_{SE}] ⇒ ('o', 'σ)MON_{SE}$
 $((2 - ← -; -) [5, 8, 8] 8)$

translations

$x ← f; g ⇒ CONST bind-SE f (% x . g)$

definition $unit-SE :: 'o ⇒ ('o, 'σ)MON_{SE} ((return -) 8)$

where $unit-SE e = (λσ. Some(e, σ))$

notation $unit-SE (unit_{SE})$

definition $fail_{SE} :: ('o, 'σ)MON_{SE}$

where $fail_{SE} = (λσ. None)$

notation $fail_{SE} (fail_{SE})$

definition $assert-SE :: ('σ ⇒ bool) ⇒ (bool, 'σ)MON_{SE}$

where $assert-SE P = (λσ. if P σ then Some(True, σ) else None)$

notation $assert-SE (assert_{SE})$

definition $assume-SE :: ('σ ⇒ bool) ⇒ (unit, 'σ)MON_{SE}$

where $assume-SE P = (λσ. if ∃ σ . P σ then Some((), SOME σ . P σ) else None)$

notation $assume-SE (assume_{SE})$

definition $if-SE :: ['σ ⇒ bool, ('α, 'σ)MON_{SE}, ('α, 'σ)MON_{SE}] ⇒ ('α, 'σ)MON_{SE}$

where $if-SE c E F = (λσ. if c σ then E σ else F σ)$

notation $if-SE (if_{SE})$

The standard monad theorems about unit and associativity:

lemma $bind-left-unit : (x ← return a; k) = k$

apply ($simp add: unit-SE-def bind-SE-def$)

done

lemma $bind-right-unit: (x ← m; return x) = m$

apply ($simp add: unit-SE-def bind-SE-def$)

apply ($rule ext$)

subgoal for $σ$

apply ($case-tac m σ$)

apply ($simp-all$)

done

done

lemma $bind-assoc: (y ← (x ← m; k); h) = (x ← m; (y ← k; h))$

apply ($simp add: unit-SE-def bind-SE-def$)

apply ($rule ext$)

subgoal for $σ$

apply ($case-tac m σ, simp-all$)

```

subgoal for  $a$ 
  apply (case-tac  $a$ , simp-all)
  done
done
done

```

In order to express test-sequences also on the object-level and to make our theory amenable to formal reasoning over test-sequences, we represent them as lists of input and generalize the bind-operator of the state-exception monad accordingly. The approach is straightforward, but comes with a price: we have to encapsulate all input and output data into one type. Assume that we have a typed interface to a module with the operations op_1, op_2, \dots, op_n with the inputs $\iota_1, \iota_2, \dots, \iota_n$ (outputs are treated analogously). Then we can encode for this interface the general input - type:

$$\text{datatype in} = op_1 :: \iota_1 \mid \dots \mid \iota_n$$

Obviously, we loose some type-safety in this approach; we have to express that in traces only *corresponding* input and output belonging to the same operation will occur; this form of side-conditions have to be expressed inside HOL. From the user perspective, this will not make much difference, since junk-data resulting from too weak typing can be ruled out by adopted front-ends.

In order to express test-sequences also on the object-level and to make our theory amenable to formal reasoning over test-sequences, we represent them as lists of input and generalize the bind-operator of the state-exception monad accordingly. Thus, the notion of test-sequence is mapped to the notion of a *computation*, a semantic notion; at times we will use reifications of computations, i.e. a data-type in order to make computation amenable to case-splitting and meta-theoretic reasoning. To this end, we have to encapsulate all input and output data into one type. Assume that we have a typed interface to a module with the operations op_1, op_2, \dots, op_n with the inputs $\iota_1, \iota_2, \dots, \iota_n$ (outputs are treated analogously). Then we can encode for this interface the general input - type:

$$\text{datatype in} = op_1 :: \iota_1 \mid \dots \mid \iota_n$$

Obviously, we loose some type-safety in this approach; we have to express that in traces only *corresponding* input and output belonging to the same operation will occur; this form of side-conditions have to be expressed inside HOL. From the user perspective, this will not make much difference, since junk-data resulting from too weak typing can be ruled out by adopted front-ends.

Note that the subsequent notion of a test-sequence allows the io stepping function (and the special case of a program under test) to stop execution *within* the sequence; such premature terminations are characterized by an output list which is shorter than the input list. Note that our primary notion of multiple execution ignores failure and reports failure steps only by missing results ...

```

fun   mbind :: ' $\iota$  list  $\Rightarrow$  ( $\iota \Rightarrow$  ( $'o, 'σ$ )  $MON_{SE}$ )  $\Rightarrow$  ( $'o$  list,  $'σ$ )  $MON_{SE}$ 

```

```

where mbind [] iostep  $\sigma = \text{Some}([], \sigma) \mid$ 
  mbind (a#H) iostep  $\sigma =$ 
    (case iostep a  $\sigma$  of
      None  $\Rightarrow \text{Some}([], \sigma)$ 
       $\mid \text{Some} (out, \sigma') \Rightarrow (\text{case } mbind\ H\ iostep\ \sigma' \text{ of}$ 
        None  $\Rightarrow \text{Some}([out], \sigma')$ 
         $\mid \text{Some}(outs, \sigma'') \Rightarrow \text{Some}(out\#outs, \sigma''))$ )

```

As mentioned, this definition is fail-safe; in case of an exception, the current state is maintained, no result is reported. An alternative is the fail-strict variant *mbind'* defined below.

```

lemma mbind-unit [simp]: mbind [] f = (return [])
by(rule ext, simp add: unit-SE-def)

```

```

lemma mbind-nofailure [simp]: mbind S f  $\sigma \neq \text{None}$ 
apply (rule-tac x= $\sigma$  in spec)
apply (induct S)
using mbind.simps(1) apply force
apply(simp add:unit-SE-def)
apply(safe)[1]
subgoal for a S x
  apply (case-tac f a x)
  apply(simp)
  apply(safe)[1]
  subgoal for aa b
    apply (erule-tac x=b in allE)
    apply (erule exE)+
    apply (simp)
  done
done
done

```

The fail-strict version of *mbind'* looks as follows:

```

fun mbind' :: 'l list  $\Rightarrow$  (l  $\Rightarrow$  (o, $\sigma$ ) MONSE)  $\Rightarrow$  (o list, $\sigma$ ) MONSE
where mbind' [] iostep  $\sigma = \text{Some}([], \sigma) \mid$ 
  mbind' (a#H) iostep  $\sigma =$ 
    (case iostep a  $\sigma$  of
      None  $\Rightarrow \text{None}$ 
       $\mid \text{Some} (out, \sigma') \Rightarrow (\text{case } mbind\ H\ iostep\ \sigma' \text{ of}$ 
        None  $\Rightarrow \text{None}$  — fail-strict
         $\mid \text{Some}(outs, \sigma'') \Rightarrow \text{Some}(out\#outs, \sigma''))$ )

```

mbind' as failure strict operator can be seen as a foldr on bind—if the types would match ...

definition $try\text{-}SE :: ('o, 'σ) MON_{SE} ⇒ ('o\ option, 'σ) MON_{SE}$

where $try\text{-}SE\ ioprogram = (\lambda\sigma. case\ ioprogram\ \sigma\ of$
 $\quad None \Rightarrow Some(None, \sigma)$
 $\quad | Some(outs, \sigma') \Rightarrow Some(Some\ outs, \sigma'))$

In contrast $mbind$ as a failure safe operator can roughly be seen as a $foldr$ on $bind$ - try : $m1 ; try\ m2 ; try\ m3 ; \dots$. Note, that the rough equivalence only holds for certain predicates in the sequence - length equivalence modulo $None$, for example. However, if a conditional is added, the equivalence can be made precise:

lemma $mbind\text{-}try$:

$(x \leftarrow mbind\ (a\#S)\ F; M\ x) =$
 $(a' \leftarrow try\text{-}SE(F\ a);$
 $\quad if\ a' = None$
 $\quad then\ (M\ [])$
 $\quad else\ (x \leftarrow mbind\ S\ F; M\ (the\ a' \# x)))$

apply ($rule\ ext$)

apply ($simp\ add: bind\text{-}SE\text{-}def\ try\text{-}SE\text{-}def$)

subgoal for x

apply ($case\text{-}tac\ F\ a\ x$)

apply ($simp$)

apply ($safe$)[1]

apply ($simp\ add: bind\text{-}SE\text{-}def\ try\text{-}SE\text{-}def$)

subgoal for $aa\ b$

apply ($case\text{-}tac\ mbind\ S\ F\ b$)

apply ($auto$)

done

done

done

On this basis, a symbolic evaluation scheme can be established that reduces $mbind$ -code to $try\text{-}SE$ -code and If-cascades.

definition $alt\text{-}SE :: [('o, 'σ) MON_{SE}, ('o, 'σ) MON_{SE}] ⇒ ('o, 'σ) MON_{SE}$ (**infixl** $\sqcap_{SE}\ 10$)

where $(f\ \sqcap_{SE}\ g) = (\lambda\sigma. case\ f\ \sigma\ of\ None \Rightarrow g\ \sigma$
 $\quad | Some\ H \Rightarrow Some\ H)$

definition $malt\text{-}SE :: ('o, 'σ) MON_{SE}\ list \Rightarrow ('o, 'σ) MON_{SE}$

where $malt\text{-}SE\ S = foldr\ alt\text{-}SE\ S\ fail_{SE}$

notation $malt\text{-}SE\ (\sqcap_{SE})$

lemma $malt\text{-}SE\text{-}mt\ [simp]: \sqcap_{SE}\ [] = fail_{SE}$

by ($simp\ add: malt\text{-}SE\text{-}def$)

lemma $malt\text{-}SE\text{-}cons\ [simp]: \sqcap_{SE}\ (a\ \# S) = (a\ \sqcap_{SE}\ (\sqcap_{SE}\ S))$

by(*simp add: malt-SE-def*)

State-Backtrack Monads

This subsection is still rudimentary and as such an interesting formal analogue to the previous monad definitions. It is doubtful that it is interesting for testing and as a computational structure at all. Clearly more relevant is “sequence” instead of “set,” which would rephrase Isabelle’s internal tactic concept.

type-synonym $(\prime o, \prime \sigma) \text{MON}_{SB} = \prime \sigma \Rightarrow (\prime o \times \prime \sigma) \text{set}$

definition $\text{bind-SB} :: (\prime o, \prime \sigma) \text{MON}_{SB} \Rightarrow (\prime o \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SB}) \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SB}$

where $\text{bind-SB } f \ g \ \sigma = \bigcup ((\lambda(out, \sigma). (g \ out \ \sigma)) \ ' (f \ \sigma))$

notation $\text{bind-SB } (\text{bind}_{SB})$

definition $\text{unit-SB} :: \prime o \Rightarrow (\prime o, \prime \sigma) \text{MON}_{SB} ((\text{returns } -) \ \delta)$

where $\text{unit-SB } e = (\lambda \sigma. \{(e, \sigma)\})$

notation $\text{unit-SB } (\text{unit}_{SB})$

syntax $\text{-bind-SB} :: [\text{ptrn}, (\prime o, \prime \sigma) \text{MON}_{SB}, (\prime o', \prime \sigma) \text{MON}_{SB}] \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SB}$
 $((\text{?} - := -; -) [5, 8, 8] \ \delta)$

translations

$x := f; g \Rightarrow \text{CONST } \text{bind-SB } f \ (\% \ x \ . \ g)$

lemma $\text{bind-left-unit-SB} : (x := \text{returns } a; m) = m$

apply (*rule ext*)

apply (*simp add: unit-SB-def bind-SB-def*)

done

lemma $\text{bind-right-unit-SB} : (x := m; \text{returns } x) = m$

apply (*rule ext*)

apply (*simp add: unit-SB-def bind-SB-def*)

done

lemma $\text{bind-assoc-SB} : (y := (x := m; k); h) = (x := m; (y := k; h))$

apply (*rule ext*)

apply (*simp add: unit-SB-def bind-SB-def split-def*)

done

State Backtrack Exception Monad

The following combination of the previous two Monad-Constructions allows for the semantic foundation of a simple generic assertion language in the style of Schirmer’s Simpl-Language or Rustan Leino’s Boogie-PL language. The key is to use the exceptional element None for violations of the assert-statement.

type-synonym $(\prime o, \prime \sigma) \text{MON}_{SBE} = \prime \sigma \Rightarrow ((\prime o \times \prime \sigma) \text{ set}) \text{ option}$

definition $\text{bind-SBE} :: (\prime o, \prime \sigma) \text{MON}_{SBE} \Rightarrow (\prime o \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SBE}) \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SBE}$

where $\text{bind-SBE } f g = (\lambda \sigma. \text{ case } f \sigma \text{ of } \text{None} \Rightarrow \text{None}$
 $\quad \quad \quad | \text{Some } S \Rightarrow (\text{let } S' = (\lambda (\text{out}, \sigma'). g \text{ out } \sigma') \text{ ' } S$
 $\quad \quad \quad \text{in if } \text{None} \in S' \text{ then } \text{None}$
 $\quad \quad \quad \text{else } \text{Some}(\bigcup (\text{the ' } S'))))$

syntax $\text{-bind-SBE} :: [\text{pttrn}, (\prime o, \prime \sigma) \text{MON}_{SBE}, (\prime o', \prime \sigma) \text{MON}_{SBE}] \Rightarrow (\prime o', \prime \sigma) \text{MON}_{SBE}$
 $((\text{?} - ::= -; -) [5, 8, 8] 8)$

translations

$x ::= f; g \Rightarrow \text{CONST bind-SBE } f (\% x . g)$

definition $\text{unit-SBE} :: \prime o \Rightarrow (\prime o, \prime \sigma) \text{MON}_{SBE} ((\text{returning } -) 8)$

where $\text{unit-SBE } e = (\lambda \sigma. \text{Some}(\{(e, \sigma)\}))$

definition $\text{assert-SBE} :: (\prime \sigma \Rightarrow \text{bool}) \Rightarrow (\text{unit}, \prime \sigma) \text{MON}_{SBE}$

where $\text{assert-SBE } e = (\lambda \sigma. \text{if } e \sigma \text{ then } \text{Some}(\{(\text{()}, \sigma)\})$
 $\quad \quad \quad \text{else } \text{None})$

notation $\text{assert-SBE } (\text{assert}_{SBE})$

definition $\text{assume-SBE} :: (\prime \sigma \Rightarrow \text{bool}) \Rightarrow (\text{unit}, \prime \sigma) \text{MON}_{SBE}$

where $\text{assume-SBE } e = (\lambda \sigma. \text{if } e \sigma \text{ then } \text{Some}(\{(\text{()}, \sigma)\})$
 $\quad \quad \quad \text{else } \text{Some } \{\})$

notation $\text{assume-SBE } (\text{assume}_{SBE})$

definition $\text{havoc-SBE} :: (\text{unit}, \prime \sigma) \text{MON}_{SBE}$

where $\text{havoc-SBE} = (\lambda \sigma. \text{Some}(\{x. \text{True}\}))$

notation $\text{havoc-SBE } (\text{havoc}_{SBE})$

lemma $\text{bind-left-unit-SBE} : (x ::= \text{returning } a; m) = m$

apply (rule ext)

apply $(\text{simp add: unit-SBE-def bind-SBE-def})$

done

lemma $\text{bind-right-unit-SBE} : (x ::= m; \text{returning } x) = m$

apply (rule ext)

apply $(\text{simp add: unit-SBE-def bind-SBE-def})$

subgoal for x

apply $(\text{case-tac } m \ x)$

apply $(\text{simp-all add: Let-def})$

apply (rule HOL.ccontr)

apply $(\text{simp add: Set.image-iff})$

```

done
done

lemmas aux = trans[OF HOL.neq-commute,OF Option.not-None-eq]

lemma bind-assoc-SBE: (y ≡ (x ≡ m; k); h) = (x ≡ m; (y ≡ k; h))
proof (rule ext, simp add: unit-SBE-def bind-SBE-def, rename-tac x,
  case-tac m x, simp-all add: Let-def Set.image-iff, safe,goal-cases)
  case (1 x a aa b ab ba a b)
  then show ?case by(rule-tac x=(a, b) in bexI, simp-all)
next
  case (2 x a aa b ab ba)
  then show ?case
    apply (rule-tac x=(aa, b) in bexI, simp-all add:split-def)
    apply (erule-tac x=(aa,b) in ballE)
    apply (auto simp: aux image-def split-def intro!: rev-bexI)
  done
next
  case (3 x a a b)
  then show ?case by(rule-tac x=(a, b) in bexI, simp-all)
next
  case (4 x a aa b)
  then show ?case
    apply (erule-tac Q=None = X for X in contrapos-pp)
    apply (erule-tac x=(aa,b) and P=λ x. None ≠ case-prod (λout. k) x in ballE)
    apply (auto simp: aux image-def split-def intro!: rev-bexI)
  done
next
  case (5 x a aa b ab ba a b)
  then show ?case apply simp apply ((erule-tac x=(ab,ba) in ballE)+)
    apply (simp-all add: aux, (erule exE)+, simp add:split-def)
    apply (erule rev-bexI, case-tac None∈(λp. h(snd p))'y,auto simp:split-def)
  done

next
  case (6 x a aa b a b)
  then show ?case apply simp apply ((erule-tac x=(a,b) in ballE)+)
    apply (simp-all add: aux, (erule exE)+, simp add:split-def)
    apply (erule rev-bexI, case-tac None∈(λp. h(snd p))'y,auto simp:split-def)
  done
qed

```


5.1.2 Valid Test Sequences in the State Exception Monad

This is still an unstructured merge of executable monad concepts and specification oriented high-level properties initiating test procedures.

definition *valid-SE* :: ' $\sigma \Rightarrow (bool, 'a) \text{MON}_{SE} \Rightarrow bool$ (**infix** \models 15)
where $(\sigma \models m) = (m \sigma \neq \text{None} \wedge \text{fst}(\text{the } (m \sigma)))$

This notation considers failures as valid—a definition inspired by I/O conformance. Note that it is not possible to define this concept once and for all in a Hindley-Milner type-system. For the moment, we present it only for the state-exception monad, although for the same definition, this notion is applicable to other monads as well.

lemma *syntax-test* :

$\sigma \models (os \leftarrow (\text{mbind } \iota s \text{ ioprogram}); \text{return}(\text{length } \iota s = \text{length } os))$

oops

lemma *valid-true[simp]*: $(\sigma \models (s \leftarrow \text{return } x ; \text{return } (P s))) = P x$
by(*simp add: valid-SE-def unit-SE-def bind-SE-def*)

Recall `mbind_unit` for the base case.

lemma *valid-failure*: $\text{ioprogram } a \sigma = \text{None} \implies$

$(\sigma \models (s \leftarrow \text{mbind } (a\#S) \text{ ioprogram } ; M s)) =$
 $(\sigma \models (M []))$

by(*simp add: valid-SE-def unit-SE-def bind-SE-def*)

lemma *valid-failure'*: $A \sigma = \text{None} \implies \neg(\sigma \models ((s \leftarrow A ; M s)))$

by(*simp add: valid-SE-def unit-SE-def bind-SE-def*)

lemma *valid-successElem*:

$M \sigma = \text{Some}(f \sigma, \sigma) \implies (\sigma \models M) = f \sigma$

by(*simp add: valid-SE-def unit-SE-def bind-SE-def*)

lemma *valid-success*: $\text{ioprogram } a \sigma = \text{Some}(b, \sigma') \implies$

$(\sigma \models (s \leftarrow \text{mbind } (a\#S) \text{ ioprogram } ; M s)) =$
 $(\sigma' \models (s \leftarrow \text{mbind } S \text{ ioprogram } ; M (b\#s)))$

apply (*simp add: valid-SE-def unit-SE-def bind-SE-def*)

apply (*cases mbind S ioprogram sigma', auto*)

done

lemma *valid-success''*: $\text{ioprogram } a \sigma = \text{Some}(b, \sigma') \implies$

$(\sigma \models (s \leftarrow \text{mbind } (a\#S) \text{ ioprogram } ; \text{return } (P s))) =$
 $(\sigma' \models (s \leftarrow \text{mbind } S \text{ ioprogram } ; \text{return } (P (b\#s))))$

```

apply (simp add: valid-SE-def unit-SE-def bind-SE-def )
apply (cases mbind S ioprogram σ')
apply (simp-all)
apply (auto)
done

```

lemma valid-success': $A \sigma = \text{Some}(b, \sigma') \implies (\sigma \models ((s \leftarrow A ; M s))) = (\sigma' \models (M b))$
by(simp add: valid-SE-def unit-SE-def bind-SE-def)

lemma valid-both: $(\sigma \models (s \leftarrow \text{mbind } (a \# S) \text{ ioprogram } ; \text{return } (P s))) =$
 $(\text{case ioprogram } a \ \sigma \ \text{of}$
 $\quad \text{None} \Rightarrow (\sigma \models (\text{return } (P [])))$
 $\quad | \text{Some}(b, \sigma') \Rightarrow (\sigma' \models (s \leftarrow \text{mbind } S \text{ ioprogram } ; \text{return } (P (b \# s))))))$
apply (case-tac ioprogram a σ)
apply (simp-all add: valid-failure valid-success'' split: prod.splits)
done

lemma valid-propagate-1 [simp]: $(\sigma \models (\text{return } P)) = (P)$
by(auto simp: valid-SE-def unit-SE-def)

lemma valid-propagate-2: $\sigma \models ((s \leftarrow A ; M s)) \implies \exists v \sigma'. \text{the}(A \sigma) = (v, \sigma') \wedge \sigma' \models$
 $(M v)$
apply (auto simp: valid-SE-def unit-SE-def bind-SE-def)
apply (cases A σ)
apply (simp-all)
apply (drule-tac x=A σ and f=the in arg-cong)
apply (simp)
apply (rename-tac a b aa)
apply (rule-tac x=fst aa in exI)
apply (rule-tac x=snd aa in exI)
by (auto)

lemma valid-propagate-2': $\sigma \models ((s \leftarrow A ; M s)) \implies \exists a. (A \sigma) = \text{Some } a \wedge (\text{snd } a)$
 $\models (M (\text{fst } a))$
apply (auto simp: valid-SE-def unit-SE-def bind-SE-def)
apply (cases A σ)
apply (simp-all)
apply (simp-all split: prod.splits)
apply (drule-tac x=A σ and f=the in arg-cong)
apply (simp)
apply (rename-tac a b aa x1 x2)
apply (rule-tac x=fst aa in exI)
apply (rule-tac x=snd aa in exI)
apply (auto)

done

lemma *valid-propagate-2''*: $\sigma \models ((s \leftarrow A ; M s)) \implies \exists v \sigma'. A \sigma = \text{Some}(v, \sigma') \wedge \sigma' \models (M v)$

apply (*auto simp: valid-SE-def unit-SE-def bind-SE-def*)
apply (*cases A σ*)
apply (*simp-all*)
apply (*drule-tac x=A σ and f=the in arg-cong*)
apply (*simp*)
apply (*rename-tac a b aa*)
apply (*rule-tac x=fst aa in exI*)
apply (*rule-tac x=snd aa in exI*)
apply (*auto*)
done

lemma *valid-propoagate-3[*simp*]*: $(\sigma_0 \models (\lambda\sigma. \text{Some}(f \sigma, \sigma))) = (f \sigma_0)$
by(*simp add: valid-SE-def*)

lemma *valid-propoagate-3'[*simp*]*: $\neg(\sigma_0 \models (\lambda\sigma. \text{None}))$
by(*simp add: valid-SE-def*)

lemma *assert-disch1* : $P \sigma \implies (\sigma \models (x \leftarrow \text{assert}_{SE} P ; M x)) = (\sigma \models (M \text{True}))$
by(*auto simp: bind-SE-def assert-SE-def valid-SE-def*)

lemma *assert-disch2* : $\neg P \sigma \implies \neg(\sigma \models (x \leftarrow \text{assert}_{SE} P ; M s))$
by(*auto simp: bind-SE-def assert-SE-def valid-SE-def*)

lemma *assert-disch3* : $\neg P \sigma \implies \neg(\sigma \models (\text{assert}_{SE} P))$
by(*auto simp: bind-SE-def assert-SE-def valid-SE-def*)

lemma *assert-D* : $(\sigma \models (x \leftarrow \text{assert}_{SE} P ; M x)) \implies P \sigma \wedge (\sigma \models (M \text{True}))$
by(*auto simp: bind-SE-def assert-SE-def valid-SE-def split: HOL.if-split-asm*)

lemma *assume-D* : $(\sigma \models (x \leftarrow \text{assume}_{SE} P ; M x)) \implies \exists \sigma. (P \sigma \wedge \sigma \models (M ()))$
apply (*auto simp: bind-SE-def assume-SE-def valid-SE-def split: HOL.if-split-asm*)

apply (*rule-tac x=Eps P in exI*)

apply (*auto*)[1]

subgoal for $x a b$

apply (*rule-tac x=True in exI, rule-tac x=b in exI*)

apply (*subst Hilbert-Choice.someI*)

apply (*assumption*)

apply (*simp*)

done

apply (*subst Hilbert-Choice.someI, assumption*)

apply (*simp*)
done

These two rule prove that the SE Monad in connection with the notion of valid sequence is actually sufficient for a representation of a Boogie-like language. The SBE monad with explicit sets of states—to be shown below—is strictly speaking not necessary (and will therefore be discontinued in the development).

lemma *if-SE-D1* : $P \sigma \implies (\sigma \models_{SE} P B_1 B_2) = (\sigma \models B_1)$
by(*auto simp: if-SE-def valid-SE-def*)

lemma *if-SE-D2* : $\neg P \sigma \implies (\sigma \models_{SE} P B_1 B_2) = (\sigma \models B_2)$
by(*auto simp: if-SE-def valid-SE-def*)

lemma *if-SE-split-asm* : $(\sigma \models_{SE} P B_1 B_2) = ((P \sigma \wedge (\sigma \models B_1)) \vee (\neg P \sigma \wedge (\sigma \models B_2)))$
by(*cases P σ , auto simp: if-SE-D1 if-SE-D2*)

lemma *if-SE-split* : $(\sigma \models_{SE} P B_1 B_2) = ((P \sigma \longrightarrow (\sigma \models B_1)) \wedge (\neg P \sigma \longrightarrow (\sigma \models B_2)))$
by(*cases P σ , auto simp: if-SE-D1 if-SE-D2*)

lemma [*code*]: $(\sigma \models m) = (case (m \sigma) of None \Rightarrow False \mid (Some (x,y)) \Rightarrow x)$
apply (*simp add: valid-SE-def*)
apply (*cases m $\sigma = None$*)
apply (*simp-all*)
apply (*insert not-None-eq*)
apply (*auto*)
done

5.1.3 Valid Test Sequences in the State Exception Backtrack Monad

This is still an unstructured merge of executable monad concepts and specification oriented high-level properties initiating test procedures.

definition *valid-SBE* :: $'\sigma \Rightarrow ('a, '\sigma) MON_{SBE} \Rightarrow bool$ (**infix** \models_{SBE} 15)
where $\sigma \models_{SBE} m \equiv (m \sigma \neq None)$

This notation considers all non-failures as valid.

lemma *assume-assert*: $(\sigma \models_{SBE} (- \equiv assume_{SBE} P ; assert_{SBE} Q)) = (P \sigma \longrightarrow Q \sigma)$
by(*simp add: valid-SBE-def assume-SBE-def assert-SBE-def bind-SBE-def*)

lemma *assert-intro*: $Q \sigma \implies \sigma \models_{SBE} (assert_{SBE} Q)$
by(*simp add: valid-SBE-def assume-SBE-def assert-SBE-def bind-SBE-def*)

end

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