Compositional Verification of Secure Applet Interactions

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Introduction

- Growing interest in verification of (control flow based) security properties
- New generation of multi-application smart cards: post-issuance loading of applets
- Decomposition of properties desirable (also useful for management of verification)

A framework for compositional verification

- Program model
- Temporal logic specification language + high level patterns
- Proof system to show correctness of decomposition

Background

- VerifiCard project: reasoning about JavaCard
- Representation of program as call-transfer graph (Jensen, Le Métayer, Thorn, 1999)
- Context Free Processes: efficient model checking algorithms (polynomial in the size of the CFP) (Burkart & Steffen, 1992, Esparza & Schwoon, 2001)
- Compositional proof systems for modal μ-calculus (Dam & Gurov, 1998)

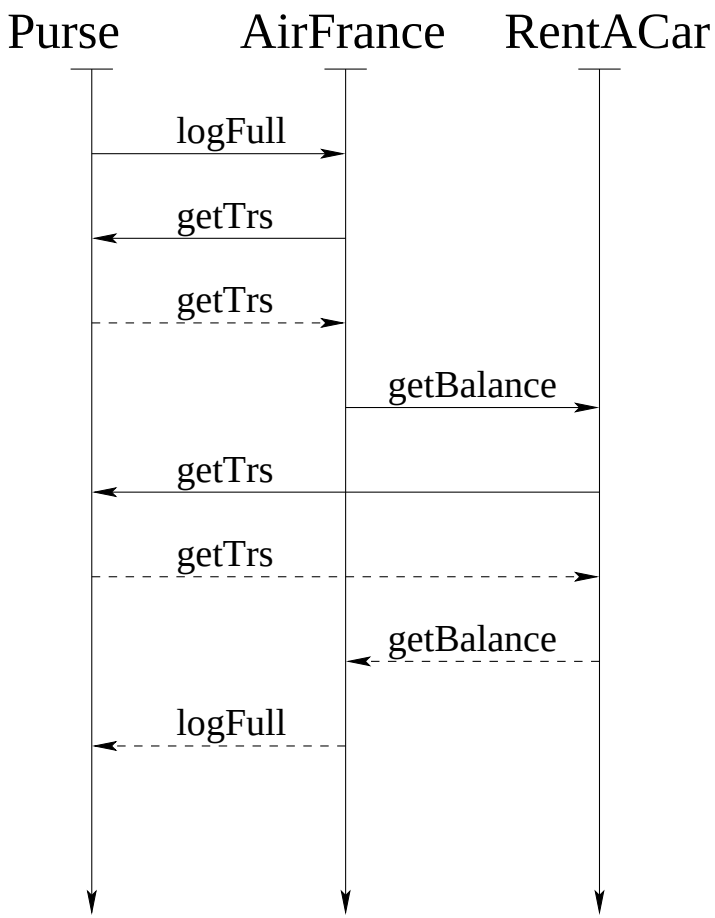
A framework for compositional verification

- Program model
- Temporal logic specification language + high level patterns
- Proof system to show correctness of decomposition

Running example: electronic purse

- Three applets: purse + 2 loyalties (AirFrance, RentACar)
- Purse keeps log table of transactions
- Loyalties can subscribe to `logFull` service
- AirFrance subscribed, RentACar not subscribed
- `logFull`: AirFrance asks purse for transactions, and RentACar for balance
- RentACar deduces that log table is full

Electronic purse: bad scenario



The program model

Compositional program model

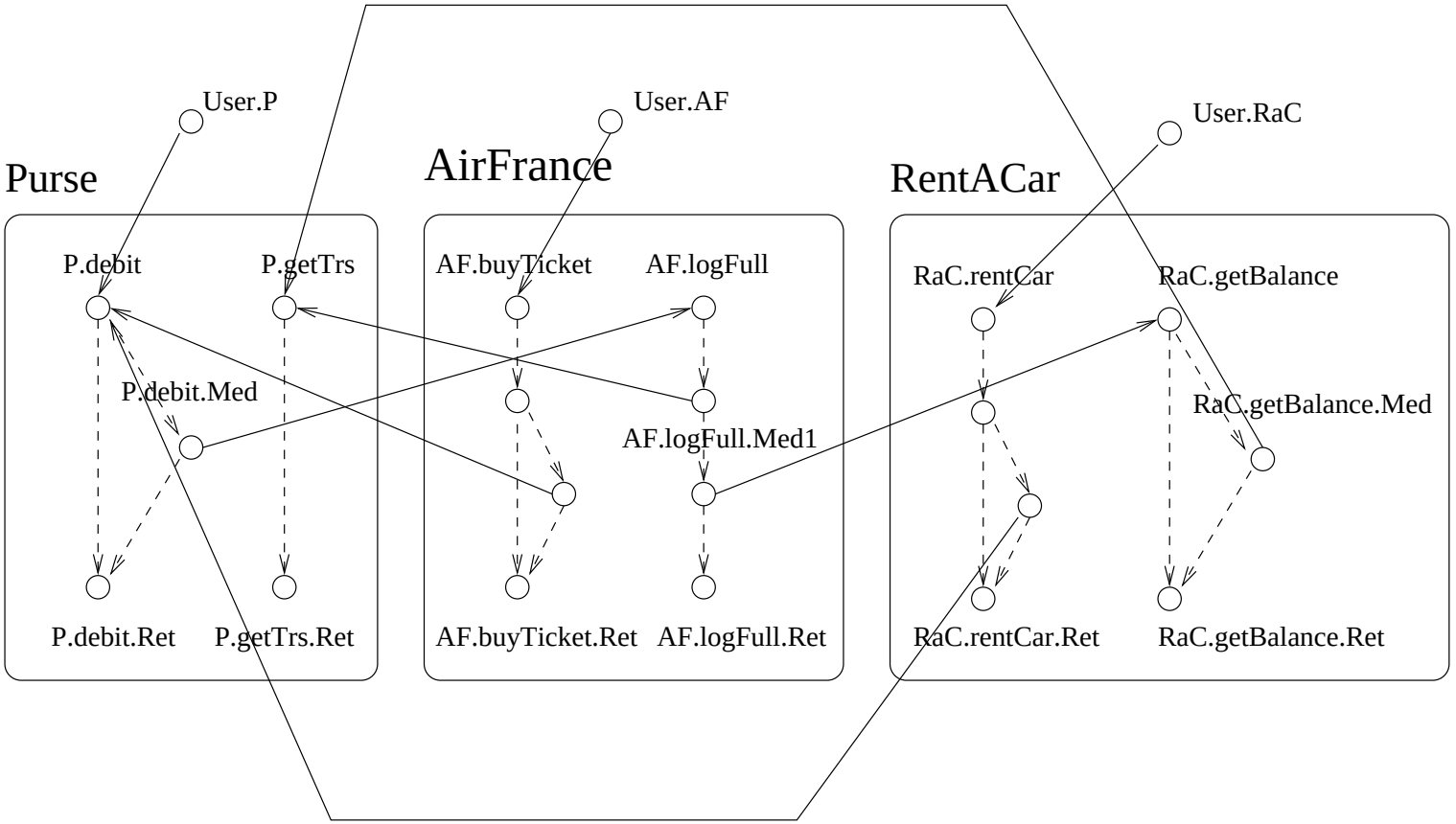
- Program: set of applets, communicating via method invocations and returns
- External program points
- Applet: transfer graph + call graph
- Each applet: local control stack
- Global state: well-formed set of local states
- Transition rules induce operational semantics

Formally

$$\mathcal{M} \triangleq (A, V; \textbf{app}, \textbf{ret}; \rightarrow^T, \rightarrow^C)$$

- A a set of applets
- vertices V are program points
- **app**: $V \rightharpoonup A$ attributes vertices to applets
- set of return vertices identified by **ret**
- program = transfer graph $\rightarrow^T$ + call graph $\rightarrow^C$, distributed over different applets

Example compositional model for electronic purse



Operational semantics

- Two sets of transition rules:
  - Applet transition rules
  - Transition rules to combine behaviour of sets of applets
- Transition labels denote method invocations and returns
  - Perfect actions: internal flow or method invocation/return local to applet set (call, ret)
  - Imperfect actions: method invocation/return over applet set boundaries (call?, call!, ret?, ret!)
- Imperfect actions can synchronise, forming perfect actions

Local state per applet

Every applet has local state: list of pairs, representing the control stack

Example: local states in the Purse

When `AF.logFull.Med1` has been reached:

- $\texttt{Purse}.\pi = \langle \texttt{User.P}, \texttt{P.debit.Med} \rangle \cdot \langle \texttt{P.debit.Med}, \texttt{AF.logFull} \rangle$
- $\texttt{AirFrance}.\pi = \langle \texttt{P.debit.Med}, \texttt{AF.logFull.Med1} \rangle$
- $\texttt{RentACar}.\pi = \epsilon$

States formally

- An applet state of $\mathcal{M}$ is a pair $a.\pi$, where $a \in A$ and $\pi \in (V \times V)^*$
- A program state of $\mathcal{M}$ is a wellformed collection $a_1.\pi_1 \,|\, a_2.\pi_2 \,|\, \ldots \,|\, a_n.\pi_n$ of applet states.

Active

- $a.\pi$ is active iff the last program point in π is local to applet a
- A program state is called active iff it contains an active applet state.

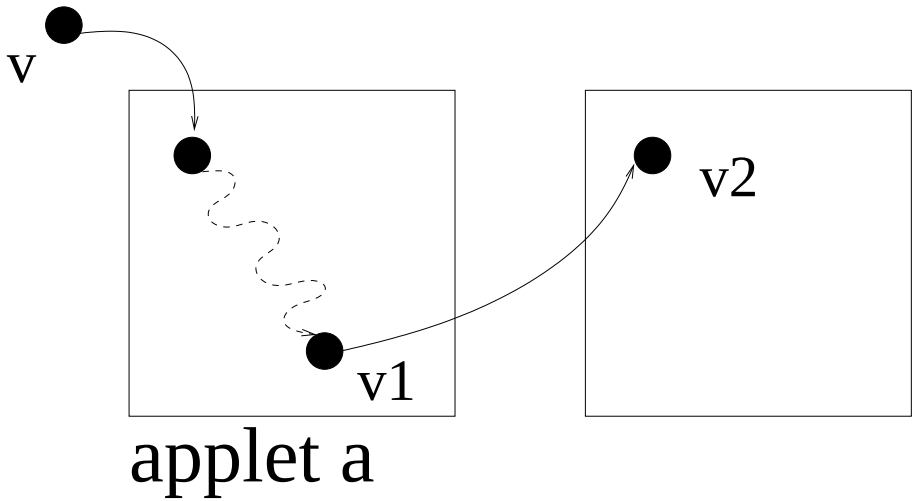
Wellformedness condition on program states

A program state is wellformed iff

- each applet name is mentioned at most once
- at most one applet is active

Example applet transition rule: send call

$$\text{[send call]}\quad \frac{v_1 \rightarrow^{C} v_2 \qquad \mathbf{loc}_a\, v_1 \qquad \neg\mathbf{loc}_a\, v_2}{a.\pi \cdot \langle v, v_1\rangle \xrightarrow{v_1\ \text{call!}\ v_2} a.\pi \cdot \langle v, v_1\rangle \cdot \langle v_1, v_2\rangle}$$



Applet transition rules

$$[\text{local call}]\quad \frac{v_1 \to^{C} v_2 \qquad \mathbf{loc}_a\, v_1 \qquad \mathbf{loc}_a\, v_2}{a.\pi \cdot \langle v, v_1\rangle \xrightarrow{v_1 \text{ call } v_2} a.\pi \cdot \langle v, v_1, \cdot\rangle\, \langle v_1, v_2\rangle}$$

$$[\text{local return}]\quad \frac{v_1 \to^{T} v_2 \qquad \mathbf{loc}_a\, v_1 \qquad \mathbf{loc}_a\, v_3 \qquad \mathbf{ret}\, v_3}{a.\pi \cdot \langle v, v_1\rangle \cdot \langle v_1, v_3\rangle \xrightarrow{v_3 \text{ ret } v_1} a.\pi \cdot \langle v, v_2\rangle}$$

$$[\text{local transfer}]\quad \frac{v_1 \to^{T} v_2 \qquad \mathbf{loc}_a\, v_1 \qquad v_1 \not\to^{C}}{a.\pi \cdot \langle v, v_1\rangle \longrightarrow a.\pi \cdot \langle v, v_2\rangle}$$

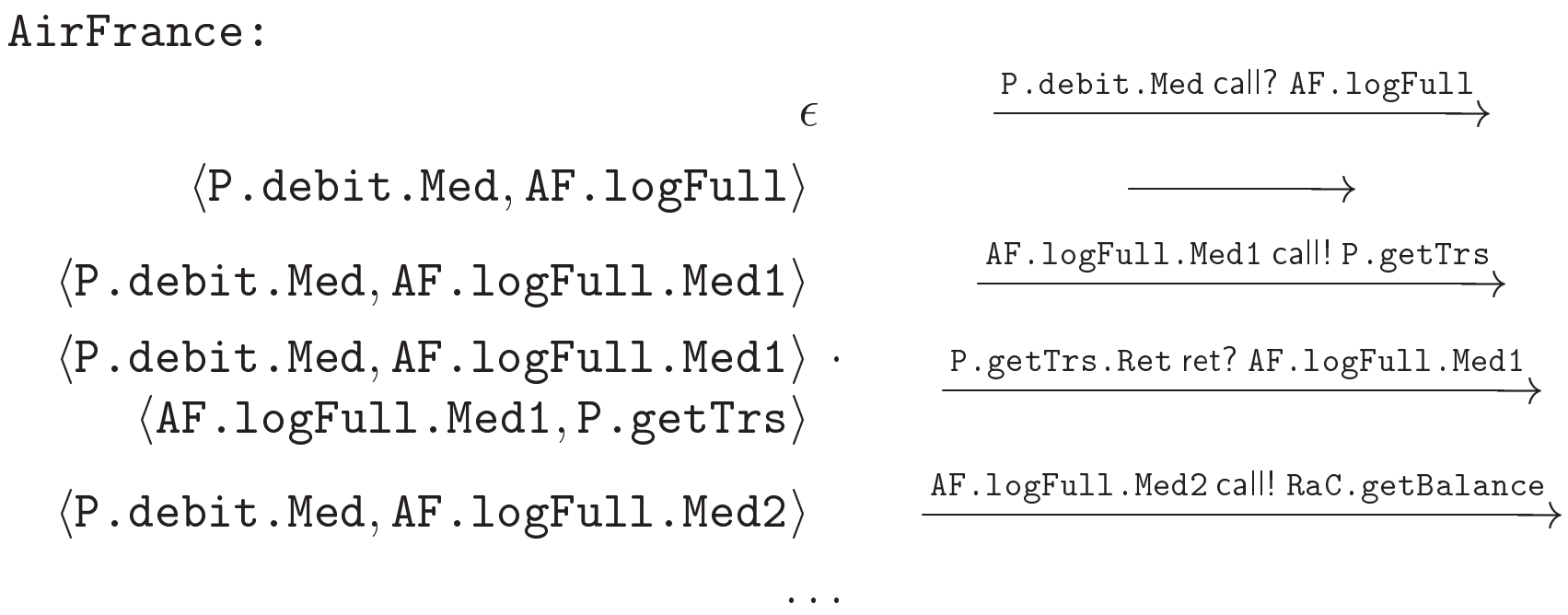
$$\text{[send call]}\quad \frac{v_1 \to^{C} v_2 \qquad \mathbf{loc}_a\, v_1 \qquad \neg\mathbf{loc}_a\, v_2}{a.\pi \cdot \langle v, v_1\rangle \xrightarrow{v_1\ \mathsf{call!}\ v_2} a.\pi \cdot \langle v, v_1\rangle \cdot \langle v_1, v_2\rangle}$$

$$\text{[receive call]}\quad \frac{v_1 \to^{C} v_2 \qquad \neg\mathbf{loc}_a\, v_1 \qquad \mathbf{loc}_a\, v_2 \qquad \neg\mathsf{active}a}{a.\pi \xrightarrow{v_1\ \mathsf{call?}\ v_2} a.\pi \cdot \langle v_1, v_2\rangle}$$

$$\text{[send return]}\quad \frac{\neg\mathbf{loc}_a\, v_1 \qquad \mathbf{loc}_a\, v_2 \qquad \mathsf{return}\ \ v_2}{a.\pi \cdot \langle v_1, v_2\rangle \xrightarrow{v_2\ \mathsf{ret!}\ v_1} a.\pi}$$

$$\text{[receive return]}\quad \frac{v_1 \to^{T} v_2 \qquad \mathbf{loc}_a\, v_1 \qquad \neg\mathbf{loc}_a\, v_3 \qquad \alpha(v_3) = \alpha(v_4)}{a.\pi \cdot \langle v, v_1\rangle \cdot \langle v_1, v_3\rangle \xrightarrow{v_4\ \mathsf{ret?}\ v_1} a.\pi \cdot \langle v, v_2\rangle}$$

Local trace AirFrance applet



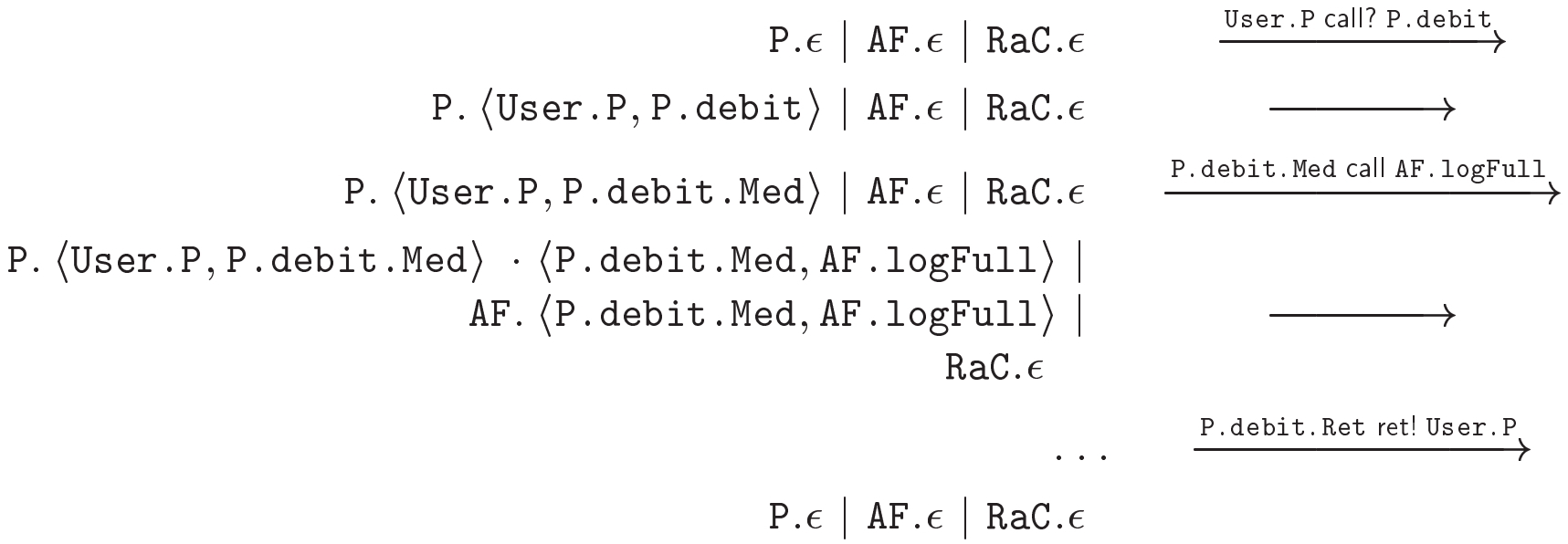
Transition rules for composite states

$$[\text{tau}] \quad \frac{\mathcal{A}_1 \xrightarrow{\tau} \mathcal{A}_1'}{\mathcal{A}_1 \mid \mathcal{A}_2 \xrightarrow{\tau} \mathcal{A}_1' \mid \mathcal{A}_2}$$

$$[\text{synchro}] \quad \frac{\mathcal{A}_1 \xrightarrow{v_1\ l?\ v_2} \mathcal{A}_1' \qquad \mathcal{A}_2 \xrightarrow{v_1\ l!\ v_2} \mathcal{A}_2'}{\mathcal{A}_1 \mid \mathcal{A}_2 \xrightarrow{v_1\ l\ v_2} \mathcal{A}_1' \mid \mathcal{A}_2'} \ \ell \in \text{call, ret}$$

$$[\text{propagation}] \quad \frac{\mathcal{A}_1 \xrightarrow{v_1\ l?!\ v_2} \mathcal{A}_1' \qquad \neg\mathbf{loc}_{\mathcal{A}_2}\, v_1 \qquad \neg\mathbf{loc}_{\mathcal{A}_2}\, v_2}{\mathcal{A}_1 \mid \mathcal{A}_2 \xrightarrow{v_1\ l?!\ v_2} \mathcal{A}_1' \mid \mathcal{A}_2}$$

Fragment of the global trace



The properties

Behavioural applet properties

- m_1 never triggers m_2 (confidentiality, integrity)
- m_1 never triggers m_2 when it triggers m_3 (exclusion)
- m_1 only triggers m_2 through m_3 (segregation of duty)
- m_1 never triggers m_2 before m_3 (authentication)

Specifying the electronic purse system

Invocation of `logFull` in `AirFrance` applet by `Purse`
should not trigger
a call from `RentACar` to `getTrs` (to ask the transactions) in `Purse`:

$$\textsc{Spec} \triangleq \textsc{Within}\ \texttt{AirFrance.logFull}\ \textsc{CannotCall}\ \texttt{RentACar Purse.getTrs}$$

Formulae

$$\phi ::= \quad \sigma \;\mid\; \text{active} \;\mid\; \neg\phi \;\mid\; \phi \wedge \phi \;\mid\; \forall x.\phi \;\mid\; [\alpha]\,\phi \;\mid\; X \;\mid\; \nu X.\phi$$

with standard semantics, and:

$$\|\text{active}\|_\rho^{\mathcal{M}} \quad \triangleq \quad \{s \in \mathcal{S}_{\mathcal{M}} \mid s \text{ is active}\}$$

$$\|\sigma\|_\rho^{\mathcal{M}} \quad \triangleq \quad \text{if } [\![\sigma]\!]_\rho^{\mathcal{M}} \text{ then } \mathcal{S}_{\mathcal{M}} \text{ else } \emptyset$$

Atomic formulae

$$\sigma ::= \quad t = t \;\mid\; \mathsf{return}\ v \;\mid\; \mathsf{local}_{\mathcal{A}}\, v$$

with semantics

$$[\![t_1 = t_2]\!]^{\mathcal{M}}_{\rho} \triangleq t_1\rho = t_2\rho$$

$$[\![\mathsf{return}\ v]\!]^{\mathcal{M}}_{\rho} \triangleq \mathbf{ret}(v\rho)$$

$$[\![\mathsf{local}_{\mathcal{A}}\, v]\!]^{\mathcal{M}}_{\rho} \triangleq \mathbf{app}(v\rho) \text{ occurs in } \mathcal{A}\rho$$

Specification patterns

$$
\begin{aligned}
&\textsc{Always}\ \phi \triangleq \\
&\quad \nu X.\ \phi \ \wedge\ [\tau]\, X \\
&\qquad \wedge\ \ \forall v_1.\ \forall v_2.\ \ [v_1\ \mathsf{call}\ v_2]\, X \\
&\qquad\qquad \wedge\ \ [v_1\ \mathsf{call?}\ v_2]\, X \\
&\qquad\qquad \wedge\ \ [v_1\ \mathsf{call!}\ v_2]\, X \\
&\qquad\qquad \wedge\ \ [v_1\ \mathsf{ret}\ v_2]\, X \\
&\qquad\qquad \wedge\ \ [v_1\ \mathsf{ret?}\ v_2]\, X \\
&\qquad\qquad \wedge\ \ [v_1\ \mathsf{ret!}\ v_2]\, X
\end{aligned}
$$

$$
\begin{aligned}
&\textsc{Within}\ v\ \phi \triangleq \\
&\quad \forall v_1.\ \ [v_1\ \mathsf{call}\ v]\, \textsc{Always}_{-\mathsf{ret}\ v_1}\phi \\
&\qquad \wedge\ \ [v_1\ \mathsf{call?}\ v]\, \textsc{Always}_{-\mathsf{ret!}\ v_1}\phi
\end{aligned}
$$

$\textsc{Always}_{-\lambda\, v}\ \phi$ is $\textsc{Always}\ \phi$ with $[v_1 \lambda\ v_2]\, X$ replaced by $[v_1 \lambda\ v_2]\, ((v_2 = v) \vee X)$.

Specifying the individual applets

$$\textsc{Spec}_{\mathsf{P}} \triangleq \mathsf{local}_{\texttt{Purse}}\,\texttt{Purse.getTrs} \wedge \textsc{Always}\ (\textsc{Within}\ \texttt{Purse.getTrs}\ (\textsc{CallsExtOnly}\ \emptyset))$$

$$\textsc{Spec}_{\mathsf{AF}} \triangleq \mathsf{local}_{\texttt{AirFrance}}\,\texttt{AirFrance.logFull} \wedge \textsc{Always}\ (\textsc{Within}\ \texttt{AirFrance.logFull}\ (\textsc{CallsExtOnly}\ \texttt{Purse.getTrs},\ \texttt{RentACar.getBalance}))$$

$$\textsc{Spec}_{\mathsf{RaC}} \triangleq \mathsf{local}_{\texttt{RentACar}}\,\texttt{RentACar.getBalance} \wedge \textsc{Always}\ (\textsc{Within}\ \texttt{RentACar.getBalance}\ (\textsc{CallsExtOnly}\ \emptyset))$$

Correctness of the decomposition

- Parameterize specifications:
  - replace concrete applet names by applet variables
  - replace concrete method names by program point variables
- Prove:

$$a_P.\pi_P : \textsc{Spec}_{\mathsf{P}},\quad a_{AF}.\pi_{AF} : \textsc{Spec}_{\mathsf{AF}},\quad a_{RaC}.\pi_{RaC} : \textsc{Spec}_{\mathsf{RaC}} \vdash a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \,|\, a_{RaC}.\pi_{RaC} : \textsc{Spec}$$

The proof system

Proof system

- Proof rules for different kind of assertions
  - atomic formula assertion σ
  - satisfaction assertion $\mathcal{A} : \phi$
  - transition assertion $\mathcal{A}_1 \xrightarrow{\alpha} \mathcal{A}_2$
  - transfer-edge assertion $v \rightarrow^T v'$
  - call-edge assertion $v \rightarrow^C v'$
- Fixed points handled with discharge condition (Dam/Gurov)
- Modal operators introduce transition assertions, transition rules introduce edge assertions

Sequents

$$\gamma_1, \ldots, \gamma_n \vdash \delta_1, \ldots, \delta_n$$

has intuitive meaning

$$\gamma_1 \wedge \ldots \wedge \gamma_n \Rightarrow \delta_1 \vee \ldots \vee \delta_n$$

Proof system – Active rules

$$(\mathsf{ActL}) \quad \frac{\Gamma,\ \Pi = \pi \cdot \langle v_1, v_2 \rangle\ ,\ \mathsf{local}_a\, v_2\ \vdash\ \Delta}{\Gamma,\ a.\Pi : \mathsf{active}\ \vdash\ \Delta}\ \mathrm{fresh}\ \pi, v_1, v_2$$

$$(\mathsf{ActR}) \quad \frac{\Gamma\ \vdash\ \Pi = \Pi' \cdot \langle v_1, v_2 \rangle\ ,\ \Delta \qquad \Gamma\ \vdash\ \mathsf{local}_a\, v_2,\ \Delta}{\Gamma\ \vdash\ a.\Pi : \mathsf{active},\ \Delta}$$

Proof system – Box rules

$$\text{(BoxL)}\quad \frac{\Gamma \vdash \mathcal{A} \xrightarrow{\alpha} \mathcal{A}',\ \Delta \qquad \Gamma,\ \mathcal{A}' : \phi \vdash \Delta}{\Gamma,\ \mathcal{A} : [\alpha]\,\phi \vdash \Delta}$$

$$\text{(BoxR)}\quad \frac{\Gamma, \mathcal{A} \xrightarrow{\alpha} \mathcal{X} \vdash \mathcal{X} : \phi,\ \Delta}{\Gamma \vdash \mathcal{A} : [\alpha]\,\phi,\ \Delta}\ \text{fresh } \mathcal{X}$$

Proof system – Transition rules

$$\text{(SendCallR)}\quad \frac{\begin{array}{c}\Gamma \vdash v_1 \to^{C} v_2,\ \Delta \\ \Gamma \vdash \mathsf{local}_a\, v_1,\ \Delta \\ \Gamma,\ \mathsf{local}_a\, v_2 \vdash \Delta \\ \Gamma \vdash \Pi = \pi \cdot \langle v, v_1 \rangle,\ \Delta\end{array}}{\Gamma \vdash a.\Pi \xrightarrow{v_1\ \mathsf{call!}\ v_2} a.(\Pi \cdot \langle v_1, v_2 \rangle),\ \Delta}$$

$$\text{(SendCallL)}\quad \frac{\begin{array}{rl}\Gamma[a.(\Pi \cdot \langle v_1, v_2 \rangle)/\mathcal{X}], & \\ \Pi = \pi \cdot \langle v, v_1 \rangle, & \\ v_1 \to^{C} v_2,\ \mathsf{local}_a\, v_1 & \vdash \mathsf{local}_a\, v_2,\ \Delta[a.(\Pi \cdot \langle v_1, v_2 \rangle)/\mathcal{X}]\end{array}}{\Gamma,\ a.\Pi \xrightarrow{v_1\ \mathsf{call!}\ v_2} \mathcal{X} \vdash \Delta}\ \mathsf{fresh}\ v, \pi$$

Proof system - Composite transition rules

$$\text{(ComPerfL)}\quad \frac{\begin{array}{c}\Gamma[(\mathcal{Y}\,|\,\mathcal{A}_2)/\mathcal{X}],\ \mathcal{A}_1 \xrightarrow{v_1 l v_2} \mathcal{Y},\ \mathsf{wf}(\mathcal{A}_1\,|\,\mathcal{A}_2),\ \mathsf{wf}(\mathcal{Y}\,|\,\mathcal{A}_2) \vdash \mathsf{local}_{\mathcal{A}_2}\ v_1,\ \mathsf{local}_{\mathcal{A}_2}\ v_2,\ \Delta[(\mathcal{Y}\,|\,\mathcal{A}_2)/\mathcal{X}] \\ \Gamma[(\mathcal{A}_1\,|\,\mathcal{Y})/\mathcal{X}],\ \mathcal{A}_2 \xrightarrow{v_1 l v_2} \mathcal{Y},\ \mathsf{wf}(\mathcal{A}_1\,|\,\mathcal{A}_2),\ \mathsf{wf}(\mathcal{A}_1\,|\,\mathcal{Y}) \vdash \mathsf{local}_{\mathcal{A}_1}\ v_1,\ \mathsf{local}_{\mathcal{A}_1}\ v_2,\ \Delta[(\mathcal{A}_1\,|\,\mathcal{Y})/\mathcal{X}] \\ \Gamma[(\mathcal{X}_1\,|\,\mathcal{X}_2)/\mathcal{X}],\ \mathcal{A}_1 \xrightarrow{v_1 l! v_2} \mathcal{X}_1,\ \mathcal{A}_2 \xrightarrow{v_1 l? v_2} \mathcal{X}_2,\ \mathsf{wf}(\mathcal{A}_1\,|\,\mathcal{A}_2),\ \mathsf{wf}(\mathcal{X}_1\,|\,\mathcal{X}_2) \vdash \Delta[(\mathcal{X}_1\,|\,\mathcal{X}_2)/\mathcal{X}] \\ \Gamma[(\mathcal{X}_1\,|\,\mathcal{X}_2)/\mathcal{X}],\ \mathcal{A}_1 \xrightarrow{v_1 l? v_2} \mathcal{X}_1,\ \mathcal{A}_2 \xrightarrow{v_1 l! v_2} \mathcal{X}_2,\ \mathsf{wf}(\mathcal{A}_1\,|\,\mathcal{A}_2),\ \mathsf{wf}(\mathcal{X}_1\,|\,\mathcal{X}_2) \vdash \Delta[(\mathcal{X}_1\,|\,\mathcal{X}_2)/\mathcal{X}]\end{array}}{\Gamma,\ \mathcal{A}_1\,|\,\mathcal{A}_2 \xrightarrow{v_1 l v_2} \mathcal{X} \vdash \Delta}\ \mathsf{fresh}\ \mathcal{X}_1, \mathcal{X}_2, \mathcal{Y}$$

Correctness

- Soundness:
  - Formalisation of program model and operational semantics
  - Formalisation of proof system
  - Proof rules sound *w.r.t.* the underlying semantics
  - All in PVS
- Completeness: future work

Example verification

The method

Prove

$$\begin{array}{rl} a_P.\pi_P : \textsc{Spec}_{\textsf{P}}, & \\ a_{AF}.\pi_{AF} : \textsc{Spec}_{\textsf{AF}}, & \\ a_{RaC}.\pi_{RaC} : \textsc{Spec}_{\textsf{RaC}} & \vdash\ a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \,|\, a_{RaC}.\pi_{RaC} : \textsc{Spec} \end{array}$$

by

- symbolic execution to compute symbolic next states
- identification of impossible states
- loop detection to close off branches in proof

Some abbreviations

$$\textsc{Spec} \triangleq \textsc{Within}\ \texttt{AirFrance.logFull}\ \textsc{Spec}'$$

$$\textsc{Spec}' \triangleq \textsc{CannotCall}\ \texttt{RentACar}\ \texttt{Purse.getTrs}$$

$$\textsc{Spec}_{\mathsf{P}} \triangleq \mathsf{local}_{\texttt{Purse}}\,\texttt{Purse.getTrs} \wedge \textsc{Spec}'_{\mathsf{P}}$$

$$\textsc{Spec}'_{\mathsf{P}} \triangleq \textsc{Always}\ (\textsc{Within}\ \texttt{Purse.getTrs}\ (\textsc{CallsExtOnly}\ \emptyset))$$

Some abbreviations - 2

$$\textsc{Spec}_{\mathsf{AF}} \triangleq \mathsf{local}_{\texttt{AirFrance}}\,\texttt{AirFrance.logFull} \wedge \textsc{Spec}'_{\mathsf{AF}}$$

$$\textsc{Spec}'_{\mathsf{AF}} \triangleq \textsc{Always}\ (\textsc{Within}\ \texttt{AirFrance.logFull}\ \textsc{Spec}''_{\mathsf{AF}})$$

$$\textsc{Spec}''_{\mathsf{AF}} \triangleq \textsc{CallsExtOnly}\ \texttt{Purse.getTrs}, \texttt{RentACar.getBalance}$$

$$\textsc{Spec}_{\mathsf{RaC}} \triangleq \mathsf{local}_{\texttt{RentACar}}\,\texttt{RentACar.getBalance} \wedge \textsc{Spec}'_{\mathsf{RaC}}$$

$$\textsc{Spec}'_{\mathsf{RaC}} \triangleq \textsc{Always}\ (\textsc{Within}\ \texttt{RentACar.getBalance}(\textsc{CallsExtOnly}\ \emptyset))$$

Step 1

- Unfold pattern
- Apply logical rules to outermost logical connectives of $\textsc{Spec}$
- Two subgoals: focus on first

$$\begin{array}{l}\mathsf{local}_{a_P}\, v_{GT},\ \mathsf{local}_{a_{AF}}\, v_{LF},\ \mathsf{local}_{a_{RaC}}\, v_{GB},\\ \quad a_P.\pi_P : \textsc{Spec}'_{\mathsf{P}},\ a_{AF}.\pi_{AF} : \textsc{Spec}'_{\mathsf{AF}},\ a_{RaC}.\pi_{RaC} : \textsc{Spec}'_{\mathsf{RaC}}\\ \quad \vdash\ a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \,|\, a_{RaC}.\pi_{RaC} : [v_1\ \mathsf{call}\ v_{LF}]\ \ \textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}'\end{array}$$

Apply rule BoxR and left transition rules

- Result: nine sequents – nine different ways in which a perfect call action can come about
- Four subgoals discarded by Id: a_{AF} is not involved in communication
- Two subgoals assume a_{AF} sends a call to an external v_{LF}, discarded by SendCallL and Id.
- Three subgoals consider the different ways of producing a perfect call to vertex v_{LF}

v_{LF} is invoked by a local call

$$
\begin{aligned}
a_P.\pi_P &: \textsc{Spec}'_{\mathsf{P}},\\
a_{AF}.\pi_{AF} &: \textsc{Spec}'_{\mathsf{AF}},\\
a_{RaC}.\pi_{RaC} &: \textsc{Spec}'_{\mathsf{RaC}},\\
a_{AF}.\pi_{AF} &\xrightarrow{v_1 \ \mathsf{call}\ v_{LF}} \mathcal{X},\\
\mathsf{wf}(a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \,|\, a_{RaC}.\pi_{RaC}),&\\
\mathsf{wf}(a_P.\pi_P \,|\, \mathcal{X} \,|\, a_{RaC}.\pi_{RaC}),&\\
\mathsf{local}_{a_P}\, v_{GT},&\\
\mathsf{local}_{a_{AF}}\, v_{LF},&\\
\mathsf{local}_{a_{RaC}}\, v_{GB} \quad &\vdash\\
a_P.\pi_P \,|\, \mathcal{X} \,|\, a_{RaC}.\pi_{RaC} &: \textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}'
\end{aligned}
$$

Deriving assumptions about $\mathcal{X}$

- Apply l.h.s. rules
- Apply BoxL to box-formula labeled v_1 call v_{LF}.
- First subgoal: show $a_{AF}.\pi_{AF} \xrightarrow{v_1 \text{ call } v_{LF}} \mathcal{X}$ by Id
- Second subgoal:

$$\begin{array}{l}
\mathsf{local}_{a_P}\, v_{GT},\ \mathsf{local}_{a_{AF}}\, v_{LF},\ \mathsf{local}_{a_{RaC}}\, v_{GB},\\
a_P.\pi_P : \textsc{Spec}'_{\mathsf{P}},\ \mathcal{X} : \textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}''_{\mathsf{AF}},\ a_{RaC}.\pi_{RaC} : \textsc{Spec}'_{\mathsf{RaC}},\\
a_{AF}.\pi_{AF} \xrightarrow{v_1 \text{ call } v_{LF}} \mathcal{X},\\
\mathsf{wf}(a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \,|\, a_{RaC}.\pi_{RaC}),\ \mathsf{wf}(a_P.\pi_P \,|\, \mathcal{X} \,|\, a_{RaC}.\pi_{RaC})\\
\vdash\ a_P.\pi_P \,|\, \mathcal{X} \,|\, a_{RaC}.\pi_{RaC} : \textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}'
\end{array}$$

Eliminate transition assertion by LocCallL

$$
\begin{aligned}
&\mathsf{local}_{a_P}\, v_{GT},\\
&\mathsf{local}_{a_{AF}}\, v_{LF},\\
&\mathsf{local}_{a_{AF}}\, v_1,\\
&\mathsf{local}_{a_{RaC}}\, v_{GB},\\
&a_P.\pi_P : \textsc{Spec}'_{\mathsf{P}},\\
a_{AF}.\pi_{AF} \cdot \langle v_1, v_{LF}\rangle &: \textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}''_{\mathsf{AF}},\\
&a_{RaC}.\pi_{RaC} : \textsc{Spec}'_{\mathsf{RaC}},\\
&\pi_{AF} = \pi \cdot \langle v, v_1\rangle\,,\\
&v_1 \to^C v_{LF},\\
&\mathsf{wf}(a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \,|\, a_{RaC}.\pi_{RaC}),\\
&\mathsf{wf}(a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \cdot \langle v_1, v_{LF}\rangle \,|\, a_{RaC}.\pi_{RaC}) \quad \vdash\\
a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \cdot \langle v_1, v_{LF}\rangle \,|\, a_{RaC}.\pi_{RaC} &: \textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}'
\end{aligned}
$$

Analysis of symbolic next-state

- Computed next-state:

$$a_P.\pi_P \,|\, a_{AF}.\pi_{AF} \cdot \langle v_1, v_{LF} \rangle \,|\, a_{RaC}.\pi_{RaC}$$

- Show in this symbolic next-state formula $\textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}'$ holds:
  - In this state $\textsc{Spec}'$ is true: trivial, because of wellformedness.
  - In all possible next states within the call (not labeled v ret v_1) $\textsc{Always}_{-\mathsf{ret}\ v_1}\textsc{Spec}'$ holds.
    External call: only two possible destinations of call v_{GT} or v_{GB}
    Continue with these states
    Other cases: loop and discharge

Ongoing and future work

- Maximal graph construction - completeness for a fragment of the logic
- Concurrency
- Keep notion of method in program model
- Extension of Erlang Verification Tool
- Verification of individual applets
- Case studies