Recalling a Witness

Foundations and Applications of Monotonic State

Danel Ahman

Prosecco Team at Inria Paris

joint work with

Cătălin Hrițcu and Kenji Maillard @ Inria Paris

Cédric Fournet, Aseem Rastogi, and Nikhil Swamy @ MSR

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Outline

- Monotonic state and program verification by example
- Key ideas behind our interface for monotonic state
- Adding monotonic state to F*
- Examples of monotonic state at work
- A glimpse of the meta-theory

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Monotonic state and program verification

- Consider a program operating on **set-valued state**

$$\texttt{insert v; complex\_procedure(); assert } (\texttt{v} \in \texttt{get()})$$

- To prove the assertion (say, in a Floyd-Hoare style logic), we could prove that the code maintains a **stateful invariant**

$$\{\lambda\,\texttt{s}\,.\,\texttt{v} \in \texttt{s}\}\ \texttt{complex\_procedure()}\ \{\lambda\,\texttt{s}\,.\,\texttt{v} \in \texttt{s}\}$$

  - likely that we have to **carry** $\lambda\,\texttt{s}\,.\,\texttt{v} \in \texttt{s}$ **through** the proof of c_p
    - **sensitive** to proving that c_p maintains $\lambda\,\texttt{s}\,.\,\texttt{w} \in \texttt{s}$ for some other $\texttt{w}$
    - **does not guarantee** that $\lambda\,\texttt{s}\,.\,\texttt{v} \in \texttt{s}$ holds at every point in c_p

- However, if c_p **only inserts**, then $\lambda\,\texttt{s}\,.\,\texttt{v} \in \texttt{s}$ is **stable**, and we would like the program logic to give us $\texttt{v} \in \texttt{get()}$ "**for free**"

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Monotonicity is really useful!

- To come later in this talk
  - reasoning about **monotonic counters**
  - implementing **typed** (`ref t`) and **untyped references** (`uref`)
  - more flexibility with **monotonic references** (`mref t rel`)
- For more examples, see

  Recalling a Witness:
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  (arXiv:1707.02466)

  which includes
  - a secure **file-transfer** application
  - pointers to works using monotonicity in **crypto** and **TLS verif.**
  - Ariadne **state continuity** protocol [Strackx, Piessens 2016]

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Overview of our solution

- We focus on **monotonic** programs and **stable** predicates
  - per verification task, we choose a **preorder** `rel` on states
    - set inclusion, heap inclusion, increasing counters, ...
  - a program e is **monotonic** (wrt. `rel`) when
$$(\mathtt{s},\mathtt{e}) \leadsto^* (\mathtt{s}',\mathtt{e}') \implies \mathtt{rel}\ \mathtt{s}\ \mathtt{s}'$$
  - a predicate p on states is **stable** (wrt. `rel`) when
$$\forall\, \mathtt{s}\, \mathtt{s}'.\ \mathtt{p}\ \mathtt{s}\ \wedge\ \mathtt{rel}\ \mathtt{s}\ \mathtt{s}' \implies \mathtt{p}\ \mathtt{s}'$$
- **Our solution:** extend Hoare-style program logics (e.g., F*) with
  - means for turning a p into a **state-independent proposition**
  - operation to **witness** the validity of p s in some state s
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Reasoning about ordinary state in F*

- An ML-like dependently typed language, aimed at verification

- F* supports Hoare-style reasoning about state via the **comp. type**

$$\mathtt{ST}\ \mathtt{t}\ (\mathtt{requires}\ \mathtt{pre})\ (\mathtt{ensures}\ \mathtt{post})$$

  where

$$\mathtt{t} : \mathtt{Type} \qquad \mathtt{pre} : \mathtt{state} \to \mathtt{Type} \qquad \mathtt{post} : \mathtt{state} \to \mathtt{t} \to \mathtt{state} \to \mathtt{Type}$$

  (formally, this type is derived from a WP calculus for state)

- The **get** and **put** actions are typed as follows

$$\mathtt{get} : \mathtt{unit} \to \mathtt{ST}\ \mathtt{state}\ (\mathtt{requires}\ (\lambda\,\_\,.\top))\ (\mathtt{ensures}\ (\lambda\,\mathtt{s}_0\,\mathtt{s}\,\mathtt{s}_1\,.\,\mathtt{s}_0 = \mathtt{s} = \mathtt{s}_1))$$

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Reasoning about monotonic state in F*

- We capture monotonic state with a new **computation type**

$$\texttt{MST rel t (requires pre) (ensures post)}$$

  where t, pre, and post are typed as in ST

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- We introduce a **logical capability**

$$\texttt{witnessed} : \texttt{pred state} \to \texttt{Type}$$

together with a **weakening** principle

$$\texttt{wk} : \texttt{p,q:pred state} \to \texttt{Lemma}\ (\texttt{requires}\ (\forall\, \texttt{s}\,.\,\texttt{p s} \implies \texttt{q s}))$$
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- We introduce an operation for **witnessing** stable predicates

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The motivating example revisited

- Recall the program operating on **set-valued state**

$$\texttt{insert v; complex\_procedure(); assert } (\texttt{v} \in \texttt{get()})$$

  - We pick **set inclusion** $\subseteq$ as our preorder on states
  - We **prove the assertion** by adding a `witness` and a `recall`

$$\texttt{insert v; witness } (\lambda\, \texttt{s} \,.\, \texttt{v} \in \texttt{s})\texttt{; c\_p(); recall } (\lambda\, \texttt{s} \,.\, \texttt{v} \in \texttt{s})\texttt{; assert } (\texttt{v} \in \texttt{get()})$$

  - For any other `w`, wrapping

$$\texttt{insert w; [ ]; assert } (\texttt{w} \in \texttt{get()})$$

    around the program is handled similarly easily

- **Monotonic counters** are analogous, with $\mathbb{N}$ and $\leq$

$$\texttt{create 0; incr(); witness } (\lambda\, \texttt{c} \,.\, \texttt{c} > 0)\texttt{; c\_p(); recall } (\lambda\, \texttt{c} \,.\, \texttt{c} > 0)$$

The motivating example revisited

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$$\texttt{insert v};\ \texttt{complex\_procedure}();\ \texttt{assert}\ (\texttt{v} \in \texttt{get}())$$

  - We pick **set inclusion** $\subseteq$ as our preorder on states
  - We **prove the assertion** by adding a `witness` and a `recall`

$$\texttt{insert v};\ \texttt{witness}\ (\lambda\, \texttt{s} \,.\, \texttt{v} \in \texttt{s});\ \texttt{c\_p}();\ \texttt{recall}\ (\lambda\, \texttt{s} \,.\, \texttt{v} \in \texttt{s});\ \texttt{assert}\ (\texttt{v} \in \texttt{get}())$$

  - For any other `w`, wrapping

$$\texttt{insert w};\ [\ \ ];\ \texttt{assert}\ (\texttt{w} \in \texttt{get}())$$

    around the program is handled similarly easily

- **Monotonic counters** are analogous, with $\mathbb{N}$ and $\leq$

$$\texttt{create 0};\ \texttt{incr}();\ \texttt{witness}\ (\lambda\, \texttt{c} \,.\, \texttt{c} > 0);\ \texttt{c\_p}();\ \texttt{recall}\ (\lambda\, \texttt{c} \,.\, \texttt{c} > 0)$$

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References: both typed and untyped

- We define **local state** using global state + monotonicity
- We define **heaps** as maps

$\mathtt{type\ heap} =$

$\quad \mid \mathtt{H} : \mathtt{h}{:}(\mathbb{N} \to \mathtt{cell}) \to \mathtt{ctr}{:}\mathbb{N}\{\forall\, \mathtt{n}\,.\, \mathtt{ctr} \leq \mathtt{n} \implies \mathtt{h\ n} = \mathtt{Unused}\} \to \mathtt{heap}$

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```
type heap =
  | H : h:(ℕ → cell) → ctr:ℕ{∀ n . ctr ≤ n ⟹ h n = Unused} → heap
```

where

```
type cell = Unused : cell | Used : a:Type → v:a → t:tag → cell
type tag  = Typed : tag | Untyped : live:bool → tag
```

- The **preorder** on heaps is given by

```
let rel (H h_0 _) (H h_1 _) = ∀ id . match h_0 id, h_1 id with
  | Used a _ Typed, Used b _ Typed → a = b
  | Used _ _ (Untyped l_0), Used _ _ (Untyped l_1) → ¬(l_0) ⟹ ¬(l_1)
  | ...
```

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- **Typed references** are defined as

$$\texttt{abstract type ref t} = \texttt{id}{:}\mathbb{N}\{\texttt{witnessed}\;(\lambda\,\texttt{h}\,.\,\texttt{has\_used\_typed id t h})\}$$

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- The state actions for **typed references** use **witness** and **recall**
  - `let alloc t (v:t) : MST (ref t) ... = ...`
    - **get** the current heap (using global state `get`)
    - **create** a fresh ref., and **add** it to the heap
    - **put** the updated heap back (using global state `put`)
    - **witness** that the created ref. is in the heap
  - `let read t (r:ref t) : MST t ... = ...`
    - **recall** that the given ref. is in the heap
    - **get** the current heap (using global state `get`)
    - **select** the given reference from the heap
  - `let write t (r:ref t) (v:t) : MST unit ... = ...`
    - **recall** that the given ref. is in the heap
    - **get** the current heap (using global state `get`)
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Monotonic references: more flexibility

- The heap now associates a **local preorder** with each reference

$\texttt{type tag a} = \texttt{Typed} : \texttt{rel:preorder a} \to \texttt{tag a} \mid \texttt{Untyped} : \texttt{live:bool} \to \texttt{tag a}$

- The **global preorder** is a point-wise lifting of the individual ones

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\begin{aligned}
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- **Monotonic references** are then given as

$\texttt{abstract type mref t rel} = \texttt{id}{:}\mathbb{N}\{\texttt{witnessed}\ (\lambda\, \texttt{h}\,.\,\texttt{has\_mref id t rel h})\}$

- State actions
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Outline

- Monotonic state and program verification by example
- Key ideas behind our interface for monotonic state
- Adding monotonic state to F*
- Examples of monotonic state at work
- A glimpse of the meta-theory

A glimpse of the meta-theory

- We formalize MST in a small dependently typed CBV calculus

$$
\begin{aligned}
t &::= \mathsf{state} \mid x{:}t_1 \to \textbf{Tot}\ t_2 \mid x{:}t_1 \to \textbf{MST}\ t_2\ (s.\varphi_{\mathsf{pre}})\ (s.y.s'.\varphi_{\mathsf{post}}) \mid \ldots \\
e &::= \mathsf{get} \mid \mathsf{put}\ v \mid \mathsf{witness}\ s.\varphi \mid \mathsf{recall}\ s.\varphi \mid \ldots \\
\varphi &::= \mathsf{rel}\ v_1\ v_2 \mid \mathsf{witnessed}\ s.\varphi \mid \ldots
\end{aligned}
$$

- **Consistency** and **props. of the logic** via seq. calc. and cut-adm.

- **Operational semantics** on configurations (e, σ, W)

$$
\begin{aligned}
(\mathsf{witness}\ s.\varphi, \sigma, W) &\rightsquigarrow (\mathsf{return}\ (), \sigma, W \cup \{s.\varphi\}) \\
(\mathsf{recall}\ s.\varphi, \sigma, W) &\rightsquigarrow (\mathsf{return}\ (), \sigma, W)
\end{aligned}
$$

- **Total correctness** via progress, preservation, and SN

$$
\begin{array}{c}
\vdash e : \textbf{MST}\ t\ (s.\varphi_{\mathsf{pre}})\ (s.x.s'.\varphi_{\mathsf{post}}) \\
\mathsf{witnessed}\ W \vdash \varphi_{\mathsf{pre}}[\sigma/s]
\end{array}
\implies
\begin{array}{c}
(e, \sigma, W) \rightsquigarrow^* (\mathsf{return}\ v, \sigma', W') \quad \vdash v : t \\
W \subseteq W' \quad \mathsf{witnessed}\ W' \vdash \mathsf{rel}\ \sigma\ \sigma' \\
\mathsf{witnessed}\ W' \vdash \varphi_{\mathsf{post}}[\sigma/s, v/x, \sigma'/s']
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(\mathsf{witness}\ s.\varphi, \sigma, W) &\rightsquigarrow (\mathsf{return}\ (), \sigma, W \cup \{s.\varphi\}) \\
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  - **Total correctness** via progress, preservation, and SN

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A glimpse of the meta-theory

- We formalize MST in a small dependently typed CBV calculus

$$
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  - using monotonicity can be distilled into a simple interface
  - useful for both programming (refs.) and verification (crypto,TLS)

- Not in this talk (see the draft paper on arXiv)
  - temporarily **escaping the preorder** via snapshots
  - **revealing the representation** via selective monadic reification

- Future work
  - extending F* with indexed effects
  - combining preorders (e.g., ala graded monads)
  - modal aspects of `witnessed p`
  - connections with other works, e.g., Iris and [Pilkiewicz,Pottier'11]

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Thank you!

Questions?

Recalling a Witness:
Foundations and Applications of Monotonic State

(arXiv:1707.02466)