Toward a Certified Information Flows Analysis for JavaScript

Martin Bodin

JSCert meeting

Motivation

Tainting, dynamic information flow

```
x = private ;
/* ... */
public = y ;
```

This has already been done for other languages, but also for JavaScript:

- *Noninterference through secure multi-execution*, Devriese and Piessens;
- *FlowFox: a Web Browser with Flexible and Precise Information Flow Control*, De Groef, Devriese, Nikiforakis and Piessens.

Direct Flows

Non-interference

If we change any private value, we don't produce any observationnal changes in the public ones.

Goal for JavaScript

Tracking direct flows (weaker than non-interference).

Undetected Flows

```
if (private)
    public = 1 ;
else public = 2 ;
```

Indirect Flows

```
if (complexFunction ())
    /* false in practise */
    public = private ;
```

Dynamic Flows

Wish List

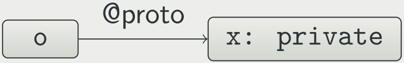
- Tracking objects.
- Prototyping.
- Functions.
- eval?
- ...

```
o = {} ;
o.x = private ;
public = o.x ;
```

Wish List

- Tracking objects.
- Prototyping.
- Functions.
- eval?
- ...

```
c = { prototype: {x: private} } ;
o = new c ;
public = o.x ;
```



Wish List

- Tracking objects.
- Prototyping.
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Wish List

- Tracking objects.
- Prototyping.
- Functions.
- eval?
- ...

Flow sensitive

Keep trace of time.

```
tmp = private ;
/* ... */
tmp = public ;
public = tmp ;
```

What We've Got: O'WHILE

$$
\begin{aligned}
s ::= \\
&\mid \underline{\text{skip}} \\
&\mid \underline{s_1 ; s_2} \\
&\mid \underline{\text{if } e \text{ then } s_1 \text{ else } s_2} \\
&\mid \underline{\text{while } e \text{ do } s} \\
&\mid \underline{\mathtt{x} = e} \\
&\mid \underline{e_1.\mathtt{f} = e_2} \\
&\mid \underline{\text{delete } e.\mathtt{f}}
\end{aligned}
$$

$$
\begin{aligned}
e ::= \\
&\mid \underline{c} \\
&\mid \underline{\mathtt{x}} \\
&\mid \underline{e_1 \ \mathtt{op} \ e_2} \\
&\mid \underline{\{\}} \\
&\mid \underline{e.\mathtt{f}}
\end{aligned}
$$

What's Lacking

- Closures.

In progress: closures à la λ_{JS}.

- `eval`.

Problems of lexing and parsing

Restraining it to an already parsed AST:

$$\mathtt{eval}\left(\begin{array}{ccc} & = & \\ / & & \backslash \\ \mathtt{x} & & e \end{array} \right).$$

- e1[e2].

Development of special lattices to track strings representing numbers, identifiers, etc.

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- `e1[e2]`.

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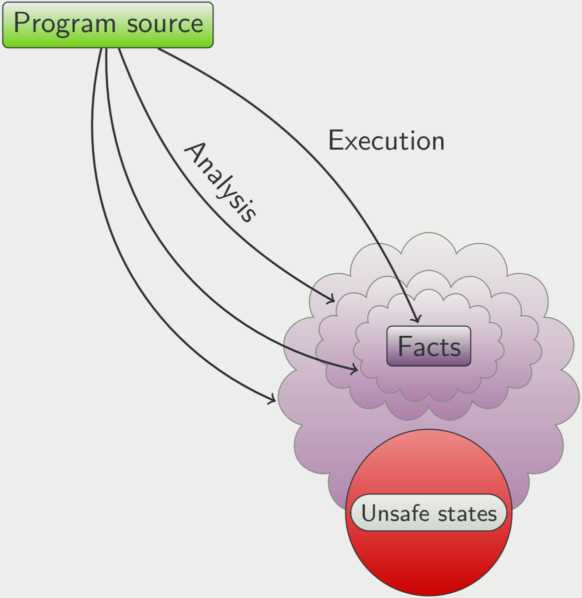
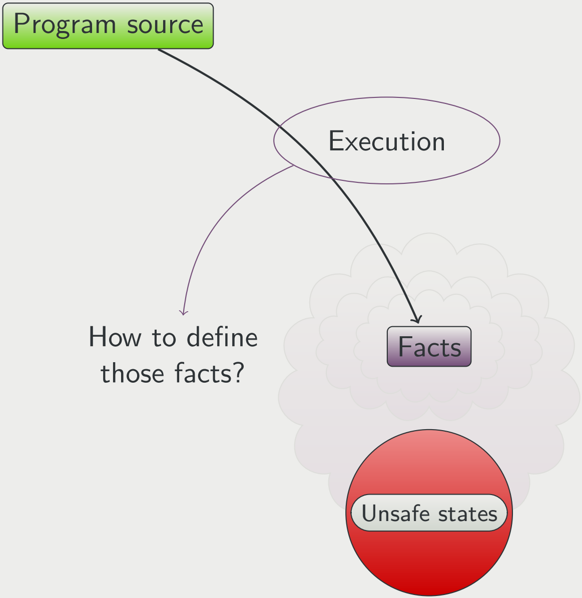
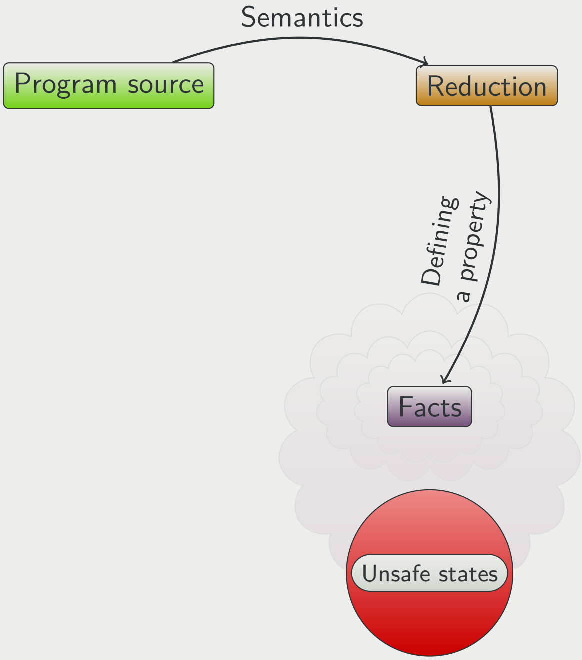

Program source
Analysis
Execution
Facts
Unsafe states


Program source
Execution
How to define
those facts?
Facts
Unsafe states


Semantics
Program source
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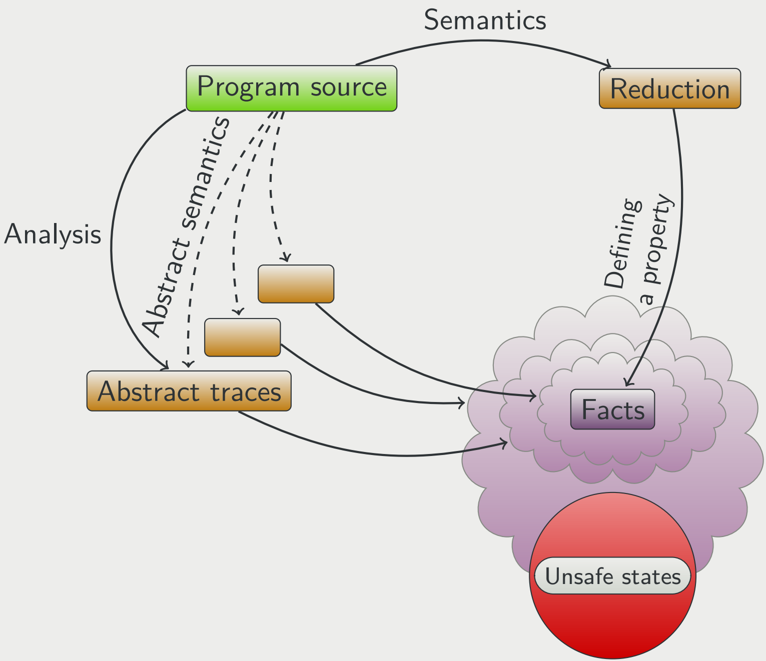
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Either a S or an error.

$$\frac{S, e \to r \qquad S, \underline{\mathrm{while1}(r, e, s)} \to r'}{S, \underline{\mathrm{while}\ e\ \mathrm{do}\ s} \to r'}\ \textsc{While}$$

E, H

$$\frac{S', s \to r \qquad S', \underline{\mathrm{while2}(r, e, s)} \to r'}{S, \underline{\mathrm{while1}((S', \mathrm{true}), e, s)} \to r'}\ \textsc{WhileTrue1}$$

$$\frac{S', \underline{\mathrm{while}\ e\ \mathrm{do}\ s} \to r}{S, \underline{\mathrm{while2}(S', e, s)} \to r}\ \textsc{WhileTrue2}$$

$$\frac{}{S, \underline{\mathrm{while1}((S', \mathrm{false}), e, s)} \to S'}\ \textsc{WhileFalse}$$

$$\frac{\mathtt{abort}(t_e) = r}{S, t_e \to r}\ \textsc{Abort}$$

Instrumentation of the Semantics

Amass information from a derivation tree, making the information flow explicit (but without adding any information).

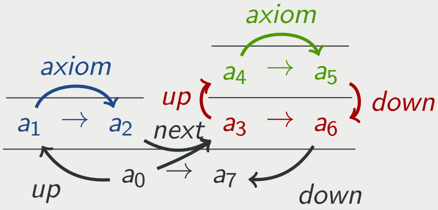
$S_\tau, t \to r$	Standard semantics
$\downarrow$	
$\tau, S_\tau, t \to \tau', r$	Adding traces
$\downarrow$	
$\tau, M_\tau, S_\tau, t \to \tau', M_{\tau'}, r$	Times of last modification
$\downarrow$	
$\tau, M_\tau, D, S_\tau, t \to \tau', M_{\tau'}, D', r$	Dependencies of expressions
$\downarrow$	
$\tau, M_\tau, D, F_\tau, S_\tau, t \to \tau', M_{\tau'}, D', F_{\tau'}, r$	Direct flows

Defining Annotations

Goal

We want this approach to scale to the full 720-rules JavaScript:

- no copy/pasting;
- a very general scheme (local rules).



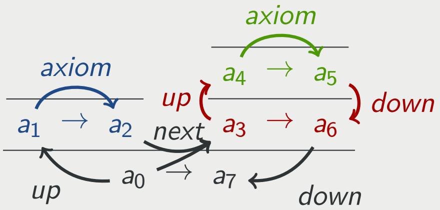
Annotations are defined directly from the semantics: we can be quite confident about them.

Defining Annotations: Example of Traces

Traces τ are used to identify a point in the derivation, that is to represent *execution time*.

Flow sensitivity

$$\text{ASG}\ \frac{S, e \rightarrow \quad r_0 \qquad S, \mathtt{x} =_1 r_0 \rightarrow \quad r}{S, \mathtt{x} = e \rightarrow \quad r}$$



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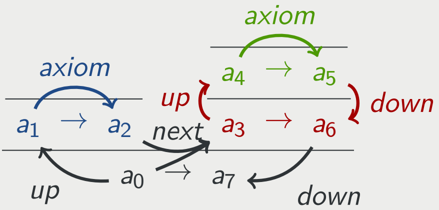

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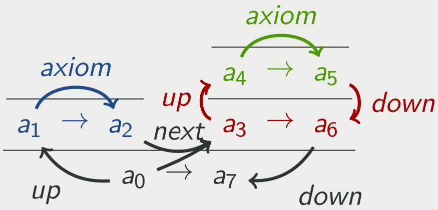

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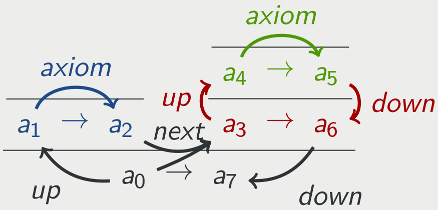

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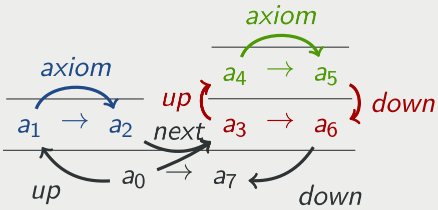

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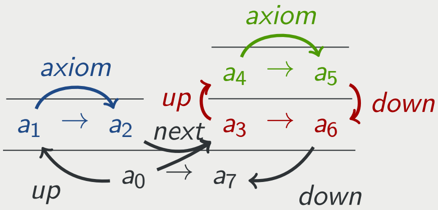

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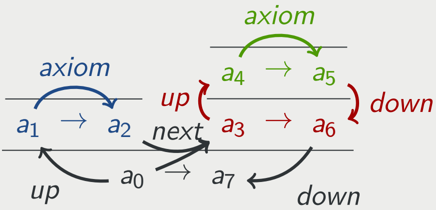
→ Flow sensitivity

$$\textsc{Asg}\ \frac{\tau_5 = \tau_4 \mathbin{+\!\!+} \textsc{Asg} \qquad \tau_1, S, e \to \tau_2, r_0 \quad \text{with } \tau_1 = \tau_0 \mathbin{+\!\!+} \textsc{AsgE} \qquad \tau_3, S, \texttt{x} =_1 r_0 \to \tau_4, r \quad \text{with } \tau_3 = \tau_2 \mathbin{+\!\!+} \textsc{Asg1}}{\tau_0, S, \texttt{x} = e \to \tau_5, r}$$



Direct Flows

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$\tau, M_\tau, D, S_\tau, t \to \tau', M_{\tau'}, D', r$	Dependencies of expressions $\mathtt{x}^\tau, l.\mathtt{f}^\tau, l \in D$
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$\tau, M_\tau, D, F_\tau, S_\tau, t \to \tau', M_{\tau'}, D', F_{\tau'}, r$	Direct flows $s \looparrowright t \in F_\tau$

Those flows $s \looparrowright t$ represent a dependency between:

- A **target**: a timed variable $\mathtt{x}^\tau$ or a timed field of a location $l.\mathtt{f}^\tau$.
- A **source**: a target or a location l.

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Direct Flows

$$\textsc{Obj}\ \frac{H[l] = \bot \qquad H_1 = H[l \mapsto \{\}] \\ \tau_1 = \tau + \textsc{Obj} \qquad M_1 = M[l \mapsto \tau_1] \qquad D_1 = D \cup \{l\}}{\tau, M, D, F, E, H, \underline{\{\}} \to \tau_1, M_1, D_1, F, E, H_1, l}$$

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Direct Flows

$$\frac{\begin{array}{c}\tau_1 = \tau_0 + \textsc{AsgE} \qquad \tau_3 = \tau_2 + \textsc{Asg1} \\ \tau_5 = \tau_4 + \textsc{Asg} \qquad \tau_1, M, \emptyset, F_0, S, e \to \tau_2, M', D, F_1, r_0 \\ \tau_3, M', D, F_1, S, \underline{\mathtt{x} =_1 r_0} \to \tau_4, M'', \emptyset, F_2, r\end{array}}{\tau_0, M, \emptyset, F_0, S, \underline{\mathtt{x} = e} \to \tau_5, M'', \emptyset, F_2, r} \textsc{Asg}$$

$$\frac{\tau' = \tau + \textsc{Asg1} \qquad E' = E[\mathtt{x} \mapsto v] \qquad M' = M[\mathtt{x} \mapsto \tau']}{\tau, M, D, F, S, \underline{\mathtt{x} =_1 (E, H, v)} \to \tau', M', \emptyset, \left\{ d \rightsquigarrow \mathtt{x}^{\tau'} | d \in D \right\} \cup F, E', H} \textsc{Asg1}$$

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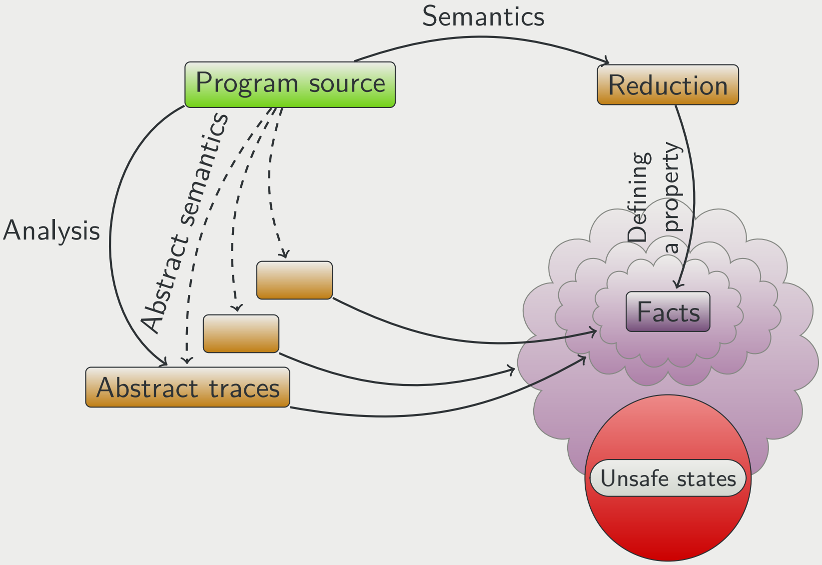
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Classical points-to abstractions

We chosed something very classical, checking whether it can fit.

- Objects are abstracted by their point of allocation.

$$l^\sharp \in \mathrm{Loc}^\sharp = \mathcal{P}\left(PP\right)$$

- Abstract values are abstract locations and the set of variable on which they depend.

$$v^\sharp \in \mathrm{Val}^\sharp = \mathrm{Loc}^\sharp \times \mathcal{P}\left(\mathrm{Var} \times PP\right)$$

Abstract Flows

- Environment and heap store the last program point of modification.

$$E^\sharp \in \mathrm{Env}^\sharp = \mathrm{Var} \to \left(\mathcal{P}\left(PP\right) \times \mathrm{Val}^\sharp\right)$$

$$H^\sharp \in \mathrm{Heap}^\sharp = \mathrm{Loc}^\sharp \to \mathrm{Field} \to \left(\mathcal{P}\left(PP\right) \times \mathrm{Val}^\sharp\right)$$

- This leads to the following abstract flows:

$$\mathrm{Store}^\sharp = (\mathrm{Var} \times PP) + (PP \times \mathrm{Field} \times PP) \qquad \mathrm{Source}^\sharp = PP + \mathrm{Store}^\sharp$$

$$s^\sharp \leadsto^\sharp t^\sharp \in \mathrm{Dep}^\sharp = \mathcal{P}\left(\mathrm{Source}^\sharp \times \mathrm{Store}^\sharp\right)$$

$$\frac{E^\sharp, H^\sharp, \underline{e} \rightarrow^\sharp v^\sharp, d^\sharp}{E^\sharp, H^\sharp, \underline{\mathtt{x}^p = e} \rightarrow^\sharp E^\sharp\left[\mathtt{x} \mapsto \left(\{p\},^\sharp v\right)\right], H^\sharp, \left(v^\sharp_l \cup d^\sharp\right)^\sharp \looparrowleft \mathtt{x}^p} \textsc{Asg}$$

$$\frac{\begin{array}{c} E^\sharp \sqsubseteq E^\sharp_0 \qquad H^\sharp \sqsubseteq H^\sharp_0 \\ E^\sharp_0, H^\sharp_0, \underline{s} \rightarrow^\sharp E^\sharp_1, H^\sharp_1, F^\sharp \\ E^\sharp_1 \sqsubseteq E^\sharp_0 \qquad H^\sharp_1 \sqsubseteq H^\sharp_0 \end{array}}{E^\sharp, H^\sharp, \underline{\text{while } e \text{ do } s} \rightarrow^\sharp E^\sharp_0, H^\sharp_0, F^\sharp} \textsc{While}$$

Correctness of the analysis

We define a relation $\prec$ relating

- Traces and PP;
- Heap and $\mathrm{Heap}^\sharp$;
- ...

Theorem (Work in progress)

If

$$[], \emptyset, [], \emptyset, \emptyset, \underline{s} \rightarrow \tau, M_\tau, F_\tau, E_\tau, H_\tau$$

and

$$\bot, \bot, \underline{s} \rightarrow^\sharp E^\sharp, H^\sharp, F^\sharp$$

then $E \prec E^\sharp$, $H \prec H^\sharp$ *and* $F_\tau \prec F^\sharp$.

Challenge

Fit It Into COQ.

$S_\tau, t \to r$	Standard semantics
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$\tau, M_\tau, D, F_\tau, S_\tau, t \to \tau', M_{\tau'}, D', F_{\tau'}, r$	Direct flows $s \rightsquigarrow t \in F_\tau$

Fit It Into Coq

```
Section LastModified.
Variable Locations : Annotations.

Definition ModifiedAnnots := annot_s_r Locations.
Record LastModifiedHeaps : Type :=
  makeLastModifiedHeaps {
    LCEnvironment : heap var ModifiedAnnots;
    LCHeap : heap loc (heap prop_name ModifiedAnnots)
  }.

Definition LastModified :=
  ConstantAnnotations LastModifiedHeaps.
```

Fit It Into Coq

```
Definition LastModifiedAxiom_s (r : LastModifiedHeaps)
  E H t o (R : red_stat Locations E H t o) :=
  let LCE := LCEnvironment r in
  let LCH := LCHeap r in
  let (_, tau) := extract_annot_s R in
  match R with
  | red_stat_ext_stat_assign_1 _ _ _ _ _ _ _ x _ _ ⇒
    let LCE' := write LCE x tau
    in makeLastModifiedHeaps LCE' LCH
  | red_stat_stat_delete _ _ _ _ _ l _ f _ _ _ _ _ _ ⇒
    let aob := read LCH l
    in let LCH' := write LCH l (write aob f tau)
    in makeLastModifiedHeaps LCE LCH'
  | red_stat_ext_stat_set_2 _ _ _ _ _ _ _ _ l _ f _ _ _ _ _ _ ⇒
    let aob := read LCH l
    in let LCH' := write LCH l (write aob f tau)
    in makeLastModifiedHeaps LCE LCH'
  | _ ⇒ makeLastModifiedHeaps LCE LCH
  end.
```

Fit It Into Coq

```
Definition annotLastModified :=
  makeIterativeAnnotations LastModified
    (init_e Transmit) (axiom_e Transmit) (up_e Transmit) (down_e
        Transmit) (next_e Transmit)
    (up_s_e Transmit) (next_e_s Transmit)
    (init_s Transmit) LastModifiedAxiom_s (up_s Transmit) (down_s
        Transmit) (next_s Transmit).

End LastModified.
```

Extensions

- Abstract domain for heap.

How to keep precision when taking as input an unknown heap?
What kind of knowledge can we assume on such a heap?

- Functions, closures: how to keep precision?
- Extensible records (how to precisely deal with prototype chains?).

$$\frac{E^\sharp, H^\sharp, \underline{e} \rightarrow^\sharp v^\sharp, d^\sharp \qquad H^\sharp[v_l^\sharp] \sqsubseteq o^\sharp \qquad o^\sharp[\mathtt{f}] = \left(p_0, v_f^\sharp\right)}{E^\sharp, H^\sharp, \underline{\text{delete } e.\mathtt{f}} \rightarrow^\sharp E^\sharp, H^\sharp, d^\sharp \hookleftarrow^\sharp v_l^\sharp.\mathtt{f}^{p_0}} \text{ DEL}$$

$$\begin{array}{rcl} \rho & ::= & \mathtt{f} : \mathit{Present}(v^\sharp) \\ & | & \mathtt{f} : \mathit{Missing}(v^\sharp) \\ & | & \mathtt{f} : \mathit{MayBeThere}(v^\sharp) \\ & | & \mathit{NoFieldsAtAll} \\ & | & \alpha \end{array}$$

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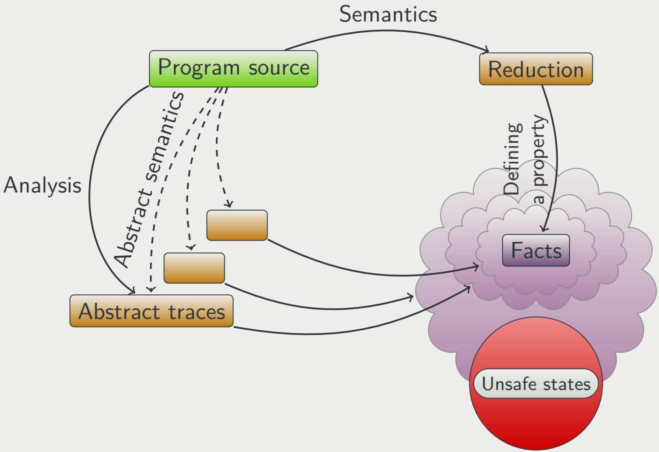

Thank you for listening!