An Abstract Semantics for Inference of Types and Effects in a Multi-Tier Web Language

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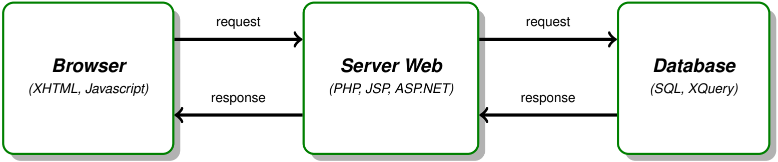
Multi-tier architecture

Standard web applications have a multi-tier architecture



Each tier runs on a different computational environment characterized by its language and its data representation (impedance mismatch problem)

LINKS: a Multi-Tier Web Language

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- from a single source code the compiler generates code for each tier
- support an unified cross-tier programming model by exploiting web continuations

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Web continuations in LINKS

Closures (expression to be executed plus bindings of free variables) stored in HTML pages

LINKS: security

Baltopoulos and Gordon have shown that

- storing web continuation in HTML page is not secure
- an attacker can violate
  1. Secrecy
  2. Data Integrity
  3. Control Integrity

LINKS: security

Solution

To overtake the security issues they have proposed a secure implementation that includes

1. a compilation strategy based on authenticated encryption
2. a types-and-effects system to enable source level reasoning about security of web applications

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The secure implementation has been formalized for TINYLINKS, a λ-calculus augmented with

1. XML values for representing web pages
2. `event` e `assert` annotation for expressing safety properties

TinyLinks

Syntax

$$
\begin{array}{l}
\mathtt{f}, \mathtt{y}, \mathtt{x} \\
\mathtt{p} \\
\mathtt{c} ::= \mathtt{Unit} \mid \mathtt{Zero} \mid \mathtt{Succ} \mid \mathtt{String} \\
\quad \mid \mathtt{Nil} \mid \mathtt{Cons} \mid \mathtt{Tuple} \mid \mathtt{Elem} \mid \mathtt{Text} \\
\mathtt{g} ::= + \mid - \mid * \mid / \\
\mathtt{L} ::= \mathtt{p}\,(\mathtt{V}_1, \ldots, \mathtt{V}_n) \\
\mathtt{V}, \mathtt{U} ::= \mathtt{x} \mid \mathtt{c}\,(\mathtt{V}_1, \ldots, \mathtt{V}_n) \mid \mathtt{href}(\mathtt{E}) \\
\quad \mid \lambda \mathtt{x}_1. \ldots, \mathtt{x}_n. \mathtt{E} \mid \mathtt{form}([\,\mathtt{l}_1, \ldots, \mathtt{l}_n\,], \mathtt{E}) \\
\mathtt{E} ::= \mathtt{V} \mid \mathtt{var}\,\mathtt{x} = \mathtt{E}_1; \mathtt{E}_2 \mid \mathtt{g}\,(\mathtt{E}_1, \mathtt{E}_2) \\
\quad \mid \mathtt{V}\,(\mathtt{U}_1, \ldots, \mathtt{U}_n) \mid \mathtt{post}([\,\mathtt{l}_1 = \mathtt{V}_1, \ldots, \mathtt{l}_n = \mathtt{V}_n\,], \mathtt{U}) \\
\quad \mid \mathtt{get}(\mathtt{V}) \mid \mathtt{event}\,\mathtt{L} \mid \mathtt{assert}\,\mathtt{L} \\
\quad \mid \begin{array}{l} \mathtt{switch}(\mathtt{V})\{ \\ \quad \mathtt{case}\,\mathtt{c}\,(\mathtt{x}_1, \ldots, \mathtt{x}_n) \to \mathtt{E}_1 \\ \quad \_ \to \mathtt{E}_2 \\ \} \end{array}
\end{array}
$$

Types-and-effects system

A powelful extension of type systems which allows one to statically reason about program's execution

$$\frac{\Gamma \vdash M_1 : \tau_1 \,\&\, \phi_1 \qquad \ldots \qquad \Gamma \vdash M_n : \tau_n \,\&\, \phi_n}{\Gamma \vdash E(M_1, \ldots, M_n) : \tau \,\&\, \phi}$$

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premise

$$\frac{\Gamma \vdash M_1 : \tau_1 \,\&\, \phi_1 \qquad \dots \qquad \Gamma \vdash M_n : \tau_n \,\&\, \phi_n}{\Gamma \vdash E(M_1, \dots, M_n) : \tau \,\&\, \phi}$$

conclusion **effects**

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premise $\Gamma \vdash M_1 : \tau_1 \,\&\, \phi_1 \quad \dots \quad \Gamma \vdash M_n : \tau_n \,\&\, \phi_n$

conclusion $\Gamma \vdash E(M_1, \dots, M_n) : \tau \,\&\, \phi$

effects

It compute for each program phrase its type augmented with a semantic property

- if $\Gamma \vdash M_i : \tau_i \,\&\, \phi_i \Rightarrow \tau_i$ is the type of the expression M_i and the semantic property ϕ_i holds
- then $\Gamma \vdash E(M_1, \dots, M_n) : \tau \,\&\, \phi \Rightarrow \tau$ is the type of the expression $E(M_1, \dots, M_n)$ and the semantic property ϕ holds

TinyLinks's types-and-effects system

Goal

Whenever an assertion `assert L` occurs in the execution there exists a previous occurrence of an event `event L`

$$\Gamma;\ \mathtt{F}\ \vdash \mathtt{E} \overset{exp}{\Rightarrow} <\_ : \mathtt{T} > \{\ \mathtt{F}_1\ \}$$

$$\Gamma;\ \mathtt{F}\ \vdash \mathtt{E} \overset{exp}{\Leftarrow} <\_ : \mathtt{T} > \{\ \mathtt{F}_1\ \}$$

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2. the preconditions

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For each expression `E` compute

1. the type
2. the preconditions
3. the post-conditions

TinyLinks's types-and-effects system

Some example of rules

$$\text{(T-Get)}\ \frac{\Gamma; \mathtt{F} \vdash \mathtt{V} \overset{val}{\Leftarrow} \mathtt{xml}}{\Gamma; \mathtt{F} \vdash \mathtt{get}(\mathtt{V}) \overset{exp}{\Rightarrow} \langle \_ : \mathtt{xml} \rangle \{\ \}}$$

TINYLINKS's types-and-effects system

Some example of rules

$$\text{(T-Post)}\ \frac{\Gamma;\mathtt{F} \vdash \mathtt{V_i} \overset{val}{\Leftarrow} \mathtt{string} \quad \forall i \in \{\,1,\,\dots\,,n\,\} \quad \Gamma;\mathtt{F} \vdash \mathtt{U} \overset{val}{\Leftarrow} \mathtt{xml}}{\Gamma;\mathtt{F} \vdash \mathtt{post}([\,(\mathtt{l_1} = \mathtt{V_1},\,\dots\,,\mathtt{l_n} = \mathtt{V_n})\,]\,,\mathtt{U}) \overset{exp}{\Rightarrow} \langle \_ : \mathtt{xml}\rangle\,\{\ \}}$$

TinyLinks's types-and-effects system

Some example of rules

$$
\text{(T-Assert)}\ \frac{\Gamma \vdash \diamond \qquad fv(\mathtt{F},\mathtt{L}) \subseteq dom(\Gamma) \qquad \mathtt{L} \in \mathtt{F} \qquad \mathtt{L} = \mathtt{p}\,(\mathtt{V_1},\,\ldots\,,\mathtt{V_n}) \qquad \Gamma;\mathtt{F} \vdash \mathtt{V_i} \overset{val}{\Rightarrow} \mathtt{T_i} \qquad \forall i \in \{\,1,\,\ldots\,,n\,\}}{\Gamma;\mathtt{F} \vdash \mathtt{assert}\,\mathtt{L} \overset{exp}{\Rightarrow} \langle \_ : \mathtt{unit} \rangle \,\{\,\mathtt{L}\,\}}
$$

TinyLinks's types-and-effects system

Some example of rules

$$\text{(T-App)}\ \frac{\Gamma; \mathtt{F} \vdash \mathtt{U} \stackrel{val}{\Rightarrow} \mathtt{T} \quad \mathtt{T} = \langle \mathtt{x_1} : \mathtt{T_1},\ \ldots,\ \mathtt{x_n} : \mathtt{T_n} \rangle \{\ \mathtt{F_1}\ \} \rightarrow \mathtt{W} \quad fv(\mathtt{T}) = \emptyset \qquad \Gamma; \mathtt{F} \vdash \mathtt{V_i} \stackrel{val}{\Leftarrow} \mathtt{T_i} \quad \forall i \in \{\ 1,\ \ldots\ , n\ \} \quad \mathtt{F_1}\,[\mathtt{V_1}/\mathtt{x_1}]\ \ldots\ [\mathtt{V_n}/\mathtt{x_n}] \subseteq \mathtt{F}}{\Gamma; \mathtt{F} \vdash \mathtt{U}\,(\mathtt{V_1},\ \ldots\ , \mathtt{V_n}) \stackrel{exp}{\Rightarrow} \mathtt{W}\,[\mathtt{V_1}/\mathtt{x_1}]\ \ldots\ [\mathtt{V_n}/\mathtt{x_n}]}$$

TINYLINKS's types-and-effects system

Safe Web Application

A web application $\mathtt{E}$ is safe if and only if there exists a proof within the types-and-effects system of the judgment

$$\emptyset; \emptyset \vdash \mathtt{E} \overset{exp}{\Leftarrow} \langle \_ : \mathtt{xml} \rangle \, \{ \ \}$$

Types-and-effects system

Usually the definition of a types-and-effects analysis requires

1. Definition of rules
2. State and prove the soundness of analysis
3. Definition of inference algorithm
4. Prove that the algorithm is correct (soundness/completeness)

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The approach used for the TinyLinks's types-and-effects system is different

- each expression is translated in an expression of F7
  - this translation hides the property of the analysis

Our goal

Reconstruct the TinyLinks's types-and-effects system by abstract interpretation

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We follow Cousot's methodology for type systems

1. we define a denotational semantics for TinyLinks (concrete semantics)
2. we define a abstract semantics that computes types augmented by effects

Concrete semantics

A denotational semantics that considers

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- TinyLinks as an untyped λ-calculus

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Domain of values

Injection (Text, Form, Fun, . . .)

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Injection (Text, Form, Fun, ...)

- the occurrence and assertion of the events

$$EEnv = Pred \to (Dval \times Mark)$$

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Domain of values

Injection (Text, Form, Fun, . . .)

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Events environment

$\{ E, EA, A \}$

values in the events are integers only

Concrete semantics

Two semantic functions

1. for values

$$\mathcal{V}[\![-]\!] : \texttt{VAL} \rightarrow Env \rightarrow EEnv \rightarrow Eval$$

2. for expressions

$$[\![-]\!] : \texttt{EXP} \rightarrow Env \rightarrow EEnv \rightarrow (Eval \times EEnv)$$

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Examples of semantic equation

$$\begin{aligned}
[\![\texttt{get(V)}]\!]\rho\,\phi \;= &\; let^{\star}\; v' \;= \mathcal{V}[\![\texttt{V}]\!]\rho\,\phi\; in \\
& case\; v'\; of \\
& \quad Href(f) \rightarrow f\,\phi \\
& \quad _ \rightarrow (\lfloor WrongValue() \rfloor,\, \iota)
\end{aligned}$$

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Examples of semantic equation

$$\begin{aligned}
[\![\texttt{assert}\,\texttt{q}(\texttt{V})]\!]\rho\,\phi \;&= let^{\star}\ ev\ = evalToDval(\mathcal{V}[\![\texttt{V}]\!]\rho\,\phi)\ in\\
&\quad let\ (ev',\, m)\ = \phi\, q\\
&\quad if\ ev\ =\ ev'\ then\\
&\qquad (\lfloor Unit() \rfloor,\, \phi\left[(ev',\, EA)/q\right])\\
&\quad else\\
&\qquad (\lfloor WrongValue() \rfloor,\, \iota)
\end{aligned}$$

Unsoundness in TinyLinks analysis

Consider the expression

$$\texttt{get}(\texttt{Text}(\texttt{"Hello World!"}))$$

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Error: the denotation of `Text("Hello World!")` is not a link

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TinyLinks's types-and-effects system

$$\emptyset; \emptyset \vdash \texttt{get}(\texttt{Text}(\texttt{"Hello World!"})) \overset{exp}{\Leftarrow} \langle \_ : \texttt{xml} \rangle \; \{ \; \}$$

the expression is type checked and the computed type is `xml`

Abstract domain

Values

Trouble

- types have annotations

$$\texttt{integer}\,\{\ \} \rightarrow \texttt{integer}\,\{\,q : 5,\ p : 3\,\}$$

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Solution: simple type and constraints

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$$\texttt{integer}\,\{\ \} \to \texttt{integer}\,\{\,\texttt{p}:3,\ \texttt{q}:5\,\}$$

Solution: simple type and constraints

- we substitute the annotations in the types with annotation variables
- we introduce constraints to restrict annotation variables

$$\texttt{integer}(\gamma_1) \to \texttt{integer}(\gamma_2) \qquad \gamma_1 \supseteq \emptyset \quad \gamma_2 \supseteq \{\,\texttt{p}:3,\ \texttt{q}:5\,\}$$

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Values

- the events depend on the concrete values ($Dval$)

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$$TipoS \times Dval \times Constr \times TPred$$

(type, substitution)∪ NoType

$Pred \rightarrow Dval$

concrete value

constraints

Abstract semantics

Example of semantic equation

$$
\begin{array}{l}
[\![\texttt{get(V)}]\!]^a \rho\, \phi \;= \\
\quad \gamma \in V_a \quad fresh \\
\quad let\ (ts,\, d,\, C,\, f)\ = \mathcal{V}[\![\texttt{V}]\!]^a \rho\, \phi\, in \\
\quad if\, ts \neq NoType\, then \\
\quad\quad case\ mgu(\{\ ts.t = link(\gamma)\ \} \cup ts.\theta)\ of \\
\quad\quad\quad S(\theta) \rightarrow let\ C'\ =\ \{\ (\theta(\gamma),\, q) \in \theta(C)\ \}\ in \\
\quad\quad\quad\quad if\, check(\theta(f \leftarrow C'),\, \phi)\ then \\
\quad\quad\quad\quad\quad (((\theta(xml(\gamma)),\, \theta), \\
\quad\quad\quad\quad\quad\quad\quad nodval,\, \theta(C) \setminus C',\, \theta(f \downarrow C)), \phi) \\
\quad\quad\quad\quad else \\
\quad\quad\quad\quad\quad (Error,\, \iota) \\
\quad\quad\quad \_ \rightarrow (Error,\, \iota) \\
\quad else \\
\quad\quad (Error,\, \iota)
\end{array}
$$

Analyzer

Both the concrete and abstract semantics have been implemented as OCaml programs

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- TinyLinks programs are represented in abstract syntax
- the implementation have an unique semantic function parametrized with respect to
  - the primitive operations
  - the semantic domain

Example 1

Expression

```
fun buy(value, dbpass) {
  var _ = assert PriceIs(value);
    Text("a")
}
```

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Abstract semantics

```
(type - :
Function(_#value#var0_, Integer(), _annvar0_,
  Function(_#dbpass#var1_, _typevar1_, _annvar2_,
    Xml(_annvar4_), _annvar3_),
  _annvar1_)
No_dval [(_annvar2_,PriceIs)]
  {PriceIs -> _#value#var0_}, {})
```

Example 2

Expression

$$\texttt{buy 5}$$

Example 2

Expression

buy 5

Abstract semantics

```
(type - :
  Function(_#dbpass#var3_, _typevar3_, _annvar7_,
         Xml(_annvar9_), _annvar8_)
  Unknown [(_annvar7_,PriceIs)] {PriceIs -> 5}, {})
```

Example 3

Expression

`buy 5 "a"`

Example 3

Expression

$$\texttt{buy}\ 5\ \texttt{"a"}$$

Abstract semantics

```
Exception: No_type "apply_fun: no preconditions"
```

Conclusions

We have reconstructed the TinyLinks's types-and-effects system by abstract interpretation

- we have precisely defined relationship between semantics and analysis
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Future work

- Consider a type system with sub-types (`link` $<:$ `xml`, `form` $<:$ `xml`)
- Extend the class of value that can be used in the events
- Generalize the methodology and apply it to further analysis