Information Flow Security in Imperative Languages

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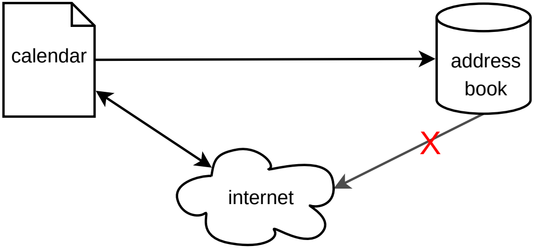
14. Kolloquium Programmiersprachen und Grundlagen der Programmierung
Timmendorfer Strand, Oktober 2007

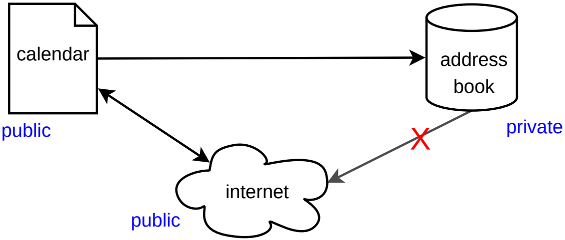
Gefördert durch DFG-Projekt InfoZert (Be 3712/2-1)

What are secure information flows?



- control flow of information between objects of a computing system (like variables, files, channels)
- restricting access to objects is not flexible enough

What are secure information flows?



- assign confidentiality domains to objects
- specify secure information flows using a *flow policy*
    - e.g. allow flows from public to private domain, but not vice versa

Secure flows in imperative languages

A simple WHILE language

$$
\begin{array}{rcl}
x \in \mathcal{X} & & \\
v \in \mathcal{V} & = & \mathbb{N} \\
e & ::= & x \mid v \mid e_1 + e_2 \mid \ldots \\
C & ::= & x := e \mid C_1 \; ; \; C_2 \mid \textbf{skip} \mid \\
 & & \textbf{if } e \textbf{ then } C_1 \textbf{ else } C_2 \mid \textbf{while } e \textbf{ do } C
\end{array}
$$

program states: $\sigma, \tau : \mathcal{X} \to \mathcal{V}$
given sematics: $[\![e]\!]_\sigma$ and $\sigma \xrightarrow{C} \tau$

Secure flows in imperative languages

Identifying secure flows

- security objects: variables
- classified into *low* and *high* domain: $\mathcal{X}_{low} \uplus \mathcal{X}_{high} = \mathcal{X}$
- flow policy: *low* $\rightsquigarrow$ *high*, but *high* $\not\rightsquigarrow$ *low*

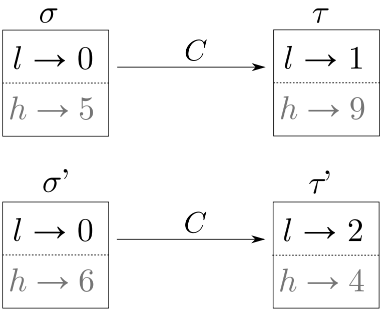
Data flow examples

assume $l \in \mathcal{X}_{low}, h \in \mathcal{X}_{high}$

$$
\begin{aligned}
h := l \qquad & (ok) \\
l := h \qquad & (insecure) \\
l := h \bmod 2 \qquad & (insecure) \\
\textbf{if } h > 0 \textbf{ then } l := 1 \textbf{ else } l := 3 \qquad & (insecure)
\end{aligned}
$$

Non-interference

- initial values of *high* variables may not affect final values of *low* variables
- equivalently: when observing only *low* variables, the behaviour of the program must be deterministic



Non-interference

Definition

Two states σ, σ' are *indistinguishable*, written $\sigma \sim \sigma'$, if for all $x \in \mathcal{X}_{low}$: $\sigma(x) = \sigma'(x)$.

A program C is *secure* if whenever $\sigma \sim \sigma'$ and $\sigma \xrightarrow{C} \tau$ and $\sigma' \xrightarrow{C} \tau'$, then $\tau \sim \tau'$.

Other types of information flows

flows not covered by non-interference definition:

- termination behaviour
- timing aspects
- resource usage
- . . .

here: only flows between variables (direct and implicit)

Static flow analysis

- type system by Volpano, Smith, Irvine (1996)
- check assignments for invalid direct flows
- implicit flows: do not allow assignment to *low* variables under *high* guard

$$\textbf{if } h > 0 \textbf{ then } l := 1 \textbf{ else } l := 3$$

Typing expressions

$k ::= low \mid high$

$\boxed{\vdash e : k}$

$$\frac{}{\vdash e : high} \qquad \frac{Vars(e) \cap \mathcal{X}_{high} = \emptyset}{\vdash e : low}$$

- if $\vdash e : low$, then e does not depend on *high* variables

Typing programs

$k ::= low \mid high \qquad h \in \mathcal{X}_{high},\ l \in \mathcal{X}_{low}$

$\boxed{[k] \vdash C}$

$$\frac{}{[high] \vdash h := e} \qquad \frac{\vdash e : low}{[low] \vdash l := e}$$

Typing programs

$k ::= low \mid high \qquad h \in \mathcal{X}_{high},\ l \in \mathcal{X}_{low}$

$\boxed{[k] \vdash C}$

$$\frac{}{[high] \vdash h := e} \qquad \frac{\vdash e : low}{[low] \vdash l := e}$$

- k is a lower bound of the types of variables assigned in C

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$$\frac{\vdash e : k \quad [k] \vdash C_1 \quad [k] \vdash C_2}{[k] \vdash \textbf{if}\ e\ \textbf{then}\ C_1\ \textbf{else}\ C_2} \qquad \frac{\vdash e : k \quad [k] \vdash C}{[k] \vdash \textbf{while}\ e\ \textbf{do}\ C}$$

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$$\frac{}{[high] \vdash \textbf{skip}} \qquad \frac{[k] \vdash C_1 \quad [k] \vdash C_2}{[k] \vdash C_1 \,;\, C_2} \qquad \frac{[high] \vdash C}{[low] \vdash C}$$

- k is a lower bound of the types of variables assigned in C

Typing programs

$k ::= low \mid high \qquad h \in \mathcal{X}_{high},\ l \in \mathcal{X}_{low}$

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- k is a lower bound of the types of variables assigned in C
- Soundness: if $[low] \vdash C$, then C is secure, i.e. non-interferent

Further extensions

Richer language

- recursive functions
- references, objects, inheritance
- exceptions

Improve analysis

- more complete type system
- program logics

Our goal: secure flow framework

secure software design

- extend UML with specifications for security domains and flow policies
- translate requirements to language level

proof-carrying code architecture

- static flow analysis during compilation
- distribute proof as certificate for compiled code
- client (e.g. mobile device) can easily check whether certificate is correct and satisfies system policy

Limitations of static analysis

Problem: data objects only known at run-time

- example: program with file I/O
- to ensure non-interference for file contents, need to know which files are manipulated
- requires model of file names
- but: file names are interpreted strings

Dynamic labels

Solution

- associate data objects with labels (type variables)
- actual type available at runtime, may be verified against policy
- prove that program is secure for every type instantiation

Extended syntax

$$C \quad ::= \quad \ldots \mid \textbf{with}\ (x_\alpha \mapsto f(e))\ \textbf{do}\ C \mid \textbf{if}\ \alpha \rightsquigarrow \beta\ \textbf{then}\ C_1\ \textbf{else}\ C_2$$

Example

with $(f_\alpha \mapsto \mathit{openFile}(\mathit{fn}))$ **do**
  if $\alpha \rightsquigarrow \mathit{low}$ **then** $l := f$ **else skip**

Other practical issues

- non-interference is often too strict
  - certain situations require a controlled way to *declassify* and release sensitive information
  - need intuitive formalisation
- concurrent and distributed systems
- portability: programmer's intended policy vs client policy

some issues covered by *Jif* (Java with information flows)

Summary

- restrict flow of information, but not access to it
- non-interference formalises confidential data confinement
- static program analysis using type system
- embed in framework for flow-secure software engineering
- challenge: adopt security notion to real-world software
- contribution: dynamic labels for run-time objects