Enforcing Dynamic Interference Policy

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Introduction

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- “Non-interference: who needs it ?”

- Numerous acceptable flows:
  - Cryptography;
  - Password check;
  - etc.

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  - The policy is generally static.
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  1. A "security profile" for each operator: rewrite rules over privacy lattice.
  2. Rewrite rules may include actions modifying the policy.
  3. Definition of high/low bisimulation wrt dynamic policy.
  4. Program safety verification by abstract execution on privacy levels.
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Plan

Programming framework

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Minimalistic programming language:

\[
\begin{align*}

\nu & ::= x | 0 | 1 | tt | ff | \ldots \\
\tau, \beta & ::= \nu | f(x_1, \ldots, x_n) \\
P & ::= x \leftarrow \tau | P; P | \\
& \quad \text{if } \beta \text{ then } P \text{ else } P | \text{while } \beta \text{ do } P | \text{skip}
\end{align*}
\]

It can be seen as an intermediate language:

\[
x := f(345, g(x_1, x_2)) \equiv (x_0 \leftarrow 345; x_3 \leftarrow g(x_2, x_3); x \leftarrow f(x_3)
\]

Natural semantics \( \langle \mu, P \rangle \rightarrow_{\text{os}} \langle \mu', P' \rangle \)
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- Program variables are attributed privacy levels.
- Privacy levels are elements of a lattice $\mathbb{L}$.
- Interference policies are based on authorised behavior of operators.
- Usually it is done through types but it is too strict.
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$\Rightarrow$ We use term rewriting system on privacy levels in order to deal with concrete privacy levels used at evaluation time.
Static interference policy

- For each operator $f$ we consider $f_{DIP}$.
- $\Sigma_{DIP} = (\mathcal{V}_{DIP}, \mathcal{V} \cup \Omega_{DIP} \cup \mathcal{L})$
- Encryption policy, $D$:
  
  $\text{encrypt}_{DIP}(\pi_{128}, \bar{x}) \rightarrow \pi_1$
  $\text{encrypt}_{DIP}(\pi_{256}, \bar{x}) \rightarrow \bot$
  $\text{SPY}_{DIP} \rightarrow \bot$
  $\text{PIN}_{DIP} \rightarrow \top$
  ...

- In the program: $\text{SPY} \leftarrow \text{encrypt}(K, \text{PIN})$
  The security level of $\text{encrypt}(K, \text{PIN})$ is computed using rules of $D$. 
Dynamicity

- Privacy levels may change during computation.
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- Rewriting rules with actions: $l \rightarrow r; a$

$$a ::= x \mapsto \pi | \overline{x} \mapsto \pi | \overline{x} \mapsto \overline{y} | x \mapsto \overline{y} | a; a$$
Dynamicity

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  \[ a ::= x \mapsto \pi \mid \overline{x} \mapsto \pi \mid \overline{x} \mapsto y \mid x \mapsto y \mid a; a \]

- The interference policy changes through the evaluation of operator security level computation:
  
  \[ \langle t[\sigma(l)], D \rangle \rightsquigarrow \langle t[\sigma(r)], D' \rangle \]
Three strikes, out

- Aim: to control the number of password checks before blocking the system.
- Program command: `ckpwd(g, PWD)`
Aim: to control the number of password checks before blocking the system.

Program command: \texttt{ckpwd}(g, \texttt{PWD})

For each operator $f$ of arity $n$ we consider $f_{DIP}$ of arity $2n$.

\textbf{distinction between the name of a program variable and its privacy level.}

Privacy level of \texttt{ckpwd}(g, \texttt{PWD}) is computed by the evaluation of:

\[ \texttt{ckpwd}_{DIP}(\pi_g, g, \pi_{pwd}, \texttt{PWD}) \]
Three strikes, out

ckpwd(⊥, g, t₀, p) → ⊥; p → t₁
ckpwd(⊥, g, t₂, p) → ⊥; p → t₃
ckpwd(⊥, (g, t₃, p) → ⊤
g → ⊥
PIN₂ → t₀

...
Three strikes, out

\[
\begin{align*}
\text{ckpwd}(\bot, \overline{g}, t_0, \overline{p}) & \rightarrow \bot; \overline{p} \rightarrow t_1 \\
\text{ckpwd}(\bot, \overline{g}, t_2, \overline{p}) & \rightarrow \bot; \overline{p} \rightarrow t_2 \\
\text{ckpwd}(\bot, \overline{g}, t_3, \overline{p}) & \rightarrow \top \\
\text{ckok}(\overline{x}, \overline{y}) & \rightarrow \bot; \overline{y} \rightarrow t_0 \\
\text{PIN}_1 & \rightarrow t_0 \\
\text{PIN}_2 & \rightarrow t_0
\end{align*}
\]

... 

In the program the evaluation modifies the DIP:
if \( \text{ckpwd}(g, \text{PIN}_1) \) then blah else next \_try
Dynamic interference policy

Definition
A DIP, \( D \), is a confluent terminating rewrite system with actions with:

1. For every \( x \in \mathcal{V} \) there is a rule \( x \rightarrow \pi \) in \( D \).
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   \[ \forall \tau_1, \tau_2 \in \mathcal{L}, \tau_1 \neq \tau_2 \implies \tau_1 \not\equiv \tau_2. \]
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   \[ \forall \tau_1, \tau_2 \in \mathcal{L}, \tau_1 \neq \tau_2 \implies \tau_1 \not\leftrightarrow \tau_2. \]
5. functions in $\Sigma$ are monotonic w.r.t. privacy levels: \[ \forall \pi_i, \pi'_i \in \mathcal{L}, \pi_i \sqsubseteq \pi'_i \implies \text{nf}^D(f(\pi_1, \ldots, \pi_n)) \sqsubseteq \text{nf}^D(f(\pi'_1, \ldots, \pi'_n)). \]
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$\langle t, \mathcal{D} \rangle \sim^* \langle \pi^\mathcal{D}(t), \overline{\mathcal{D}}^t \rangle$
Privacy level of a term wrt $\mathcal{D}$

- to compute the privacy level of $f(x, y)$ we consider
  \[ t = f_{\text{DIP}}(nf^\mathcal{D}(x), x, nf^\mathcal{D}(y), y) \]

- The evaluation of this term in $\mathcal{D}$ gives the privacy level and a new interference policy:
  \[ \langle t, \mathcal{D} \rangle \sim^* \langle \pi^\mathcal{D}(t), \overline{\mathcal{D}}^{t} \rangle \]
Plan

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Program safety

- Traditionally: a program is safe if every modification of a value above $\pi$ cannot be observed below $\pi$:

$$\langle \mu_1, P \rangle \overset{\ast}{\rightarrow}_{\text{os}} \mu'_1$$

$$\langle \mu_2, P \rangle \overset{\ast}{\rightarrow}_{\text{os}} \mu'_2$$

$$\mu'_1 \equiv_{\pi} \mu'_2$$

- What to do with the policy:

$$\text{encrypt}(\pi_{1024}, K, \top, \overline{p}) \rightarrow \perp$$

making possible program as:

$$\text{SPY} \leftarrow \text{encrypt}(\text{key}_{1024}, \text{PIN})$$
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▶ What to do with the policy:

$$\text{encrypt}(\pi_{1024}, K, \top, p) \rightarrow \bot$$

making possible program as:

$$\text{SPY} \leftarrow \text{encrypt}(\text{key}_{1024}, \text{PIN})$$

⇒ Use an alternate operational semantics in which declared leaks are treated specifically.

▶ Notion of declassified operational semantics.

$$\langle \mu_1, P \rangle \xrightarrow{\mu_d} \langle \mu'_1, P' \rangle$$
A term is declassifying if its privacy level is lower than one of its arguments.

Such terms will be subjected to specific rules in the declassified operational semantics.

Definition (Declassifying terms and assignments)

\( t = f(x_1, \ldots, x_n) \) is declassifying wrt \( \mathcal{D} \), written \( \mathcal{D} \vdash f(x_1, \ldots, x_n) \downarrow \) if:

\[
\pi^\mathcal{D}(t) \sqsubseteq \bigcup_{i=1}^{n} \pi^\mathcal{D}(t_i)
\]
Declassified evaluation

- $\langle P, \mu \rangle \xrightarrow{\mu_d} \langle P', \mu', D' \rangle$

- Declassifying assignment:

$$
D \vdash f_{DIP}((\pi^D(x), x) \downarrow \left[ f(x) \right])_{\mu_d} = v
\quad \frac{\langle f(\pi^D(x), x), D \rangle \leadsto^* \langle \pi, Df(\pi^D(x), x) \rangle}{\langle y \leftarrow f(x), \mu, D \rangle \xrightarrow{\mu_d} \langle \text{skip}, \mu[y := v], Df(\pi^D(x), x) \rangle}
$$
Definition (Bisimulation)

A $\pi$-bisimulation is a symmetric relation $R$ on couples formed by a program and a DIP such that:

If $\langle P_1, D_1 \rangle R \langle P_2, D_2 \rangle$ and

$\langle \mu_1, P_1, D_1 \rangle \xrightarrow{\mu_1} \langle \mu'_1, P'_1, D'_1 \rangle$

and $\mu_1 \simeq_{D_1 \uplus D_2}^{\pi} \mu_2$
Definition (Bisimulation)

A \( \pi \)-bisimulation is a symmetric relation \( \mathcal{R} \) on couples formed by a program and a DIP such that:

If \( \langle P_1, D_1 \rangle \mathcal{R} \langle P_2, D_2 \rangle \) and

\[
\langle \mu_1, P_1, D_1 \rangle \xrightarrow{\mu_1} \langle \mu'_1, P'_1, D'_1 \rangle \quad \Rightarrow \quad \exists P'_2, D'_2 \text{ and } \mu'_2 \text{ s.t.}
\]

\[
\langle \mu_2, P_2, D_2 \rangle \xrightarrow{\mu_1}^* \langle \mu'_2, P'_2, D'_2 \rangle
\]

and \( \mu'_1 \sim_{\pi} D'_1 \sqcup D'_2 \mu_2 \)

and \( \langle P'_1, D'_1 \rangle \mathcal{R} \langle P'_2, D'_2 \rangle \)
The union of two $\pi$-bisimulation is a $\pi$-bisimulation.

The biggest $\pi$-bisimulation is written $\simeq$ and is the union of all $\pi$-bisimulation.
Program safety w.r.t. a DIP

- The union of two $\pi$-bisimulation is a $\pi$-bisimulation.
- The biggest $\pi$-bisimulation is written $\simeq$ and is the union of all $\pi$-bisimulation.

Definition (Safe program)

A program $P$ is safe with relation DIP $\mathcal{D}$, written $\mathcal{D} \models P$, if for all privacy level $\pi$ $\langle P, \mathcal{D} \rangle \simeq^{\pi} \langle P, \mathcal{D} \rangle$. 
Plan

Programming framework

Dynamic interference policy

Program safety w.r.t. DIP

Program Verification

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Abstract execution principle (1)

Idea: to execute the program on $L$.

An abstract memory record associates variables with their privacy levels.

Record of the highest privacy level encountered in if-then-else and while guards to avoid indirect leaks, e.g.:

$$\text{if } \text{pin} = 0 \text{ then while } \text{tt} \text{ do } \text{skip else } \text{skip;} \text{ spy} \leftarrow 0$$

Check assignments wrt $D$ and $:\n
x \leftarrow f(\ldots) \implies \pi_D(x) \subseteq (\pi_D(f(\ldots)) \sqcup \pi_g)$

raises a failure if the inequality is not satisfied.
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  \]
- Check assignments wrt $\mathcal{D}$ and:
  \[
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Abstract execution principle (2)

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- Problem: it is not possible to merge DIPs resulting from the branches of an if-then-else construct.
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- Problem: it is not possible to merge DIPs resulting from the branches of an if-then-else construct.
  \[\implies\text{Creation of a DIP list recording DIP’s for each execution paths.}\]
- Fixpoint problem for the while construct.
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- Moreover evaluation of terms modify the DIP.
- Problem: it is not possible to merge DIPs resulting from the branches of an if-then-else construct.
  \[\rightarrow\] Creation of a DIP list recording DIP’s for each execution paths.
- Fixpoint problem for the while construct.
  \[\rightarrow\] Finite number of DIP lists.
Abstract execution result

Theorem

$$\exists \mathcal{L}. (\langle\{\langle D, \bot \rangle\}, P \rangle \rightarrow^* \mathcal{L}) \implies D \models P$$
Abstract execution result

Theorem

\[ \exists \mathcal{L}. (\langle \{\{D, \bot\}\}, P\rangle \rightarrow^* \mathcal{L}) \implies D \models P \]

- Converse implication does not hold:

  if PIN = 0 then SPY ← 1 else SPY ← 1

  this safe program raises a failure in the abstract operational semantics.
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- We have introduced dynamicity aspects in interference policies.
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  - Definition of program safety wrt DIP.
  - Sound program analysis algorithm.
- Encompass more real life scenarios than traditional noninterference based methods.
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- We have introduced dynamicity aspects in interference policies.
  - Definition of privacy levels.
  - Definition of program safety wrt DIP.
  - Sound program analysis algorithm.
  - Encompass more real life scenarios than traditional noninterference based methods.
- Dynamic aspects are limited to the evolution of data privacy levels.
- Extension in presence of concurrency?