Typing Illegal Information Flows as Program Effects

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Outline

Information Flow Security Analysis

General Goal

Prevent the execution of programs that leak information

What do we mean by information leak?

- **Information Flow Policy:**
  - A lattice of security levels: $\mathcal{L} = \langle L, \sqsubseteq, \sqcup, \sqcap, \bot, \top \rangle$
  - Assign a security level to each resource: $\Sigma : \mathcal{R}ef \rightarrow L$
- Information is not allowed to flow from high security levels to low security levels:
  - $l_1 \sqsubseteq l_2 \Rightarrow l_1 \rightarrow l_2$ - **Legal**
  - $l_1 \not\sqsubseteq l_2 \Rightarrow l_1 \rightarrow l_2$ - **Illegal**

Goal

We want to...

Be able to reason to reason about illegal programs

Why?

- Order illegal programs wrt their degree of illegality
- Express arbitrary policy relaxations

Goal

Standard Type Systems

- The type assigned to each program is generally not meaningfull
- Essentially there are only two types: **secure** and **insecure**

Our approach

- Type each program with a **summary** of the illegal flows that it may trigger:

Program declassification effect

Reinterpreting the Declassification Effect

Type interpretation

A summary of the illegal flows that may occur during the exectution of the program

Policy interpretation

- A relaxation of the original policy
- The strictest IF policy to which the program complies

Outline

Representing Illegal Flows

Kernels

The declassification effect is modeled as kernel on the original lattice

Kernel???

A kernel is a function k on a lattice which is:

- **contractant:** $k(l) \sqsubseteq l$
- **idempotent:** $k(k(l)) = k(l)$
- **monotone:** $l_1 \sqsubseteq l_2 \;\Rightarrow\; k(l_1) \sqsubseteq k(l_2)$

Informally, a kernel is a function on a lattice that...

maps each point in the lattice to itself or to a lower point preserving the original relative orders.

Representing Illegal Flows

Kernels

The declassification effect is modeled as kernel on the original lattice

Capturing illegal flows

- Kernel k is said to **admit** flow $l_1 \to l_2$ if: $k(l_1) \sqsubseteq k(l_2)$
- Given a set of illegal flows the **strictest kernel** that admits all its flows is always defined!

Why Kernels?

Kernels can be ordered in a meaningful way

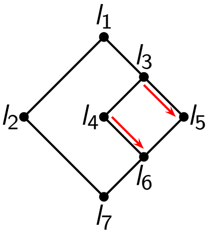
- $k_1 \sqsubseteq k_2$: k_1 collapses more levels down than k_2
- **Interpretation:** k_1 is equally or less strict than k_2

The set of all kernels is a lattice

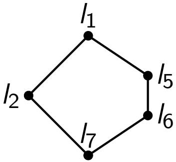
- Given two kernels k_1 and k_2, $k_1 \sqcap k_2$ is always defined
- $k_1 \sqcap k_2$ is the strictest kernel that is simulaneously less confidential than k_1 and k_2
- The **strictest kernel** maps each level to itself
- The **most permissive kernel** maps all levels to the bottom level

Kernels as Declassification Effects

Original Lattice



Illegal Flow: $l_3 \rightarrow l_5$



$l_3 \rightarrow l_5$

Kernels as Declassification Effects

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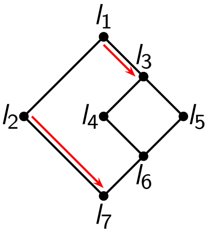
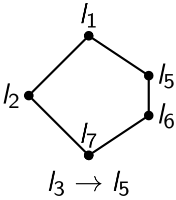
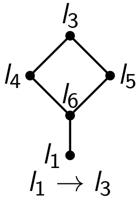


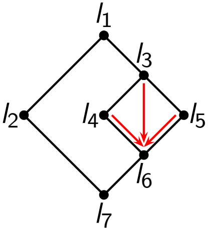
Illegal Flow: $l_1 \rightarrow l_3$



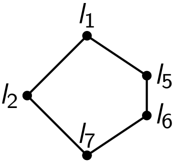


Kernels as Declassification Effects

Original Lattice



Illegal Flow: $l_3 \to l_6$



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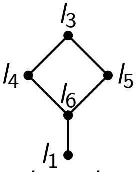

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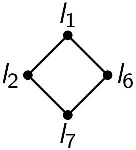

$l_3 \to l_6$

Kernels as Declassification Effects

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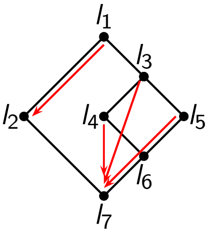
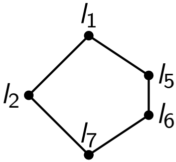
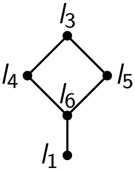


Illegal Flow: $l_1 \rightarrow l_2$



$l_3 \rightarrow l_5$



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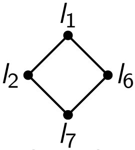

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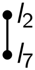

$l_1 \rightarrow l_2$

Relaxing IF Settings

Kernels as policy relaxations

- An illegal flow $l_1 \to l_2$ in the original setting is deemed legal by a given kernel k if:

$$k(l_1) = k(l_2)$$

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- **Lattice:** $\mathcal{L}$
- **Labeling:** Σ

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Original IF Setting

- **Lattice:** $\mathcal{L}$
- **Labeling:** Σ

$\xrightarrow{\mathbf{k}}$

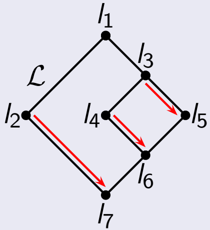
Relaxed IF Setting

- **Lattice:** $k(\mathcal{L})$
- **Labeling:** $k \circ \Sigma$

Relaxing IF Settings

Original IF Setting

$$\Sigma = \left\{ \begin{array}{c} a \mapsto l_2, b \mapsto l_3 \\ c \mapsto l_5, d \mapsto l_7 \end{array} \right\}$$



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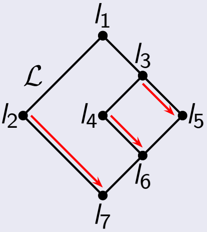
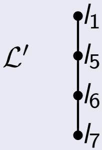


Relaxed IF Setting

$$\Sigma' = \left\{ \begin{array}{c} a \mapsto l_7, b \mapsto l_5 \\ c \mapsto l_5, d \mapsto l_5 \end{array} \right\}$$



Outline

Language

Syntax

- **Expressions:** λ-Calculus + Reference Creation + Thread creation

Language

Syntax

- **Expressions:** λ-Calculus + Reference Creation + Thread creation

Small-step operational semantics

- **Transitions:** $\langle P, S \rangle \rightarrow \langle P', S' \rangle$
- P: **pool of threads**
- S: **memory**

Security Property

$(\mathcal{L}, \Sigma, k, \Gamma)$-Noninterference

A pool of expressions P satisfies Noninterference with respect to a setting $(\mathcal{L}, \Sigma, k)$ and a typing environment Γ if it satisfies $P \approx^{\mathcal{L},\Sigma,k}_{\Gamma,l} P$ for all security levels l.

Where:

- $\approx^{\mathcal{L},\Sigma,k}_{\Gamma,l}$ is the **largest** $(\mathcal{L}, \Sigma, k, \Gamma, l)$-bissimulation

Information Flow Analysis

Checking Type System

$$\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M : s, \tau$$

Informative Type System

$$\Gamma \vdash_{\mathcal{L},\Sigma} M : \langle s, s_d \rangle, \tau$$

- Γ: **a map from variables to security levels**

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- Γ: **a map from variables to security levels**
- $\mathcal{L}$: **Lattice of security levels**

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- Γ: **a map from variables to security levels**
- $\mathcal{L}$: **lattice of security levels**
- Σ: **a map from references to security levels**
- s: **security effect**

Information Flow Analysis

Checking Type System

$$\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M : s, \tau$$

- k: **parametrizing kernel**

Informative Type System

$$\Gamma \vdash_{\mathcal{L},\Sigma} M : \langle s, s_d \rangle, \tau$$

- s_d: **declassification effect**

- Γ: **a map from variables to security levels**
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Information Flow Analysis

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- The type system is parameterized with a fixed kernel: k
- The typing rules **constrain** the information flows that may take place and **type out** illegal programs

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Informative Type System

$$\Gamma \vdash_{\mathcal{L},\Sigma} M : \langle s, s_d \rangle, \tau$$

- The type system is not parameterized with any kernel
- The typing rules **update** the **declassification effect** to include the detected information flows

Information Flow Analysis

Checking Type System - Assign Rule

$$\frac{\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M : s_1, \theta \ \mathrm{ref}_l \qquad k(s_1.t) \sqsubseteq k(s_2.w) \qquad \Gamma \vdash^{k}_{\mathcal{L},\Sigma} N : s_2, \theta \qquad k(s_1.r), k(s_2.r) \sqsubseteq k(l)}{\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M := N : s_1 \sqcup s_2 \sqcup s_l, \mathrm{unit}}$$

Where: $s_l = \langle \bot, k(l), \bot \rangle$

Information Flow Analysis

Checking Type System - Assign Rule

$$\frac{\begin{array}{ll}\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M : s_1, \theta\ \mathsf{ref}_l & k(s_1.t) \sqsubseteq k(s_2.w) \\ \Gamma \vdash^{k}_{\mathcal{L},\Sigma} N : s_2, \theta & k(s_1.r), k(s_2.r) \sqsubseteq k(l)\end{array}}{\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M := N : s_1 \sqcup s_2 \sqcup s_l, \mathsf{unit}}$$

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Informative Type System - Assign Rule

$$\frac{\Gamma \vdash_{\mathcal{L},\Sigma} M : \langle s_1, s_1^d \rangle, \theta\ \mathsf{ref}_l \quad \Gamma \vdash_{\mathcal{L},\Sigma} N : \langle s_2, s_2^d \rangle, \theta}{\Gamma \vdash_{\mathcal{L},\Sigma} M := N : \langle s, s_d \rangle, \mathsf{unit}}$$

Where:

$s_d = s_1^d \sqcup s_2^d \sqcup \upharpoonright \{(s_1.t, s_2.w), (s_1.r, l), (s_2.r, l)\}$

$s = s_1 \sqcup s_2 \sqcup \langle \bot, l, \bot \rangle$

Soundness

Checking Type System

If $\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M : s, \tau$, then P satisfies $(\mathcal{L}, \Sigma, k, \Gamma)$-Noninterference

Informative Type System

If $\Gamma \vdash_{\mathcal{L},\Sigma} M : \langle s, s_d \rangle, \tau$, then P satisfies $(\mathcal{L}, \Sigma, s_d, \Gamma)$-Noninterference

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Proof Sketch

$$\Gamma \vdash_{\mathcal{L},\Sigma} M : \langle s, s_d \rangle, \tau$$
$$\Downarrow$$
$$\Gamma \vdash^{s_d}_{\mathcal{L},\Sigma} M : s', \tau$$

Soundness

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Optimality

$$\Gamma \vdash^{k}_{\mathcal{L},\Sigma} M : s_1, \tau \quad \textbf{and} \quad \Gamma \vdash_{\mathcal{L},\Sigma} M : \langle s_2, s_d^2 \rangle, \tau$$
$$\Downarrow$$
$$k \sqsubseteq s_d^2$$

Outline

Flow Relations as IF Setting Relaxations

Ingredients

- **Set of Principals: Pri**
- **Security levels:** subsets of **Pri**
- **Security lattice:** $\langle \mathcal{P}(\mathbf{Pri}), \supseteq \rangle$
- **Flow Relations:** binary relations on **Pri**
  - $(A, B) \in f$: information may flow A to B

Flow Relations as IF Setting Relaxations

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Remark

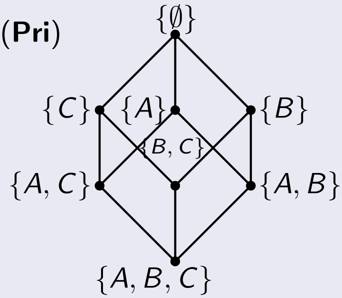
Flow Relations correspond to the co-additive kernels on Pri

Flow Relations as IF Setting Relaxations

Original IF Setting

$$\mathbf{Pri} = \{A, B, C\}$$

$\mathcal{P}(\mathbf{Pri})$



Flow Relations as IF Setting Relaxations

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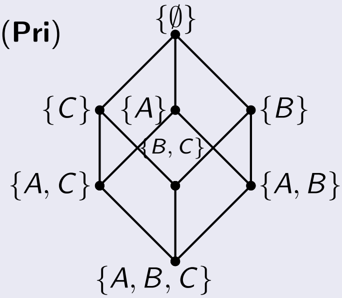
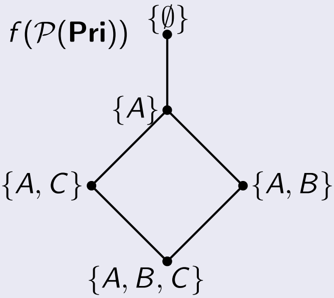


Relaxed IF Setting

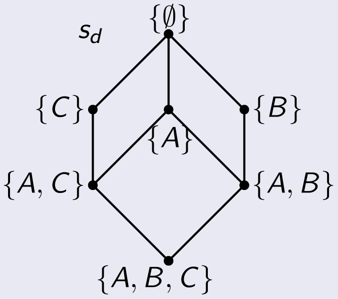
$$\mathbf{f} = \{(B, A), (C, A)\}$$

$f(\mathcal{P}(\mathbf{Pri}))$

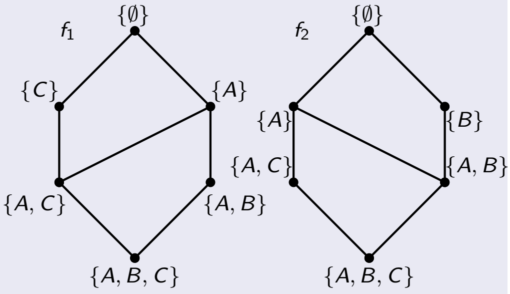


Flow Relations as IF Setting Relaxations

Declassification Effect



Flow Relations below s_d



No optimality result for flow relations!

- $f_1, f_2 \preccurlyeq s_d$ **and** $f_1 \not\preccurlyeq f_2$ **and** $f_2 \not\preccurlyeq f_1$

Outline

Permissivity Contexts as Kernels

Scenario

- **Permissivity context:** relaxation of the original IF setting
- Each program executes under a permissivity context
- Permissivity contexts are allowed to change dynamically

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Our approach

- Model the permissivity context as a kernel
- Label each thread with the corresponding declassification effect

Permissivity Contexts as Kernels

Dynamic Enforcement Mechanism

When the permissivity context changes:

- **Abort** all threads which are not compatible with the new permissivity context
- To determine compatibility just compare the kernels

Security Property

All threads that are allowed to terminate verify Noninterference wrt **all** the permissivity contexts.

Future Work

Study new program constructs that **dynamically** interact with the permissivity context:

- Check if an expression is compliant with the current permissivity context
- Test the current permissivity context

Thank You!

Questions?