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On Dynamic Information-Flow Analysis for Object-Oriented Programs

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Introduction

- Modern object-oriented languages, such as Java and C#, are designed for extensible systems and internet applications
  - Untrusted code may run in the same process as trusted code

- Stack-based access control is used to manage the security requirements of program code
  - Cannot prevent information-flow security vulnerabilities such as confidentiality and integrity violations

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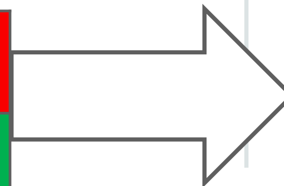
Tainted Information Used in Sensitive Operation

```
public class A {
   public static void main(String[] args) throws Exception {
      L l = ...; B b = ...;
      String name = b.getName();
      l.createResource(name);
      ...
   }
}

public class B {
   public String getName() {
      return "password";
   }
   ...
}
```

```
public class L {
   private Resource resource;

   private native Resource create(String name);

   public void createResource(String name) {
      AccessController.checkPermission(
         new ResourcePermission(name, "create"));
      resource = create(name);
   }
}
```

B.getName	ϕ
A.main	ResourcePermission("*", "create")



AC.checkPermission	AllPermission
L.createResource	AllPermission
A.main	ResourcePermission("*", "create")

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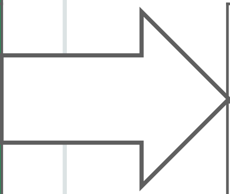
Leaked Sensitive Information

```
public class A {
   public static void main(String[] args) throws Exception {
      L l = ...; B b = ...;
      ...
      Resource r = l.getResource();
      b.useResource(r);
   }
}

public class B {
   ...
   public void useResource(Resource res) { ... }
}
```

```
public class L {
   private Resource resource;

   ...

   public Resource getResource() {
      AccessController.checkPermission(
         new ResourcePermission("*", "get"));
      return resource;
   }
}
```

AC.checkPermission	AllPermission
L.getResource	AllPermission
A.main	ResourcePermission("*", "create") ResourcePermission("*", "get")



B.useResource	ϕ
A.main	ResourcePermission("*", "create") ResourcePermission("*", "get")

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Our Research on Information-flow Security for Java

- A security model extends existing access control to track secure information flow
  - Static analysis with proved whole-program security guarantee
  - A points-to analysis based prototype can detect known vulnerabilities
  - False positives due to over-approximation of data structures, call graphs and dynamic features

- Dynamic program analysis (**this talk**)
  - Track information propagation during execution
  - Add runtime checks to reject insecure executions
  - More precise than static analysis, but with limited coverage

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Core Language

$$
\begin{array}{lll}
C & ::= & \text{class } c\ [\text{extends } c]\ \{\overline{f};\ \overline{M}\} \\
M & ::= & m(x)\ \{s\} \\
s & ::= & x{=}\text{new } c \mid x{=}e \mid x.f{=}x \mid x.m(x) \mid \text{if } x \text{ then } s \text{ else } s \mid s;\ s \\
e & ::= & x \mid x.f
\end{array}
$$

- Variables and fields are labelled with a security label
  - e.g. label(x), label(f)

- Standard type safety is assumed

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Dynamic Semantics

- Stack maps local variables to **labelled values** and heap maps locations and fields to **labelled values**
  - e.g. $S(x) = v\ \varphi$, $H(l)(f) = v\ \varphi$
- Programs are evaluated in the execution state $E ::= S\ H$
- Expression evaluation in big-step: $e\ E \Downarrow v\ \varphi$
- Statement evaluation for side effects: $s\ \varphi\ E_1 \Downarrow E_2$

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Generic Information-Flow Analysis

- Security labels φ can be levels, principals, roles, permissions, etc.
  - Information-flow relation $\varphi_1 \rhd \varphi_2$
  - Joined labels $\varphi_1 \sqcup \varphi_2$

- Simple information-flow rules:

$$\text{[VAR]}\quad \frac{S(x) = v\ \varphi}{x\ S\ H\ \Downarrow\ v\ \varphi \sqcup label(x)}$$

$$\text{[ASSIGN]}\quad \frac{e\ S\ H\ \Downarrow\ v\ \varphi_0 \qquad \varphi \sqcup \varphi_0 \rhd label(x)}{x{=}e\ \varphi\ S\ H\ \Downarrow\ S[x \mapsto (v\ \varphi \sqcup \varphi_0)]\ H}$$

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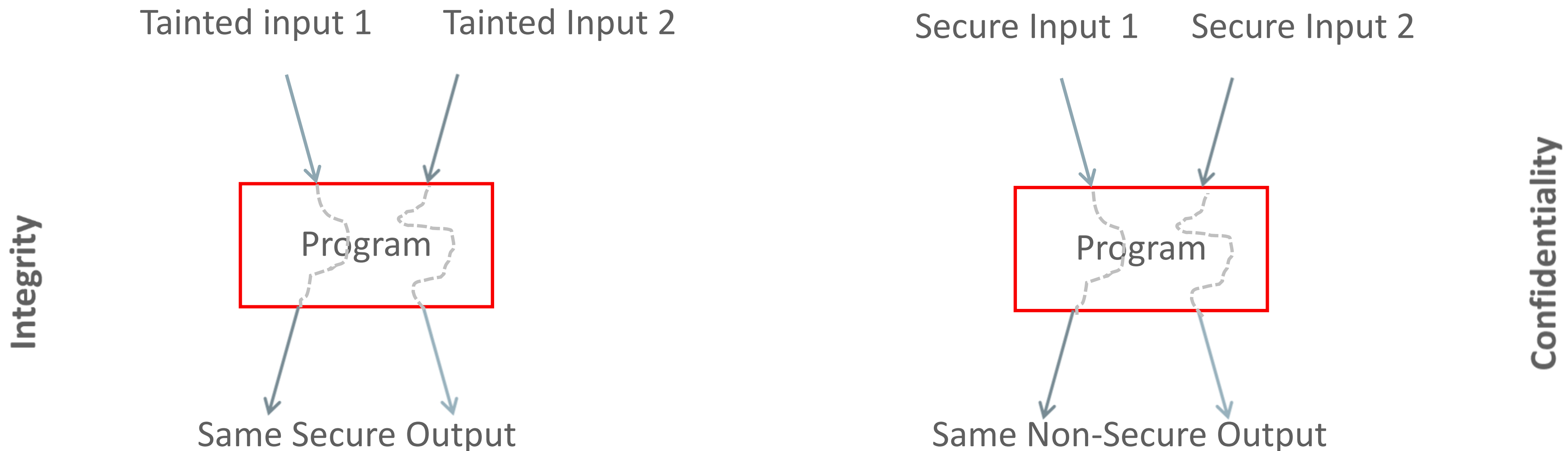
Noninterference

- Attacker/system should not be able to distinguish two executions from their outputs with a given security label, if they only vary in their inputs with security labels that are not allowed to access it



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Noninterference

- Attacker/system should not be able to distinguish two executions from their outputs with a given security label, if they only vary in their inputs with security labels that are not allowed to access it

$$\left.\begin{array}{c} E_1 \overset{\varphi}{\approx} E_2 \\ E_1 \overset{\triangleright\varphi}{\approx} E_2 \\ \vdash E_1 \\ \vdash E_2 \\ s\ \varphi_0\ E_1 \Downarrow E_3 \\ s\ \varphi_0\ E_2 \Downarrow E_4 \end{array}\right\} \Longrightarrow E_3 \overset{\varphi}{\approx} E_4$$

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Implicit Flows via Control Structures

```
x = new c;  // location o

if (h) {
    x = a;
}

l = x;
```

- Assume information with label(h) must not flow to label(l)
- Security labels are propagated along with information flows
  - S(x)=o H
  - Sufficient for static analysis

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Implicit Flows via Control Structures

```
x = new c;  // location o

if (h) {
   x = a;
}

l = x;
```

- Assume information with label(h) must not flow to label(l)
- Security labels arepropagated along with information flows
  - S(x)=o H
  - Not sufficient for dynamic analysis
  - Attacker may observe from l that h is false

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State Convergence of Branches

$$\frac{x\ E \Downarrow l\ \varphi_0 \qquad s_1\ \varphi \sqcup \varphi_0\ E \Downarrow E_1 \qquad s_2\ \varphi \sqcup \varphi_0\ E \Downarrow E_2}{(\textsf{if}\ x\ \textsf{then}\ s_1\ \textsf{else}\ s_2)\ \varphi\ E \Downarrow E_1 \uplus E_2}\ [\text{TRUE}]$$

$$\frac{\left.\begin{array}{r} S_1(x) = v\ \varphi_1 \\ S_2(x) = _\ \varphi_2 \end{array}\right\} \Longrightarrow S(x) = v\ \varphi_1 \sqcup \varphi_2 \qquad \left.\begin{array}{r} H_1(l)(f) = v\ \varphi_1 \\ H_2(l)(f) = _\ \varphi_2 \end{array}\right\} \Longrightarrow H(l)(f) = v\ \varphi_1 \sqcup \varphi_2}{S_1\ H_1 \uplus S_2\ H_2 = S\ H}$$

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Implicit Flows via Dynamic Dispatch

```
x = new c;  // location o

h.m(x);
l = x.f;

class c1 extend c {
    m(x) { x.f = a; }
}

class c2 extend c {
    m(x) { // not update x.f
    }
}
```

- Assume information with label(h) must not flow to label(l)
- Dynamic dispatch is an implicit switch on the type of target object
  - Attacker may observe from l that h is type c1

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State Convergence of Possible Target Methods

$$\frac{\begin{array}{c} x\ S\ H\ \Downarrow\ l^o\ \varphi_0 \qquad y\ S\ H\ \Downarrow\ v\ \varphi_1 \qquad S_0 = \{\textsf{this} \mapsto (l^o\ \varphi_0), z \mapsto (v\ \varphi_1)\} \\ method(type(o), m) = m(z)\{s\} \qquad s\ \varphi \sqcup \varphi_0\ S_0\ H\ \Downarrow\ _\ H_0 \\ c_{1..n} = \{c \mid c \preceq type(x)\} \qquad \forall i \in 1..n \cdot \left\{ \begin{array}{c} method(c_i, m) = m(z)\{s_i\} \\ s_i\ \varphi \sqcup \varphi_0\ S_0\ H\ \Downarrow\ _\ H_i \end{array} \right. \end{array}}{x.m(y)\ \varphi\ S\ H\ \Downarrow\ S\ H_0 \uplus H_1 \uplus .. \uplus H_n}\ [\text{CALL}]$$

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Implicit Flows on Heap Objects

```
x = new c;  // location o
b = x.f;

if (h) {
    x = a;
}

l = (x.f==b);
```

- Assume information with label(h) must not flow to label(l)
- Field selection can be affected indirectly by variable update
  - Attacker may observe from l that h is false

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Field Selections Depend on Target Object

$$\text{[LOAD]}\quad \frac{S(x) = l\ \varphi_0 \qquad H(l)(f) = v\ \varphi}{x.f\ S\ H\ \Downarrow\ v\ \varphi \sqcup \varphi_0 \sqcup label(f)}$$

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Implicit Flows on Heap Objects

```
x = new c;  // location o
y = x;
b = y.f;

if (h) {
    x.f = a;
}

l = (y.f==b);
```

- Assume information with label(h) must not flow to label(l)
- Aliases must be protected
  - Attacker may observe from l that h is false

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Field Updates Depend on Target Object

$$\frac{S(x) = l\ \varphi_0 \qquad y\ S\ H\ \Downarrow\ v\ \varphi_1 \qquad \varphi \sqcup \varphi_1 \rhd label(f)}{x.f{=}y\ \varphi\ S\ H\ \Downarrow\ S\ H[l \mapsto H(l)[f \mapsto (v\ \varphi \sqcup \varphi_0 \sqcup \varphi_1)]]}\ [\text{STORE}]$$

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Related Work

- Pure dynamic analysis
  - Pistoia, Banerjee and Naumann, S&P'07
  - Askarov and Sabelfeld, CSF'09
  - Austin and Flanagan, PLAS'09
- Hybrid analysis
  - Le Guernic, Banerjee, Jensen, and Schmidt, ASIAN'06
  - Shroff, Smith, and Thober, CSF'07

- *Some works do not consider objects; restricted dynamic analysis may be more conservative than static analysis in cases; none of the works has been used in practice*

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Conclusion

- Theoretically possible to obtain soundness result for dynamic analysis of information-flow security
- Practically infeasible to develop a purely dynamic analysis in the presence of shared objects and implicit information flows
  - Need exhaustive evaluation on all possible branches

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