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Unifying Access Control & Information Flow

A Security Model for Programs Consisting of Trusted and Untrusted Code

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Background

- Languages designed for internet applications and extensible systems
- Untrusted code may run in the same process as trusted code
- Fine-grained language-based security needed to manage the complex security requirements of program code

Agenda

- Examine stack-inspection based security model
  - Limitations and security requirements
- Propose a new security model to apply access control to enforce secure information flow
  - Dynamic semantics and security property
- Static enforcement of the new security model for OO programs

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Stack-based Access Control

- Used in Java and C#, known as sandboxing
  - An implementation of *the principle of least privilege*
- Code attempting sensitive operations may be privileged with permissions
  - Permissions granted to classes by policy files
- **All code on the call stack** must have sufficient privilege to perform specific sensitive operation
  - Permissions tested at runtime

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Stack Inspection Example

```
public class A {
    public static void main(String[] args){

        L l = ...;
        ...
        l.createResource(name);
        ...
    }
}
```

```
public class L {
    private Resource resource;

    private Resource create(String name);

    public void createResource(String name)
{

      checkPermission(new
         ResourcePermission(name,"create"));

        resource = create(name);
    }
}
```

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Stack Inspection Example

```
public class A {
    public static void main(String[] args){
        L l = ...;
        …
        l.createResource(name);
        ...
    }
}
```

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

```
public class L {
    private Resource resource;

    private  Resource create(String name);

    public void createResource(String name)
{

        checkPermission(new
          ResourcePermission(name, create"));

         resource = create(name);
    }
}
```

Stack Inspection Unsuccessful: Exception Thrown

```
public class A {
    public static void main(String[] args){
        L l = ...;
        …
        l.createResource(name);
        ...
    }
}
```

```
public class L {
    private Resource resource;

    private  Resource create(String name);

    public void createResource(String name)
{

      checkPermission(new
        ResourcePermission(name,"create"));

        resource = create(name);
    }
}
```

AC.checkPermission	AllPermission
L.createResource	AllPermission
A.main	ϕ

Security Exception

Unauthorised Data Used in Sensitive Operation

```
public class A {
    public static void main(String[] args) {
        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  Resource create(String name);

    public void createResource(String name)
{

      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 to Unauthorised Code

```
public class A {
    public static void main(String[] args){
        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() {

       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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Forbid Desired Operation

```
public class A {
   public static void main(String[] args)  {
      L l = ...;
      …
      l.initResource();
      ...
   }
}
```

```
public class L {
   private Resource resource;

   private Resource create(String name);

   public void createResource(String name) {

     checkPermission(new
         ResourcePermission(name, "create"));

      resource = create(name);
   }
   public void initResource() {
      final String name = "initial";
      createResource(name);
   }
}
```

AC.checkPermission	AllPermission
L.createResource	AllPermission
L.initResource	AllPermission
A.main	ϕ

Security Exception

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Limitations of Stack Inspection

- Cannot prevent all information flow attacks
  - E.g. *the confused deputy problem*
    - Untrusted code may inject data used by trusted code to perform sensitive operations
    - Data generated from sensitive operations by trusted code received by untrusted code

- Too strong to allow desired information flows
  - Often have to elevate code privilege at runtime

- Rely on programmer discipline
  - No enforceable security model or policy

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Related Work

- Stack-based access control
  - Wallach and Felten, S&P'98
  - Fournet and Gordon, POPL'02
- History-based access control
  - Abadi and Fournet, NDSS'03
- Information-based access control
  - Pistoia, Banerjee and Naumann, S&P'07

- *Hard to state a useful security goal that captures the intent for a general class of trusted and untrusted code*

Informal Security Requirements

- Propagation of information needs to be controlled
  - Data from unauthorised code should not reach sensitive operations
  - Sensitive data should not leak to unauthorised code
- Authorisation determined by the privilege assigned to code
  - Code needs sufficient privilege to send/receive data to/from other code
  - Mutual information flows desirable
- Can classic information security models meet the requirements?

Information Flow Security

- Transfer information between variables according to security levels
  - Each variable assigned a security level (e.g. privilege)
  - Security levels form a lattice: $L \leq H$

- Provide guarantees about information propagation
  - Confidentiality: Do not allow information flows from H to L
  - Integrity: Do not allow information flows from L to H

- Transitive information flow policy precludes cyclic flows between levels
  - A richer information flow structure desired

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Overview of the New Security Model

- Each code/variable associated with a dual access control specification
  - A pair of partially ordered security levels
- *Capability* or cap(x) determines privilege/trust of variable x
  - e.g. the privilege granted to untrusted code
- *Accessibility* or acc(x) determines secrecy/sensitivity of variable x
  - e.g. the privilege required by sensitive code
- Information is transferred according to access control specification

Security Model and Java

- Java provides access control but also requires information flow security
  - Stack inspection misses certain information flow based issues
- No clear separation of confidentiality and integrity
  - Programmatically expressed using `checkPermission()`
- Our Model identifies security requirements for Java programs
  - JDK : Trusted: All capabilities
  - JDK: `checkPermission()` : Accessibility requirements
  - Application: capability assigned via policy

Example Revisited

```
@requires{}
@holds{ResourcePermission("*", "create")}
public class A {
    public static void main(String[] args){
        L l = ...; B b = ...;
        String name = b.getName();
        l.createResource(name);
        ...
    }
}

@requires{}
@holds{}
public class B {
    public String getName() {
        return "password";
    }
    …
}
```

```
@requires{}
@holds{AllPermission}
public class L {
    private Resource resource;

    @requires{ResourcePermission(name,
"create")}
    private Resource create(String name);

    public void createResource(String name)
{
      checkPermission(new
         ResourcePermission(name,"create"));

        resource = create(name);
    }
}
```

Informal Security Policy

$$x \to y \implies acc(x) \leq cap(y) \land acc(y) \leq cap(x)$$

- $x \to y$: information may flow from x to y
- Both confidentiality and integrity can be guaranteed
- General information flow policy allows richer flow structure
- Transitive policy in classic model a special case
  - Examples: $acc(x) = cap(y)$, $acc(x) \leq acc(y) \leq cap(x) \leq cap(y)$
  - Such relations too strong

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Informal Security Policy

$$x \to y \implies acc(x) \leq cap(y) \land acc(y) \leq cap(x)$$

- Confidentiality
  - The receiver must have sufficient privilege to receive the information
- Integrity
  - The sender must have sufficient privilege to send the information
- Mutual information flows supported

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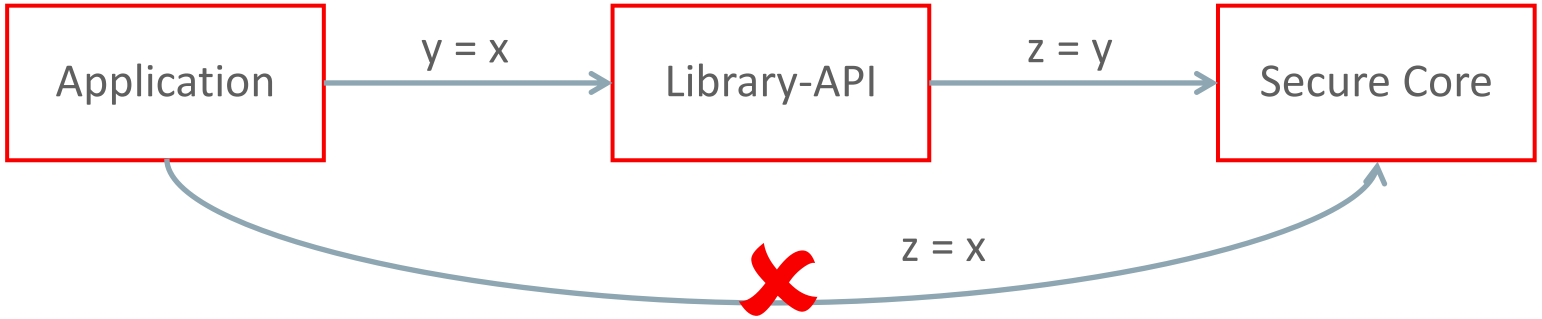
Novelty

- Unified treatment of confidentiality and integrity
- Intransitive policy
  - Permits flows across different levels
- Existing lattice-based information flow models use transitive policy
  - Flows only within single level: Anti-symmetry

Example



- Transitive: $\mathrm{label}(x) \leq \mathrm{label}(y) \wedge \mathrm{label}(y) \leq \mathrm{label}(z) \implies \mathrm{label}(x) \leq \mathrm{label}(z)$
- Intransitive Policy
  - $x \rightarrow y \implies acc(x) \leq cap(y), y \rightarrow z \implies acc(y) \leq cap(z)$
  - $acc(x) \nleq cap(z) \implies x \nrightarrow z$

Unauthorised Data Used in Sensitive Operation Revisited

```
@requires{}
@holds{ResourcePermission("*", "create")}
public class A {
    public static void main(String[] args)
{
        L l = ...; B b = ...;
        String name = b.getName();
        l.createResource(name);
        ...
    }
}
@requires{}
@holds{}
public class B {
    public String getName() {
        return "password";
    }
    …
}
```

```
@requires{}
@holds{AllPermission}
public class L {
    private Resource resource;

    @requires{ResourcePermission(name,
"create")}
    private  Resource create(String name);

    public void createResource(String name)
{

      checkPermission(new
        ResourcePermission(name, "create"));

        resource = create(name);
    }
}
```

"password" → name ⟹ {} ≤ {AllPermission} ∧ {ResourcePermission(name,"create")} ≤ {} ✗

Forbid Desired Operation Revisited

```
@requires{}
@holds{}
public class A {
    public static void main(String[] args) {
        L l = ...;
        …
        l.initResource();
        ...
    }
}
```

```
@requires{}
@holds{AllPermission}
public class L {
    private Resource resource;

    @requires{ResourcePermission(name,
"create")}
    private Resource create(String name);

    public void createResource(String name)
{
        checkPermission(new
         ResourcePermission(name, create"));

        resource = create(name);
    }
    public void initResource() {
        final String name = "initial";
        createResource(name);
    }
}
```

"initial" → name ⟹ {} ≤ {AllPermission} ∧ {ResourcePermission(name,"create")} ≤ {AllPermission}

Leaked Sensitive Information Revisited

```
@requires{}
@holds{ResourcePermission("*", "get")}
public class A {
    public static void main(String[] args) {
        L l = ...; B b = ...;
        ...
        Resource r = l.getResource();
        b.useResource(r);
    }
}

@requires{} @holds{}
public class B {
    …
    public void useResource(Resource res) {
... }
}
```

```
@requires{}
@holds{AllPermission}
public class L {
    @requires{ResourcePermission("*",
"get")}
    private Resource resource;

    …

    public Resource getResource() {

        checkPermission(new
           ResourcePermission("*", "get"));
        return resource;
    }
}
```

$$\text{"resource"} \rightarrow \text{res} \Longrightarrow \{\text{ResourcePermission("*","get")}\} \leq \{\} \wedge \{\} \leq \{\text{AllPermission}\}$$

✗

Aims of Formal Security Model

- Extend access control with information flow
- Handle both confidentiality and integrity in intransitive policies
- Proof of security property guaranteed by model

Overview of Formal Security Model

- Access control specification $\varphi \quad ::= \quad \mathcal{A} \cdot \mathcal{C}$
- Union $\mathcal{A}_1 \cdot \mathcal{C}_1 \sqcup \mathcal{A}_2 \cdot \mathcal{C}_2 = \mathcal{A}_1 \vee \mathcal{A}_2 \cdot \mathcal{C}_1 \wedge \mathcal{C}_2$
- Security policy

$$\frac{\mathcal{A}_1 \leq \mathcal{C}_2 \qquad \mathcal{A}_2 \leq \mathcal{C}_1}{\mathcal{A}_1 \cdot \mathcal{C}_1 \ \rhd \ \mathcal{A}_2 \cdot \mathcal{C}_2}$$

$$\frac{\varphi_1 \rhd \varphi \qquad \varphi_2 \rhd \varphi}{\varphi_1 \sqcup \varphi_2 \ \rhd \ \varphi}$$

Overview of Formal Security Model

- Access control subsumption

$$\frac{\mathcal{A}_1 \leq \mathcal{A}_2 \qquad \mathcal{C}_2 \leq \mathcal{C}_1}{\mathcal{A}_1 {\cdot} \mathcal{C}_1 \sqsubseteq \mathcal{A}_2 {\cdot} \mathcal{C}_2}$$

$$\frac{\mathcal{A}_1 \leq \mathcal{A} \qquad \mathcal{A}_2 \leq \mathcal{A} \qquad \mathcal{C} \leq \mathcal{C}_1 \qquad \mathcal{C} \leq \mathcal{C}_2}{\mathcal{A}_1 {\cdot} \mathcal{C}_1 \sqcup \mathcal{A}_2 {\cdot} \mathcal{C}_2 \sqsubseteq \mathcal{A} {\cdot} \mathcal{C}}$$

- Derived access control property

$$\frac{\varphi_1 \sqsubseteq \varphi_3 \qquad \varphi_2 \sqsubseteq \varphi_4 \qquad \varphi_3 \rhd \varphi_4}{\varphi_1 \rhd \varphi_2}$$

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Dynamic Semantics of the Security Model

- Big step operational semantics
  - Statements

$$s \ \varphi \ E_1 \ \Downarrow \ E_2$$

  - Expressions: No side-effects

$$e \ E_1 \ \Downarrow \ v \ \varphi$$

Explicit Information Flow

- Reading from variable

$$\frac{S(x) = v\ \varphi}{x\ S\ H\ \Downarrow\ v\ \varphi \sqcup label(x)}$$

- Writing to variable

$$\frac{e\ S\ H\ \Downarrow\ v\ \varphi_1 \qquad \varphi \sqcup \varphi_1 \rhd label(x)}{x{=}e\ \varphi\ S\ H\ \Downarrow\ S[x \mapsto (v\ \varphi \sqcup \varphi_1)]\ H}$$

Information Flow via Heap

- Load

$$\frac{S(x) = l\ \varphi_1 \qquad H(l)(f) = v\ \varphi}{x.f\ S\ H\ \Downarrow\ v\ \varphi_1 \sqcup \varphi \sqcup label(f)}$$

- Store

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

Implicit Information Flow

- Implicit flow via conditional

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

$$\frac{x\ E \Downarrow \text{null}\ \varphi_0 \qquad s_1\ \varphi\sqcup\varphi_0\ E \Downarrow E_1 \quad s_2\ \varphi\sqcup\varphi_0\ E \Downarrow E_2}{(\text{if } x \text{ then } s_1 \text{ else } s_2)\ \varphi\ E \Downarrow E_2 \uplus E_1}$$

  - $E \uplus F$: Value from E, union of flows from E and F

- Implicit flow via dynamic dispatch supported
  - All potential targets considered

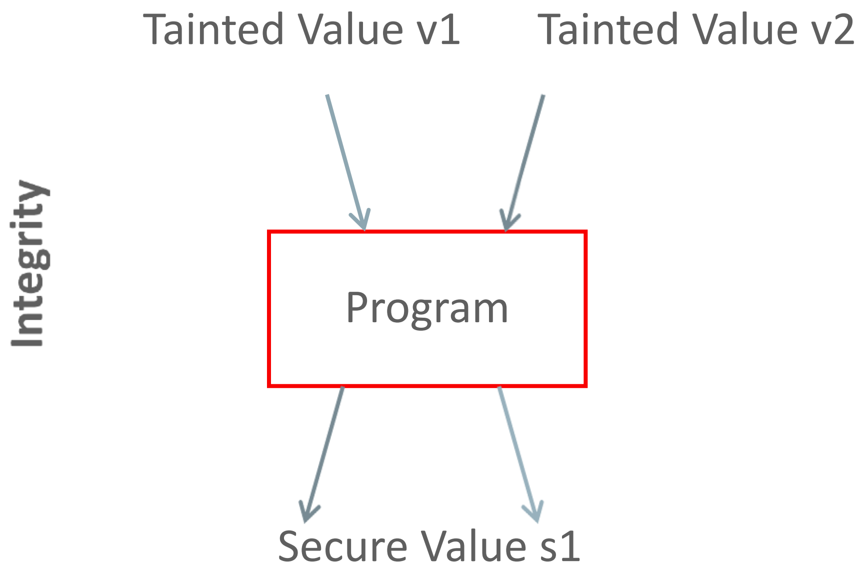
Example: Virtual Dispatch

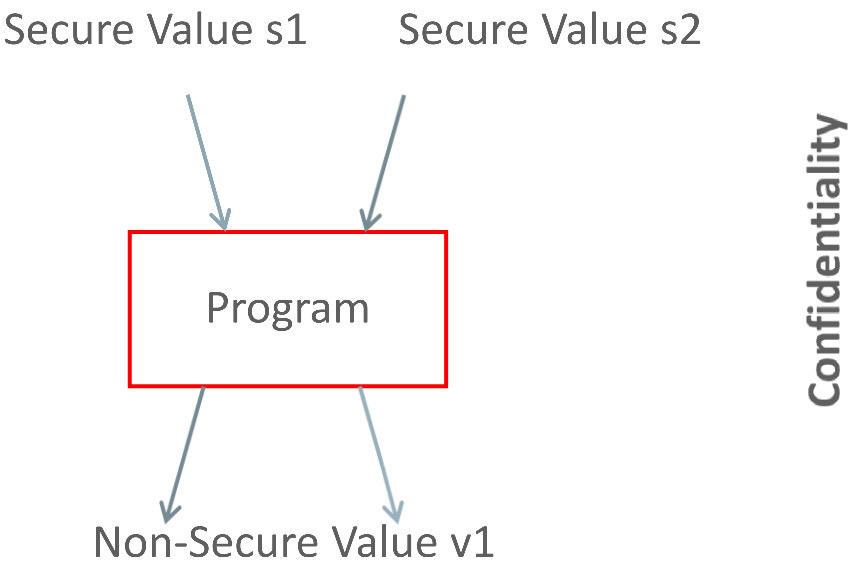
```
class C1 {
   public m(C3 z) {return;}
}
class C2 extends C1 {
  public m(C3 z) {z.f = new T();}
}
class C3 {T f;}
```

```
C1  y = new C2();
if(x)
   y = new C1();
z = new C3();
y.m(z);
// the called m depends on x
// the update on z.f depends on x
```

Noninterference Theorem

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





Underlying Concepts

- Indistinguishability

$$\frac{\begin{array}{lcl} label(x) = \varphi & \implies & S_1(x) = S_2(x) \\ label(f) = \varphi & \implies & H_1(l)(f) = H_2(l)(f) \end{array}}{S_1\ H_1 \overset{\varphi}{\approx} S_2\ H_2}$$

$$\frac{\begin{array}{lcl} label(x) \rhd \varphi & \implies & S_1(x) = S_2(x) \\ label(f) \rhd \varphi & \implies & H_1(l)(f) = H_2(l)(f) \end{array}}{S_1\ H_1 \overset{\rhd\varphi}{\approx} S_2\ H_2}$$

Noninterference Theorem

- Start states indistinguishable
- States are well-formed
- Executing the same statement in E_1 and E_2 results in indistinguishable states

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

Overview of Static Semantics

- To prove noninterference by static analysis
  - Approximate dynamic semantics with abstract domains
  - Enforce access control policy on the abstract domains

- Defined in type inference rules by $\Gamma\ \Sigma \vdash e : \tau\ \varphi$

- Assignment

$$\frac{\Gamma(x) = \tau\ \varphi_1 \qquad \Gamma\ \Sigma \vdash e : \tau\ \varphi_1 \qquad \varphi \sqsubseteq \varphi_1}{\Gamma\ \Sigma \vdash x{=}e : \varphi}$$

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Static Semantics: Field-sensitive

- Load

$$\frac{\Gamma(x) = \tau_0\ \varphi_1 \qquad o \in \tau_0 \qquad \Sigma(o)(f) = \tau\ \varphi}{\Gamma\ \Sigma \vdash x.f : \tau\ \varphi_1 \sqcup \varphi \sqcup label(f)}$$

- Store

$$\frac{\Gamma(x) = \tau_0\ \varphi_1 \qquad o \in \tau_0 \qquad \Sigma(o)(f) = \tau\ \varphi \qquad \Gamma\ \Sigma \vdash y : \tau\ \varphi}{\Gamma\ \Sigma \vdash x.f{=}y : \varphi_1 \sqcup \varphi}$$

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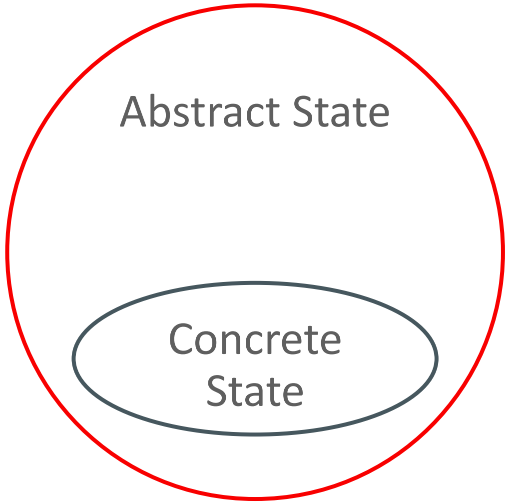
Static Guarantee

- Correspondence between concrete and abstract state

$$
\frac{
\begin{array}{c}
S(x) = v\ \varphi_0 \implies \begin{cases} \Gamma(x) = \tau\ \varphi \\ \{v\} \subseteq \tau \\ \varphi_0 \sqsubseteq \varphi \end{cases} \\
H(l^o)(f) = v\ \varphi_0 \implies \begin{cases} \Sigma(o)(f) = \tau\ \varphi \\ \{v\} \subseteq \tau \\ \varphi_0 \sqsubseteq \varphi \end{cases}
\end{array}
}{
\Gamma\ \Sigma \vdash S\ H
}
$$



Observations

- Dynamic checking impractical
  - Need to track all branches including virtual calls
- Static program analysis provides guarantee
  - Conservative: Can reject safe programs

Summary

- DAC security model: Combines access control and secure information flow
  - General class of trusted and untrusted code
  - Intransitive security policy allows a richer information flow structure

- Prove a general intransitive noninterference property
  - Handles implicit information flow including dynamic dispatch
  - Provide both confidentiality and integrity guarantees

- Security model enforced by static program analysis

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Distinct Integral/Confidential Requirements

```
@requires{} @holds{AllPermission}
public class A {
   public static void main(String[] args) throws Exception {
      L l = ...; B b = ...; C c = ...;
      l.setResource(b.get());
      Resource r = l.getResource();
      c.use(r);
   }
}

@requires{} @holds{ResourcePermission("*", "set")}
public class B {
   public Resource get() { return new Resource("password"); }

}
@requires{} @holds{ResourcePermission("*", "get")}
public class C {
   public void use(Resource res) { ... }
}
```

```
@requires{} @holds{AllPermission}
public class L {
   @requires_conf{ResourcePermission("*", "get")}
   @requires_inte{ResourcePermission("*", "set")}
   private Resource resource;

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

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Security Policy for Distinct Integrity/Confidentiality

$$x \rightarrow y \implies conf(x) \leq cap(y) \wedge inte(y) \leq cap(x)$$

- The receiver must satisfy the **confidential requirement** of the sender
- The sender must satisfy the **integral requirement** of the receiver

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Distinct Integral/Confidential Requirements

```
@requires{} @holds{AllPermission}
public class A {
   public static void main(String[] args) throws Exception {
      L l = ...; B b = ...; C c = ...;
      l.setResource(b.get());
      Resource r = l.getResource();
      c.use(r);
   }
}

@requires{} @holds{ResourcePermission("*", "set")}
public class B {
   public Resource get() { return new Resource("password"); }

}
@requires{} @holds{ResourcePermission("*", "get")}
public class C {
   public void use(Resource res) { ... }
}
```

```
@requires{} @holds{AllPermission}
public class L {
   @requires_conf{ResourcePermission("*", "get")}
   @requires_inte{ResourcePermission("*", "set")}
   private Resource resource;

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

$$\text{new Resource("password")} \rightarrow \text{resource} \Longrightarrow \{\} \leq \{\text{AllPermission}\}$$
$$\wedge \{\text{ResourcePermission("}*\text{","set")}\} \leq \{\text{ResourcePermission("}*\text{","set")}\}$$

✓

Distinct Integral/Confidential Requirements

```
@requires{} @holds{AllPermission}
public class A {
   public static void main(String[] args) throws Exception {
      L l = ...; B b = ...; C c = ...;
      l.setResource(b.get());
      Resource r = l.getResource();
      c.use(r);
   }
}

@requires{} @holds{ResourcePermission("*", "set")}
public class B {
   public Resource get() { return new Resource("password"); }

}
@requires{} @holds{ResourcePermission("*", "get")}
public class C {
   public void use(Resource res) { ... }
}
```

```
@requires{} @holds{AllPermission}
public class L {
   @requires_conf{ResourcePermission("*", "get")}
   @requires_inte{ResourcePermission("*", "set")}
   private Resource resource;

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

$$\text{resource} \rightarrow \text{res} \Longrightarrow \{\text{ResourcePermission}(\text{"}*\text{"},\text{"get"})\} \leq \{\text{ResourcePermission}(\text{"}*\text{"},\text{"get"})\}$$
$$\wedge \{\} \leq \{\text{AllPermission}\}$$

✓