Discretionary Capability Confinement

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Overview

1. Language-Based Capability Systems
2. Discretionary Capability Confinement (DCC)
   - Programming model
   - Confinement guarantees
   - Discussions

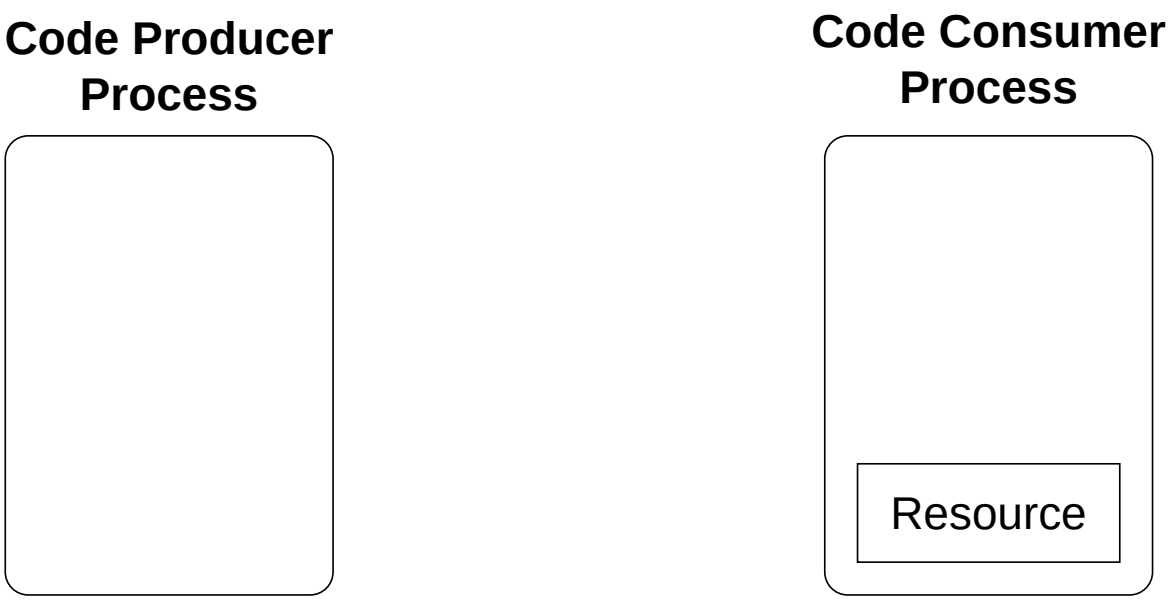
Language-Based Capability Systems

Dynamically Extensible Systems

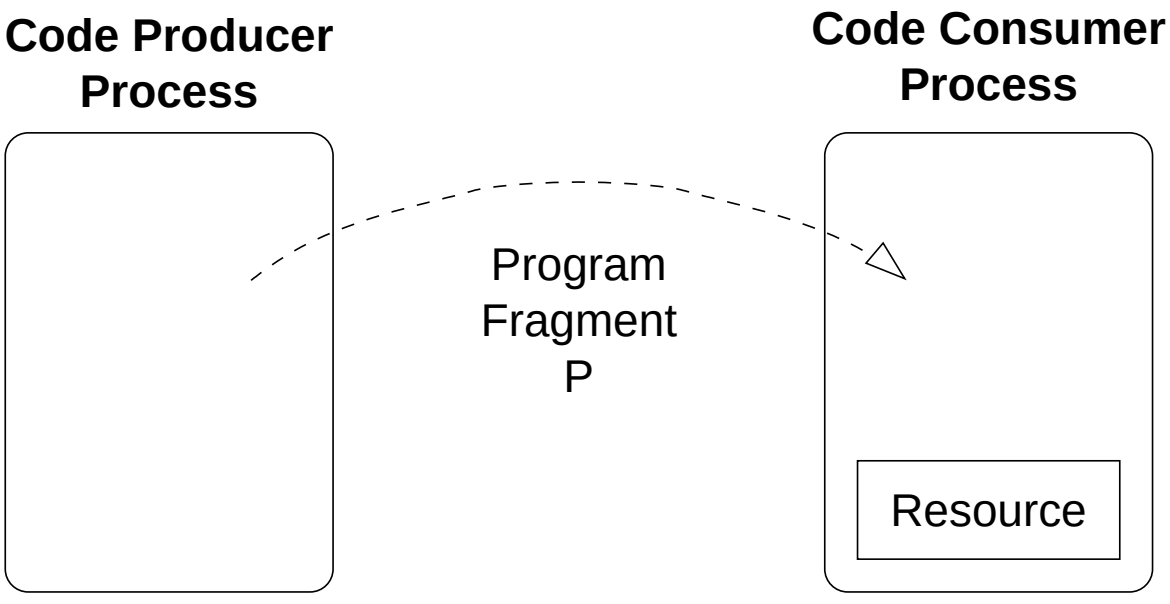
- Impossible to anticipate user requirements:
  - $\Rightarrow$ late binding of functionalities
- **Dynamically Extensible Systems**

  Executable extensions are dynamically linked into the address space of a software system, either to deliver a short-lived service, or to augment the capability of the host system in a permanent manner.
- Examples:
  - Mobile code systems
  - Scriptable applications
  - Software systems with plug-in architectures

Dynamic Extension (1)



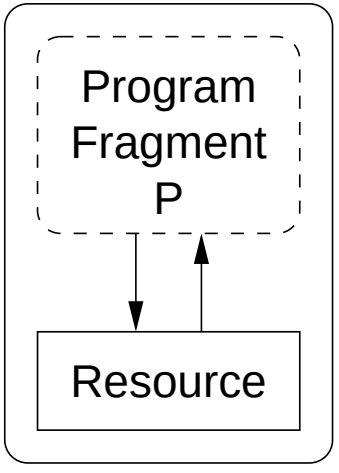
Dynamic Extension (2)



Dynamic Extension (3)

Code Producer Process

Code Consumer Process



Mutual Suspicion

Mutual Suspicion: *Collaborating code units within the same process are suspicious of one another.*

- Traditional OS protection mechanisms use a process to define protection boundaries.
- Code units within the same process are supposed to trust one another.

  The left hand does not trust the right hand!

- An extensible system must now assume the security posture of a multiprogramming operating system.

Language-Based Security

- **Language-Based Security *[Schneider* et al. *2001]***
  - Employing programming language technologies to address the security challenges of complex software systems.

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  - Employing programming language technologies to address the security challenges of complex software systems.
- **Examples**
  - Program analysis
    - type systems
    - program verification
  - Program rewriting

Plan

- **Goal:**
  - Supporting mutual suspicion in extensible systems
- **Means:**
  - Language-based capability systems

Two Related Phenomena

1. Why do we have Trojan Horses?

[Rees 1996]

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1. Why do we have Trojan Horses?
   - Programs inherits all the privileges of the users who invoke them.
2. What can go wrong when mutually suspicious code units collaborate with one another?
   - Callee inherits privileges of the caller.
   - Input to subprograms can be tweaked to cause privilege escalation.

[Rees 1996]

The Confused Deputy Anomaly

```
public class Compiler {
  public void compile(String src, String obj) { ... }
}
```

[Hardy 1988]

- **Setting:**
  - Compiler has privilege to write to a global log file.
  - Compiler must also inherit the privilege of caller so that it can write to the specified object file.

The Confused Deputy Anomaly

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- **Setting:**
  - Compiler has privilege to write to a global log file.
  - Compiler must also inherit the privilege of caller so that it can write to the specified object file.
- **What if:**
  - Caller pass in the name of the log file as the object file name . . .
  - Log file will be overwritten!

Principle of Least Privilege

- *Every program and every user of the system should operate using the least set of privileges necessary to complete the job.*

[Saltzer & Schroeder 1975]

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- **Want:**
  - a fine-grained mechanism for dynamically granting the least possible privilege to a subprogram

Capability

- A **capability** *[Dennis & Van Horn 1966]* is an unforgeable pair:

$$\langle \textit{object-reference}, \textit{access-rights} \rangle$$

Possession of a capability is **both** the necessary and sufficient condition for access.

Capability

- A **capability** *[Dennis & Van Horn 1966]* is an unforgeable pair:

$$\langle \textit{object-reference}, \textit{access-rights} \rangle$$

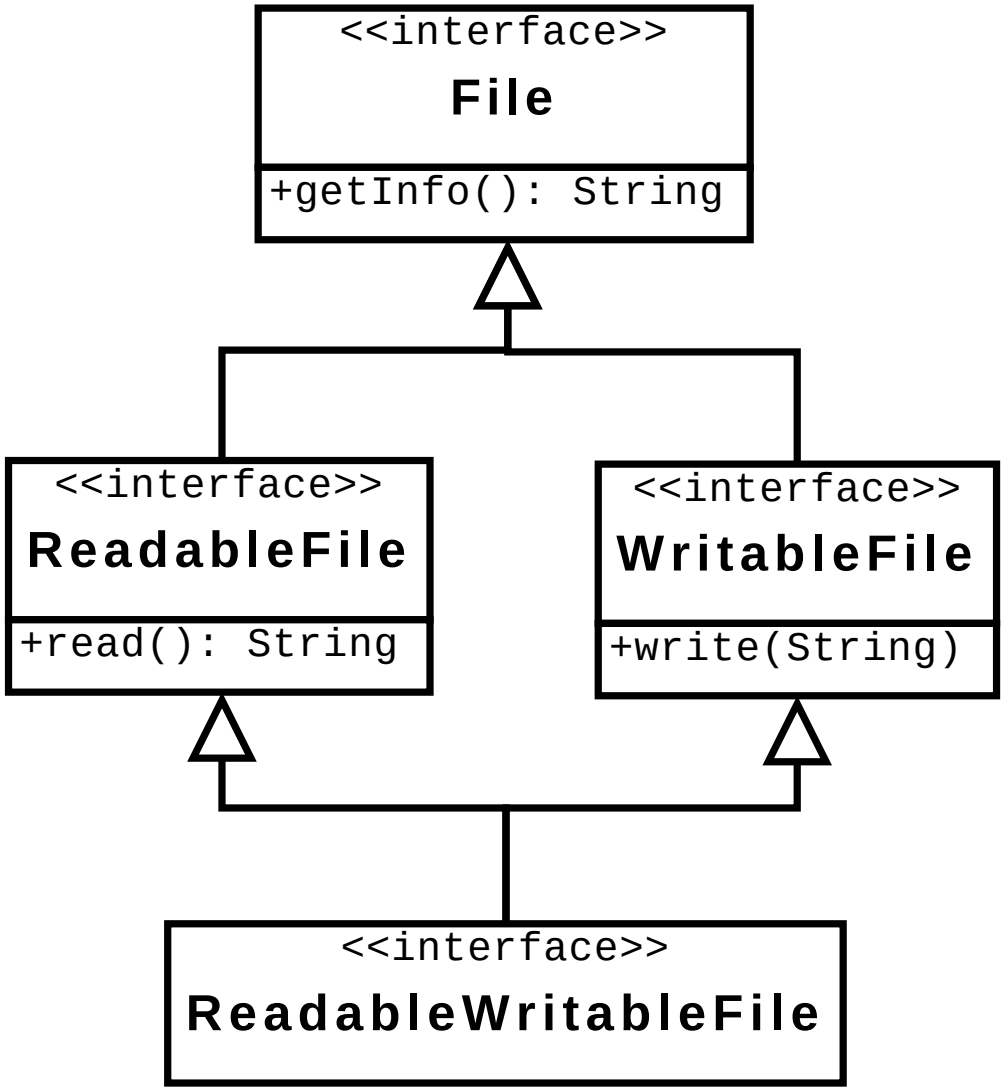
  Possession of a capability is **both** the necessary and sufficient condition for access.

- In a type-safe programming language, a type plays the role of *access-rights*.

$$T \ \mathtt{x};$$

  A statically-typed reference is a capability!

A Java Example



Want This . . .

```
class Alice {
  ReadableWritableFile file;
  void delegate() {
    Bob.process(file);
  }
}
class Bob {
  static void process(ReadableFile file) {
    ...
  }
}
```

Merits of Capability

1. Fine-grained
2. Name and privilege are no longer separated

Wait! What about Capability Confinement?

1. **Capability Theft**
   - "steal" capabilities from foreign protection domains
2. **Capability Leakage**
   - "push" capabilities to less privileged protection domains

- The lack of **capability confinement** is considered to be the main weakness of capability systems *[Wallach* et al. *1997, Chander* et al. *2001]*.

Contributions

Discretionary Capability Confinement (DCC)

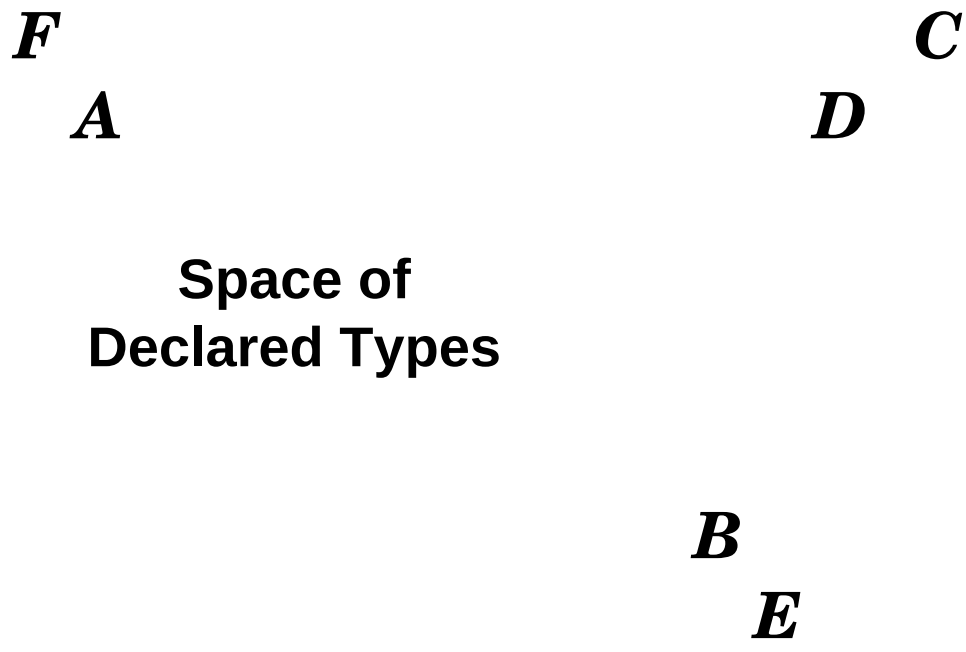
A static annotation system for Java:

- Statically typed references as capabilities
- Provably avoids capability theft and leakage
- Support a strong form of static separation of duty known as **hereditary mutual suspicion**

ESORICS 2006, IJIS 2008

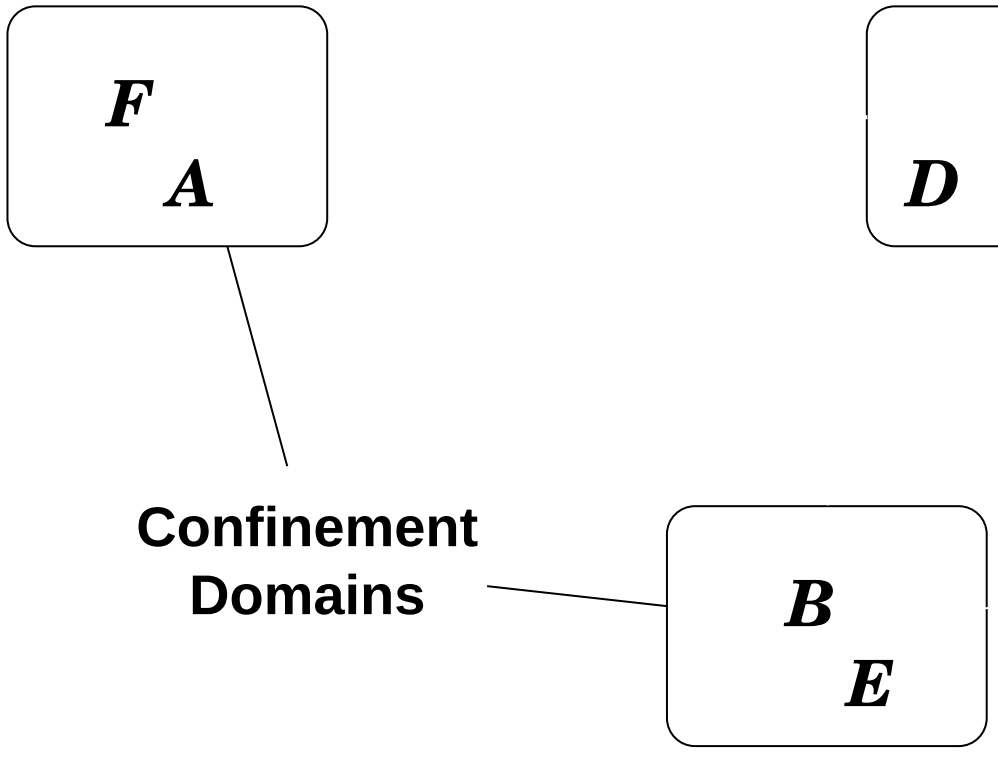
Programming Model

Confinement Domains & Capabilities (1)



- Declared Types: classes or interfaces

Confinement Domains & Capabilities (2)



[Vitek et al.*]*

- Every declared type is a member of a **Confinement Domain**.
  - A confinement domain is a statically defined protection domain.

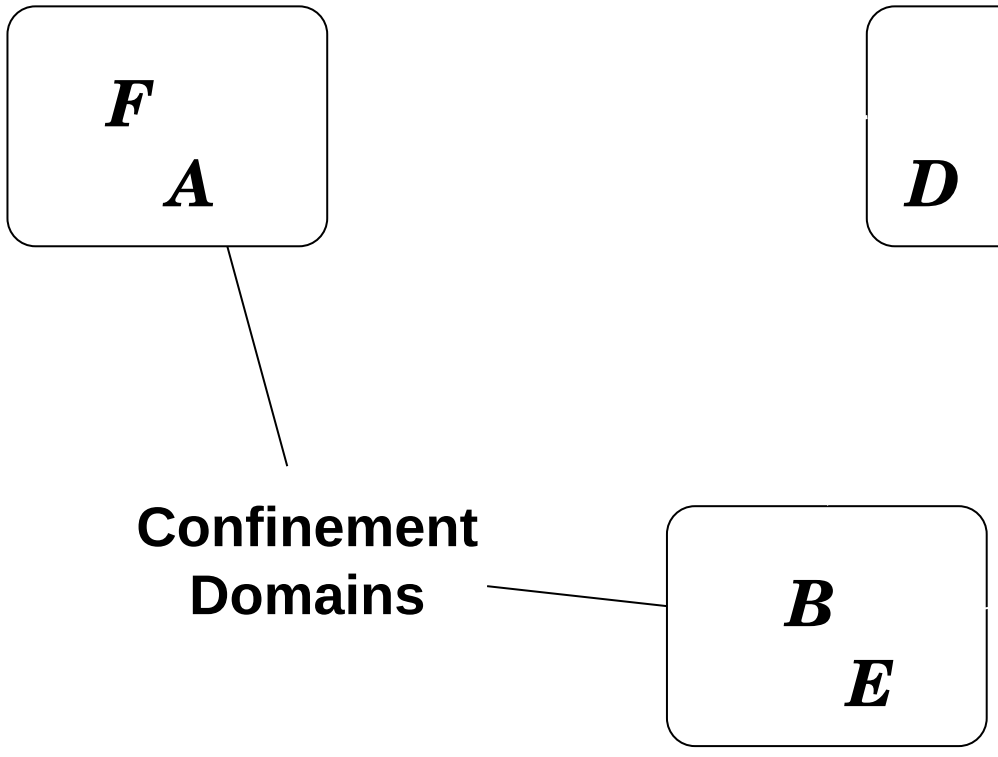
Example: Domain Membership

```
@Confined( Dom1.class )
public class A { ... }

@Confined( Dom2.class )
public class B { ... }

@Confined( Dom3.class )
public class C { ... }
```

Confinement Domains & Capabilities (2)



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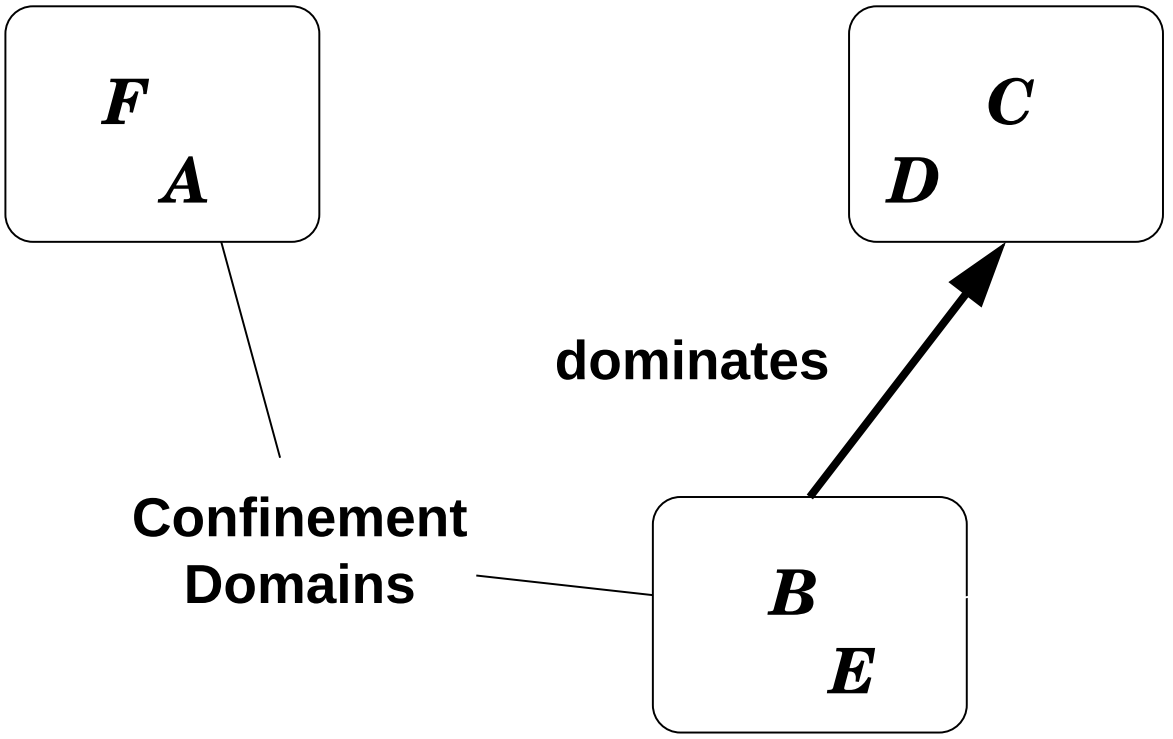
Confinement Domains & Capabilities (3)



- A **dominance relation** (pre-order) is defined among the domains.
  - The more dominating domains are freer to acquire typed references.

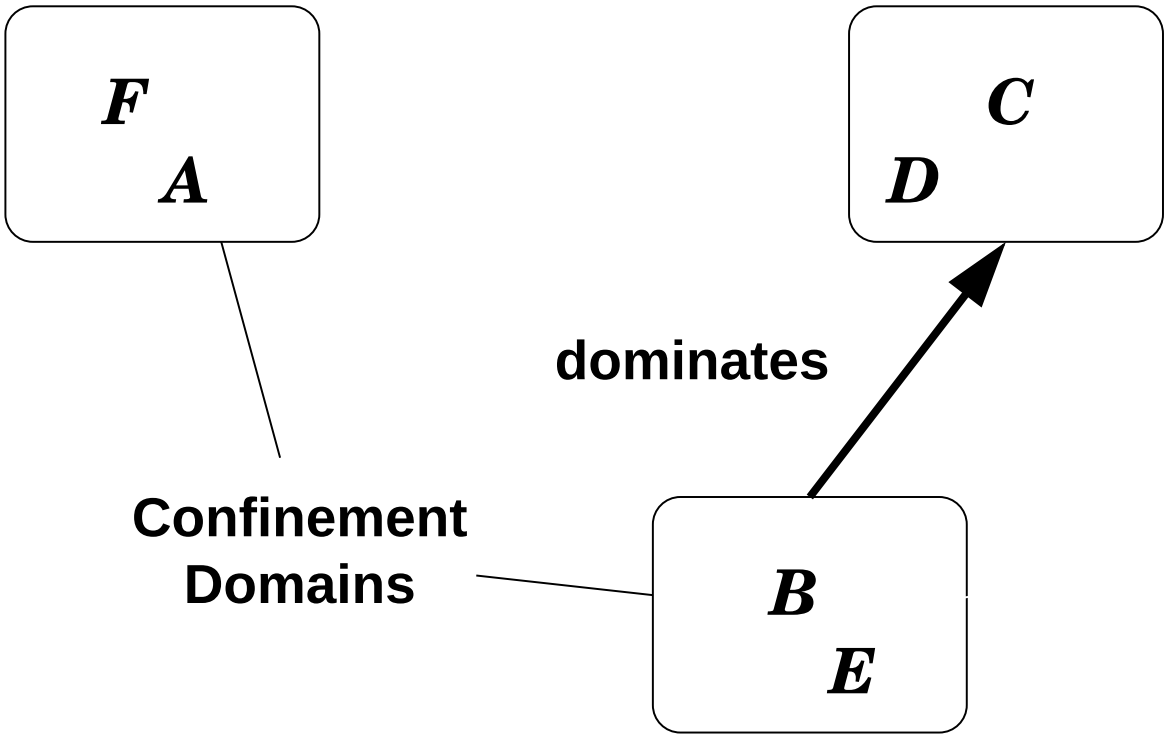
Example: Dominance Hierarchy

```
@Domain
public interface Dom1 extends Root { }

@Domain
public interface Dom2 extends Dom3 { }

@Domain
public interface Dom3 extends Root { }
```

Confinement Domains & Capabilities (3)



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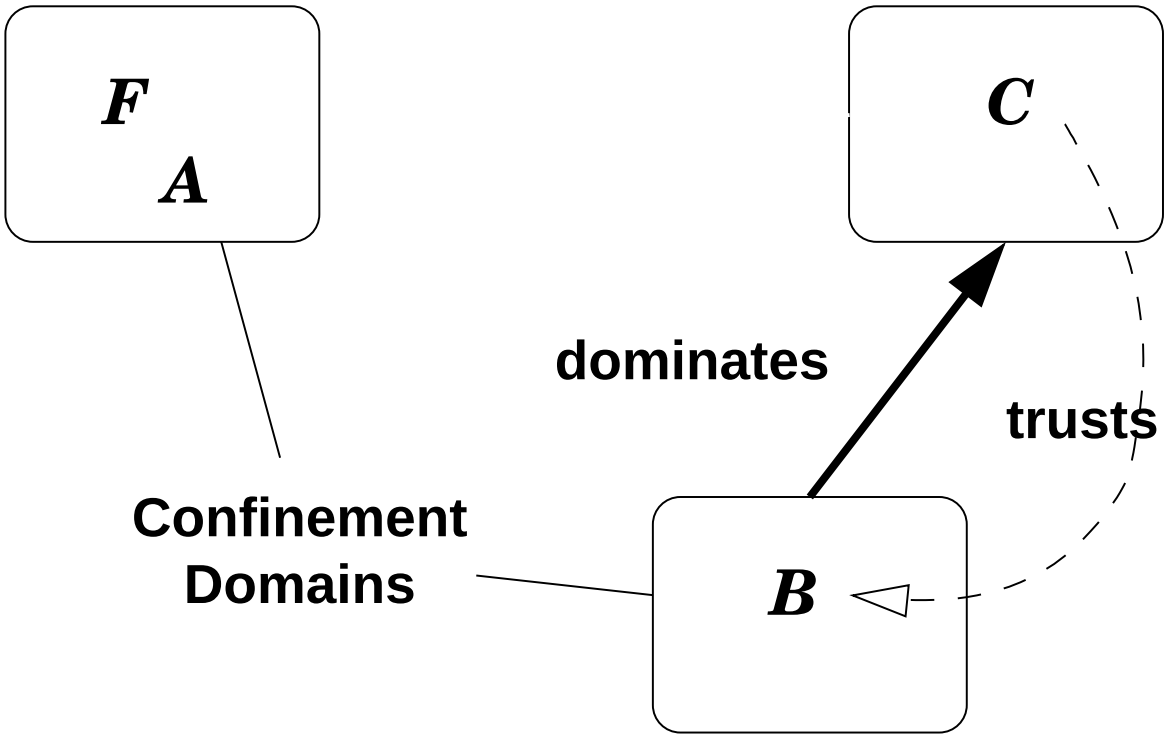
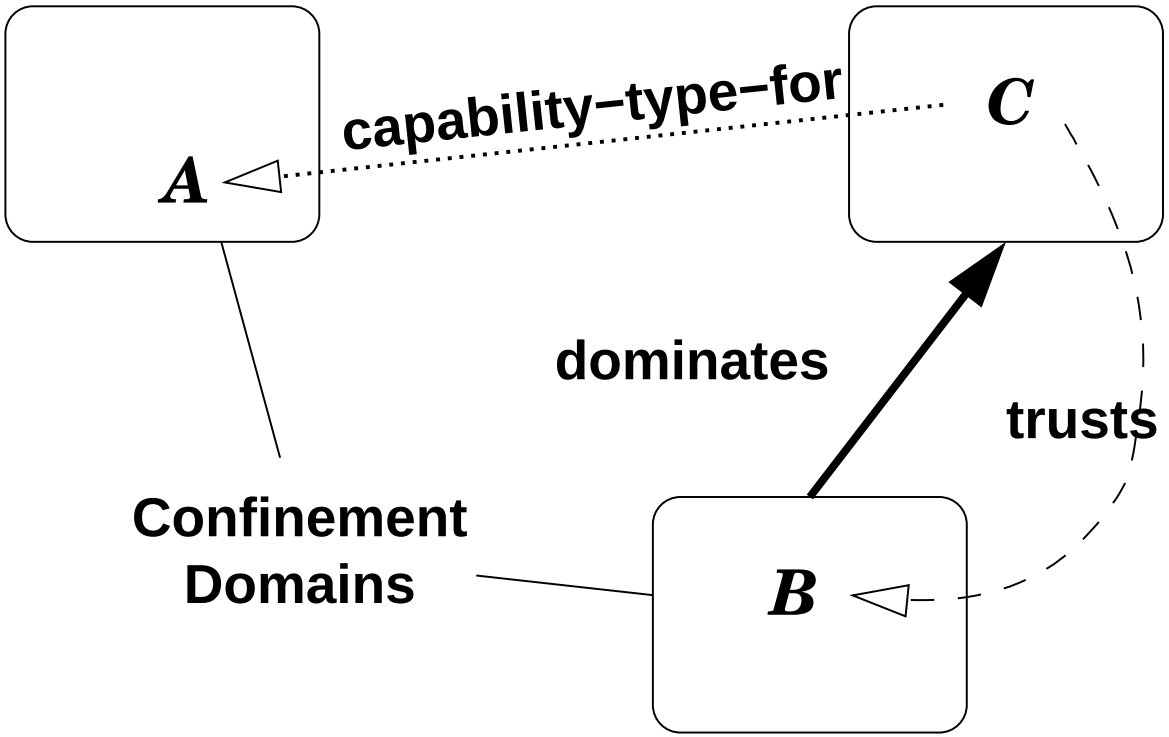
Confinement Domains & Capabilities (4)



- The dominance relation (over domains) induces a partial order over declared types.
  - The more dominating domains contain more trusted declared types.

Confinement Domains & Capabilities (5)



- If C does not trust A, then C is a capability type from the perspective of A.
  - Acquisition of C-type references by A should be carefully controlled.

Capability Propagation

Consider a statically typed reference $r : C$

- Once $r : C$ enters a domain, it roams freely within that domain.
- $r : C$ may escape from the domain only if one of the following holds:
  1. $r : C$ is not a capability of the receiving domain
  2. r is passed as a type-C argument

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We are **NOT** confining **references** (r)

We are confining **statically typed references** ($r : C$)

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- $r : C$ may escape from the domain only if one of the following holds:
  1. $r : C$ is not a capability of the receiving domain
  2. r is passed as a type-C argument
     - . . . subject to the control of the caller's **capability granting policy** . . .

Capability Granting Policies

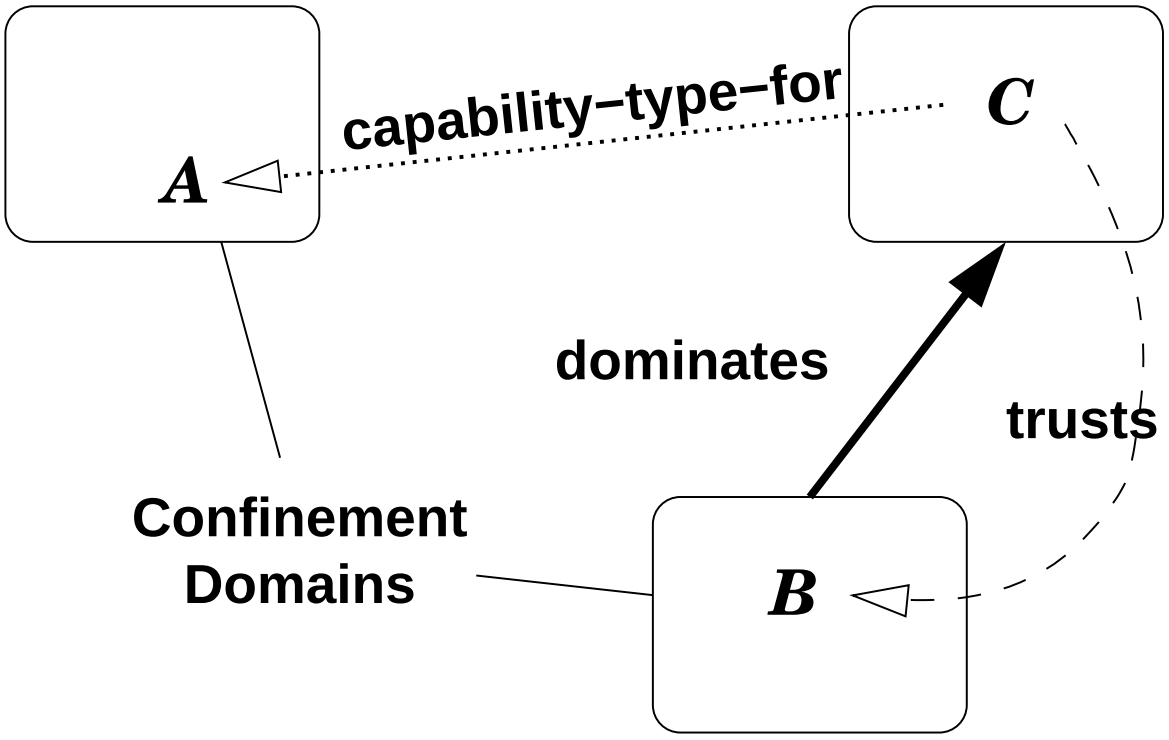
- Every method m is annotated with a ***capability granting policy*** *[Gong 1989]*, which specifies
  1. the types of capabilities that can be granted by m
  2. the domains to which m may grant a capability

Example: Capability Granting Policy

```
@Confined( Dom2.class )
public class B {
  @Grants( Dom2.class )
  void m() {
    C.n(new B());
  }
}

@Confined( Dom3.class )
public class C {
  public static void n(B x) { ... }
}
```

Example: Capability Granting Policy

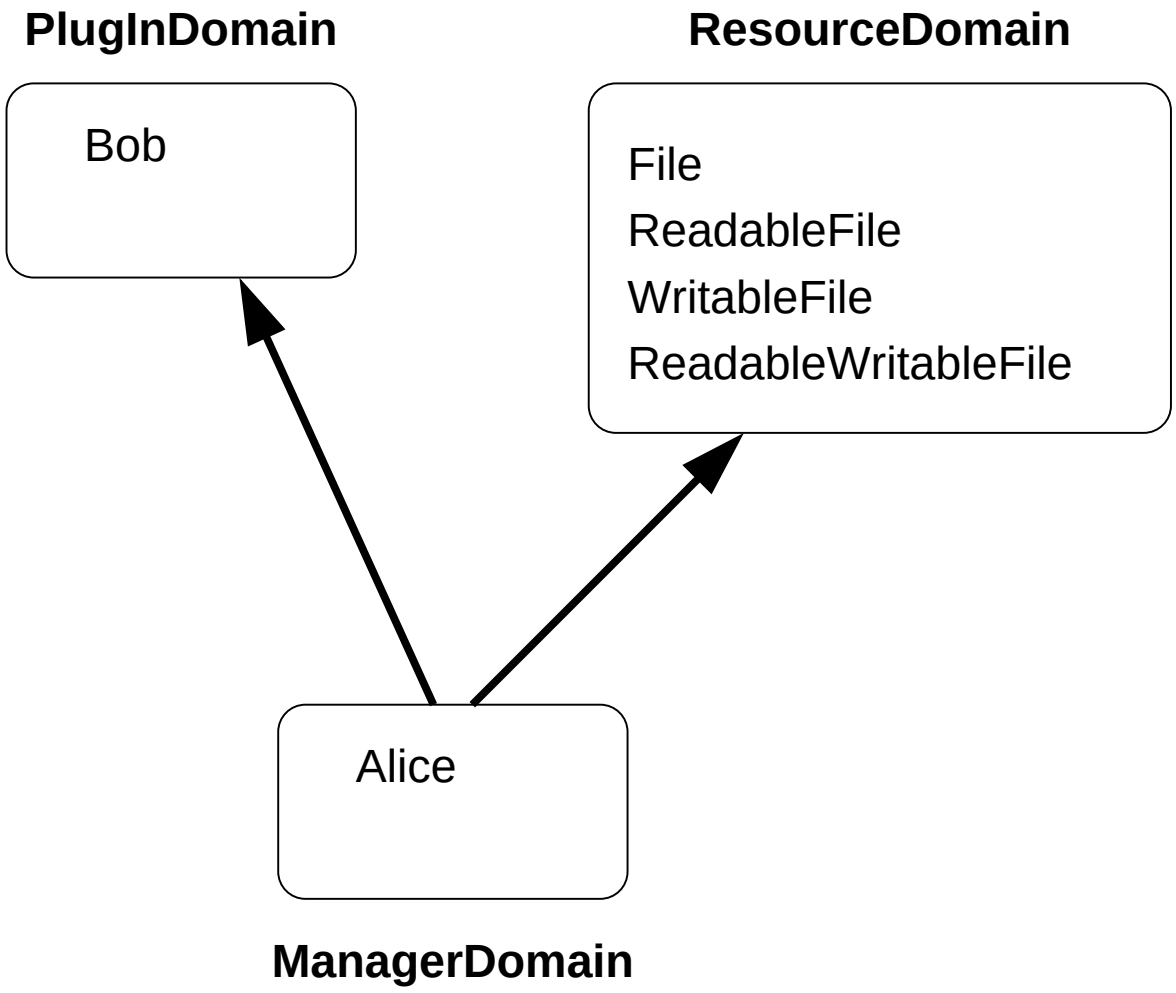


Hereditary Mutual Suspicion

Definition Declared types A and B are said to be ***mutually suspicious*** if they do not trust one another.

Hereditary Mutual Suspicion If A and B are mutually suspicious, then so are a subtype of A and a subtype of B.

Example: Alic, Bob, and Files



Subtlety #1: Static Method

- **Mediated Access:**
  - A is not allowed to invoke static method $C.m$ if C is a capability type for A
  - This ensures accesses are mediated via capabilities.

Subtlety #2: Confused Deputy

- **No Amplification of Privilege:**
  - Method $A.m$ is not allowed to invoke method $B.n$ if the capability granting policy of $A.m$ is more restrictive than that of $B.n$.
  - Capability granting privilege diminishes along a call chain.

Subtlety #3: Dynamic Method Dispatching

- **Impersonation Avoidance:**
  - Each method interface promises the caller the following:
    1. destination domain of capability arguments
    2. origin domain of returned capability
    3. capability granting policy
  - Method $B'.n'$ is not allowed to override $B.n$ unless $B'.n'$ "preserves" the interface promised by $B.n$.
  - Avoid "*impersonation*" caused by method overriding.

Subtlety #4: Principle of Subsumption

- **Save Widening:**
  - B is not allowed to be a subtype of A if B is a capability type for A.
  - Preserve substitutivity by ensuring that upcast never turn a capability to a non-capability.

Confinement Guarantees

Semantic Model

Featherweight JVM

- a non-deterministic production system for modeling all possible execution traces of a JVM
- reasoning about **reachability** and **stack invariants**
- appeared in **SCP 2007**

Confinement Theorem

Theorem (Discretionary Capability Confinement)

Suppose $S \xrightarrow{*}_{\Sigma} T$, where S has the form $\langle \Pi, \Gamma; \Phi, A.m, \diamond \rangle$. Let $\mathcal{D}$ be an arbitrary domain. If $\mathit{Accessible}_{[\mathcal{D}]}(r : C \mid T)$, then at least one of the following conditions holds:

1. $\mathit{Accessible}_{[\mathcal{D}]}(r : C \mid S)$ (previously accessible)
2. $\mathit{I}(C) \blacktriangleright \mathcal{D}$ (not a capability)
3. $C \triangleright m \ \wedge \ \mathcal{D} \blacktriangleright \mathit{I}(m)$ (controlled capability propagation)

Safe Methods

Definition

A method $A.m$ is said to be ***safe*** iff $m \triangleright A$.

Inuition

Executing a safe method $A.m$ will only cause those domains dominated by $I(A)$ to acquire capabilities that A can instantiate.

Corollaries

Corollary (No Theft)

Invoking a safe method never leads to capability theft.

Corollary (No Leakage)

A safe method never leaks capabilities to a domain that is not dominated by the home domain of the method.

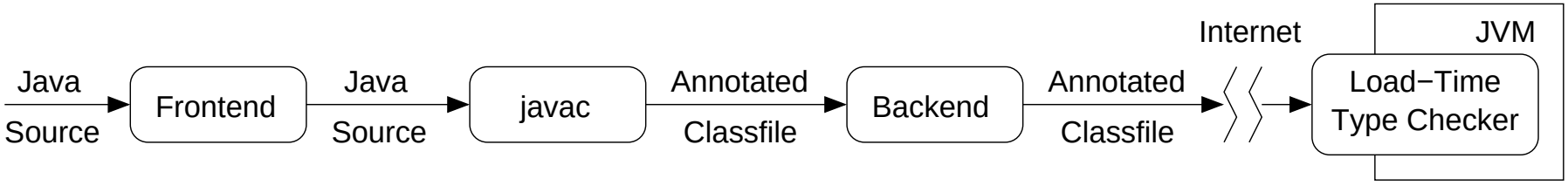
Discussions

Extensions

- Handling arrays, genericity, nested classes
- Modular enforcement of Hereditary Mutual Suspicion
- Finer-grained representation of capability granting policies

[See IJIS 2008 paper for more details.]

Implementation



DCC Constraints are Scoping Rules

- DCC typing constraints are nothing more than **scoping rules**:
  - Scoping rules govern whether a symbol is visible to a given code unit.
  - DCC typing constraints have been completely encoded in the IsoMod policy language.
    - IsoMod is a system that allows programmers to customize the scoping rules for Java (appeared in **ACSAC 2006**).
- Very efficient to check.
  - No dataflow analysis involved.

Future Work

- Inferring DCC annotations from legacy code
- Allowing a limited form of right amplification while maintaining privilege attenuation
- Delegation control
- Obligations

Questions?