Proof Linking

A Modular Verification Architecture for Mobile Code Systems

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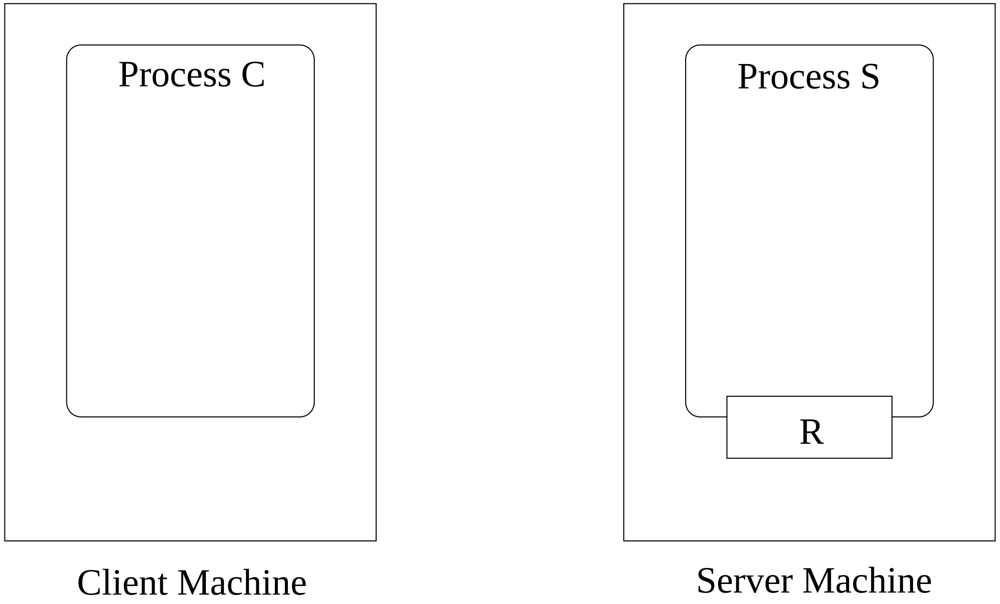
Mobile Code Systems

Code Mobility



Mobile Code Systems

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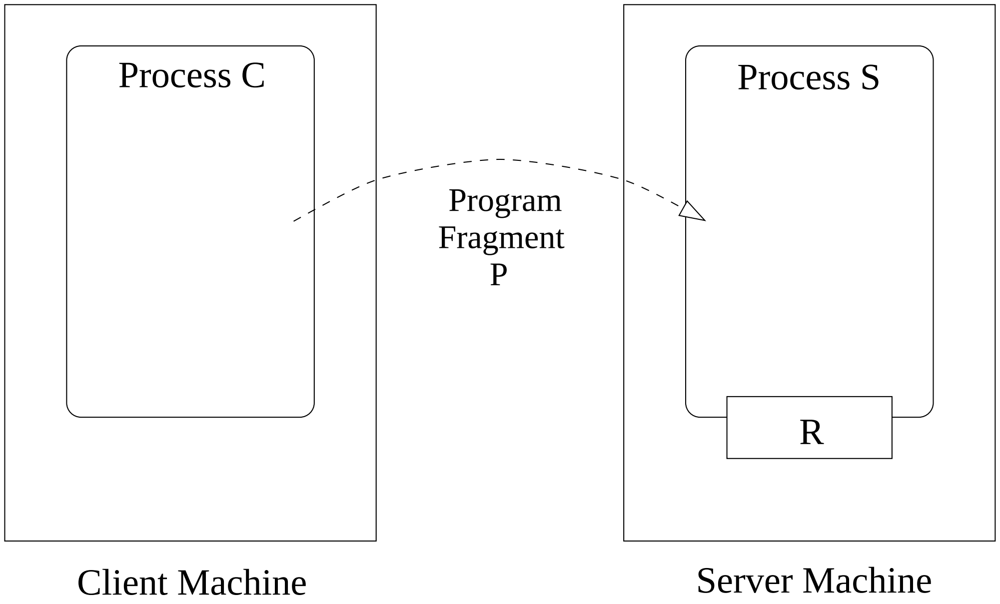

Mobile Code Systems

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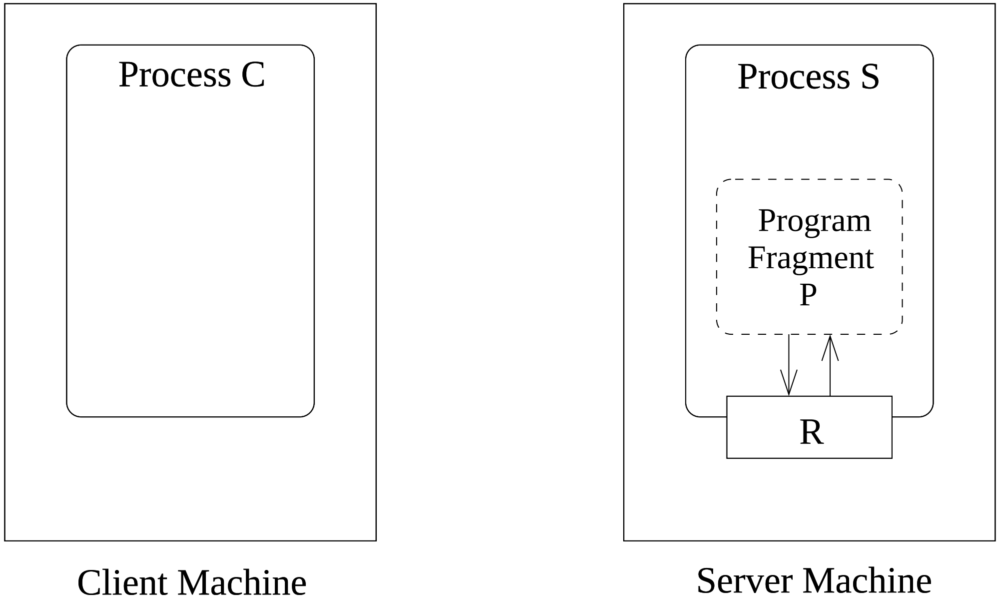
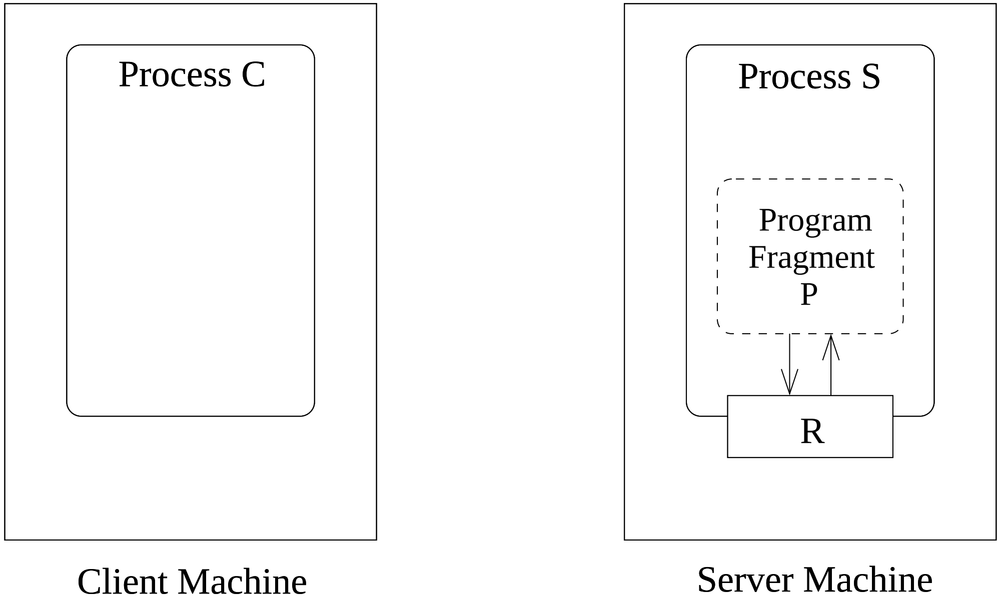


Mobile Code Systems

Code Mobility



Examples

Postscript files
Active Disks
Active Packets
Java Applets

Java Virtual Machine

- JVM as an archetypical mobile code platform
- Java type safety

$$\text{Loader} \xrightarrow{\text{Classfile}} \text{Verifier} \xrightarrow{\text{Classfile}} \text{Runtime Env.}$$

- No type confusion $\Rightarrow$ Security manager protected

The JVM Verification Architecture

- Program safety is a whole-program notion:

  Intrachecking

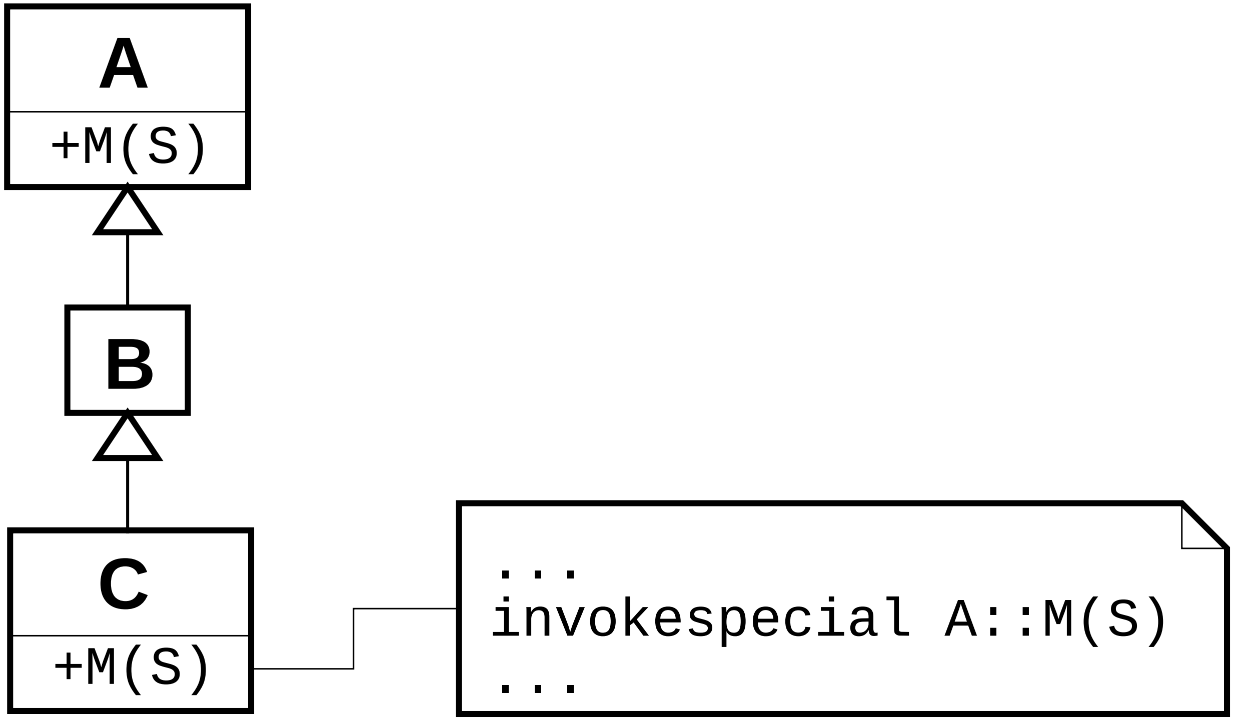
  Inferring the static properties of a classfile.

  Interchecking

  Checking that the inferred properties are compatible with the run-time environment.

- Interchecking and intrachecking are not cleanly separated in the JVM bytecode verifier.

Running Example



Need to show that C is a subclass of A.

Architectural Problems

Crux:

Lack of modularity: Tight coupling among loader, verifier and linker

Want:

1. Stand-alone verification modules
2. Distributed verification
3. Augmented type systems

The Proof Linking Architecture

1. **Modular verification:**

   Avoid the interchecking of external dependencies while intrachecking a code unit.

2. **Verification interface:**

   Record external dependencies in terms of proof obligations and commitments.

3. **Proof linking:**

   Incrementally discharge proof obligations at link time.

Verification Interface

Record external dependencies by a well-defined **verification interface**:

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2. **Commitments:**

   Example:

   `extends(`C`, `B`)`

Verification Interface

Record external dependencies by a well-defined **verification interface**:

1. **Proof obligations:**

   Example:

   `subclass(`C`, `A`)`   **// resolve** A::$M(S)$ **in** C

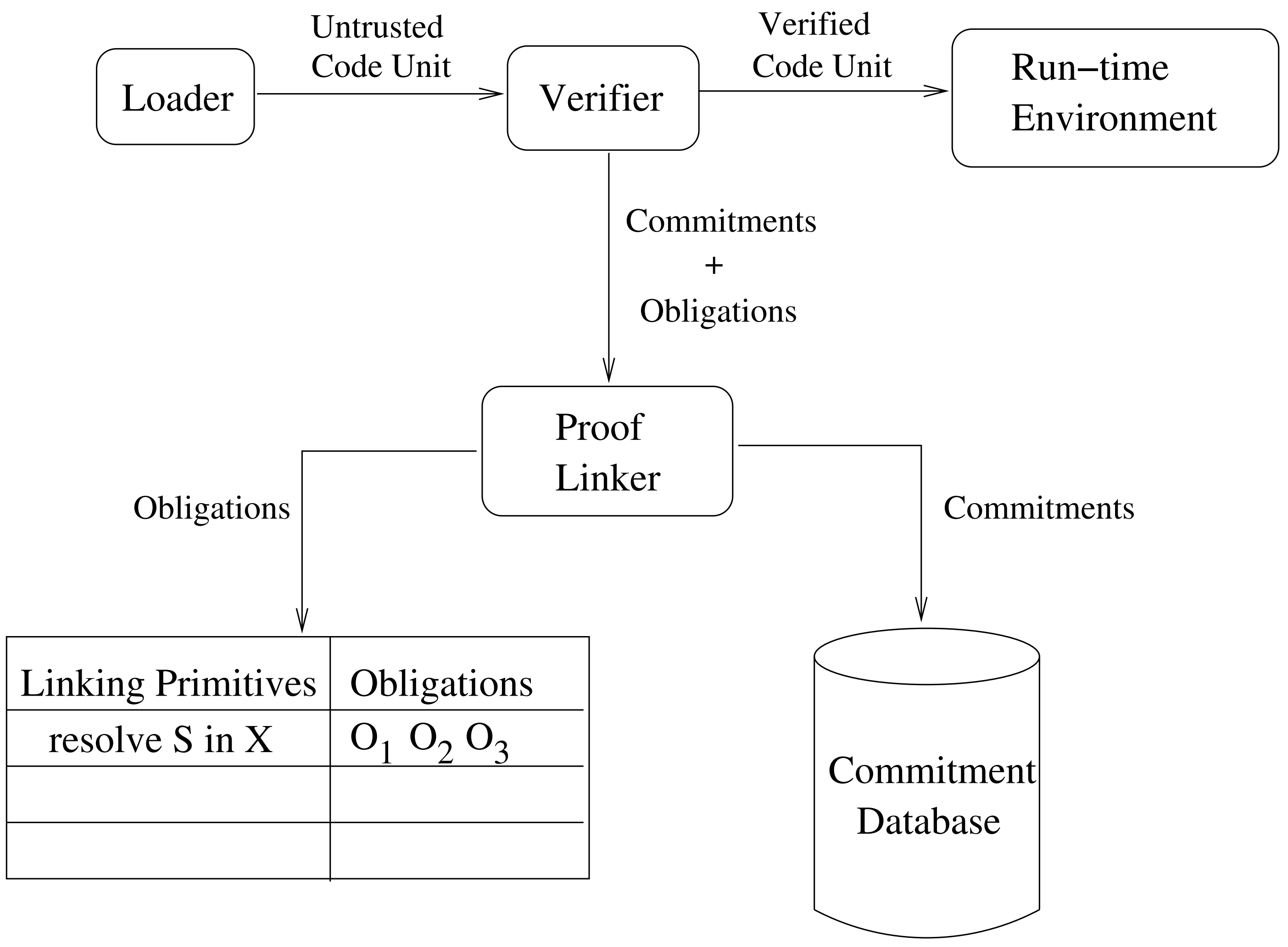
2. **Commitments:**

   Example:

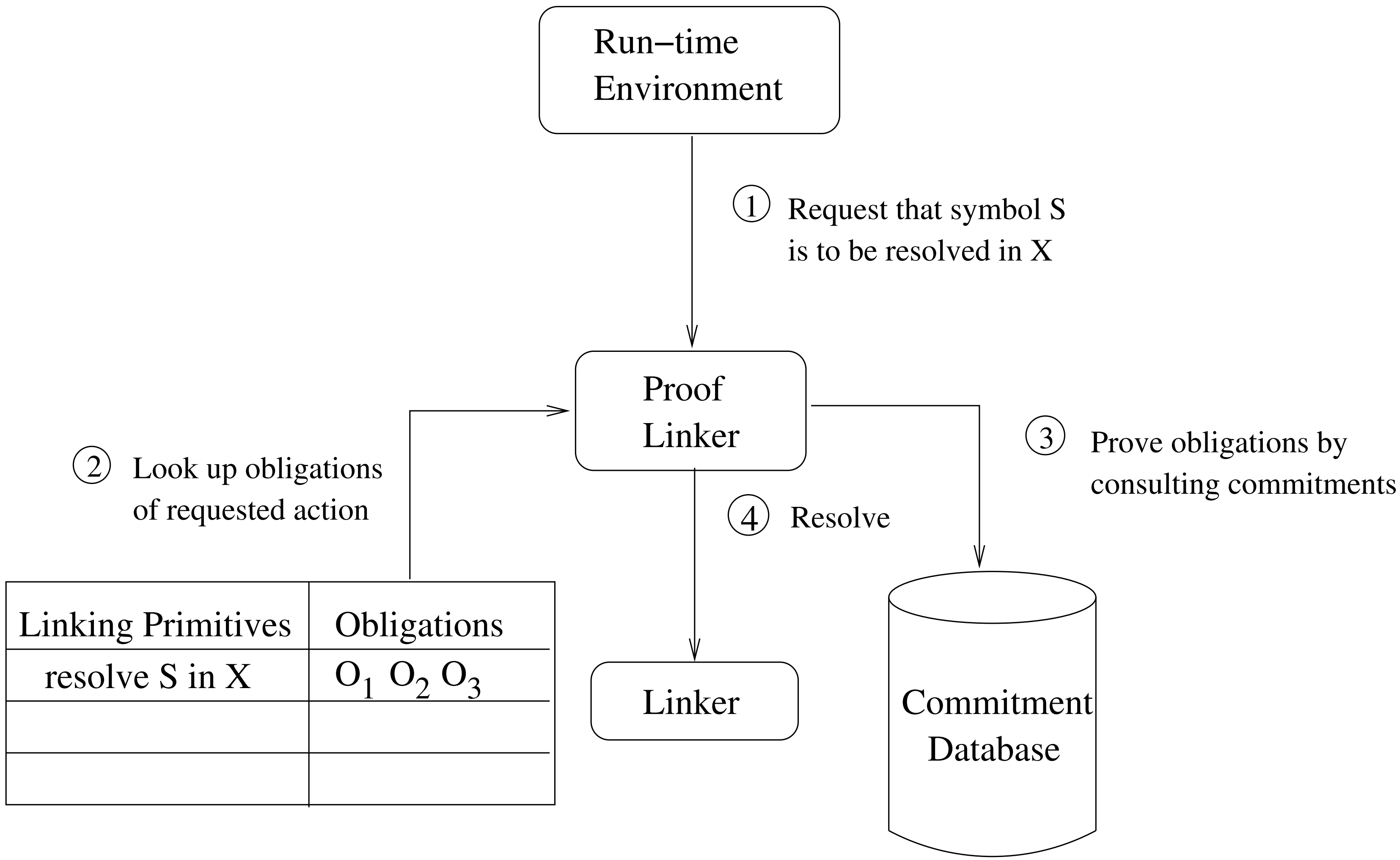
   `extends(`C`, `B`)`

3. **Obligation discharging schedule**

Modular Verification



Incremental Proof Linking



Initial Theory

- Arbitrary logic programs expressing type rules:

  Example:

  $\texttt{subclass(}X\texttt{,}\,X\texttt{)}$.

  $\texttt{subclass(}X\texttt{,}\,Y\texttt{)}$:-

  $\texttt{extends(}X\texttt{,}\,Z\texttt{)}$, $\texttt{subclass(}Z\texttt{,}\,Y\texttt{)}$.

- When coupled with commitments, Initial Theory allows proof linker to discharge proof obligations:

  Example:

  The following commitments

  $\texttt{extends(}C\texttt{,}\,B\texttt{)}$.

  $\texttt{extends(}B\texttt{,}\,A\texttt{)}$.

  allow us to discharge

  $\texttt{subclass(}C\texttt{,}\,A\texttt{)}$

Outline

1. *Modeling Adequacy and Soundness*

   The Proof Linking architecture can be instantiated to adequately model the semantic complexity of a production mobile code system, and to do so in a provably sound manner.

2. *Implementation Feasibility*

   The Proof Linking architecture can be feasibly realized to provide support for stand-alone verification modules, distributed verification and augmented type systems.

Modeling Adequacy and Soundness

Correctness Conditions

1. **Safety:**

   All obligations relevant to the safe execution of a linking primitive are generated and checked before that primitive is executed.

2. **Monotonicity:**

   Checked obligations may not be contradicted by subsequently asserted commitments.

3. **Completion:**

   All commitments that may be used for satisfying an obligation are generated before the obligation is checked.

Formal Modeling of Proof Linking

1. **Linking primitives**

load X	Acquire classfile X
verify X	Verify class X
endorse X	Endorse class X for resolution
endorse X::$M(S)$	Endorse member X::$M(S)$ for resolution
resolve Y **in** X	Resolve class symbol Y in class X
resolve Y::$M(S)$ **in** X	Resolve member symbol Y::$M(S)$ in class X

2. **Proof obligations and commitments**
3. **Initial theory**
4. **Linking strategy**

   Schedule of linking events in the form of a partial ordering on the linking primitives.

Linking Strategy

1. **Natural Progression Property**

$$\textbf{load } X < \textbf{verify } X < \textbf{endorse } X < \textbf{resolve } Y \textbf{ in } X < \textbf{resolve } Y{::}M(S) \textbf{ in } X$$

2. **Import-Checked Property**

$$\textbf{endorse } Y < \textbf{resolve } Y \textbf{ in } X$$

$$\textbf{endorse } Y < \textbf{endorse } Y{::}M(S) < \textbf{resolve } Y{::}M(S) \textbf{ in } X$$

3. **Subtype Dependency Property**

$$\textbf{verify } Y < \textbf{endorse } X \qquad \text{if } Y \text{ is a supertype of } X$$

4. **Referential Dependency Property**

$$\textbf{endorse } Y < \textbf{endorse } X{::}M(S) \qquad \text{if } Y \text{ is referenced in } X{::}M(S)$$

Establishing Correctness

Safety

Example:

verify $C \xrightarrow{\texttt{subclass}(C,A)}$ **resolve** $A{::}M(S)$ **in** C

Monotonicity

Use definite clause logic (aka Horn clauses).

Completion

Example:

1. $\texttt{subclass}(C, A)$ // **resolve** $A{::}M(S)$ **in** C
   1.1. $\texttt{extends}(C, B)$ // **verify** C
   1.2. $\texttt{subclass}(B, A)$
      1.2.1. $\texttt{extends}(B, A)$ // **verify** B
      1.2.2. $\texttt{subclass}(A, A)$

Correctness Results

- Established Safety, Monotonicity and Completion for a simplified model of Java dynamic linking *[FSE'98]*
- Formal verification by PVS *[TOSEM 9(4)]*
- Extension to account for multiple classloaders *[JVM'01]*

Implementation Feasibility

Implementation Efforts

- Aegis VM (`aegisvm.sourceforge.net`)
  - Reference implementation of Proof Linking
  - Open source JVM on GNU/Linux (x86)
- Three components
  - Generic proof linking framework
  - Stand-alone bytecode verifier
  - Pluggable Verification Modules (PVMs)
- Application
  - JAC – Java Access Control
- *UR CS TR 2003-11 (submitted for review)*

Generic Proof Linking Framework

- User-defined verification domains
  - Obligation discharging as native function dispatching
  - Pluggable Obligation Library
  - API for interrogating the internal state of the VM
- Standard representation of verification interface
  - Expressive obligation encoding scheme
- Correctness considerations
  - Safety and Completion guaranteed
- High fidelity to the Sun linking strategy

Pluggable Verification Modules

- An *extensible protection mechanism*
- Link-time bytecode verification is turned into a pluggable service that can be readily replaced, reconfigured and augmented.
- Application-specific verification services can be safely introduced into the dynamic linking process of the Aegis VM.
- Supports link-time enforcement of augmented type systems.

JAC – Java Access Control

Write-protecting the transitive state of an object:

```
public class List {
  public int data;
  public List next;
  public List(int data, List next) {
    this.data = data; this.next = next;
  }
}

readonly List x = new List(1, new List(2, null));
x.data = 5;      // Error: Writing to immediate state
x.next.data = 6; // Error: Writing to transitive state
```

JAC (Cont.)

```
public class Alice {
    public static void main(String[] args) throws Throwable
        List L = new List(1, new List(2, new List(3, null)));
        Class C = Class.forName(args[0]);
        Bob b = (Bob) C.newInstance();
        System.out.println(b.sum(L));
    }
}

public interface Bob {
    int sum(readonly List L);
}
```

JAC (Cont.)

```
public class Charlie implements Bob {
    public int sum(         List L) {
        int acc = 0;
        while (L != null) {
            if (L.next == null)  // corrupt last node
                L.data = 0;
            acc += L.data;
            L = L.next;
        }
        return acc;
    }
}
```

JAC (Cont.)

```
public class Charlie implements Bob {
    public int sum(readonly List L) {
        int acc = 0;
        while (L != null) {
            if (L.next == null)  // corrupt last node
                L.data = 0;
            acc += L.data;
            L = L.next;
        }
        return acc;
    }
}
```

Future Works

- Architectural constraints as security policies for software extensions
- Control flow constraints as proof obligations
- Aspect-oriented approaches to extensible protection mechanisms

Summary of Contributions

1. **The Proof Linking architecture**
   (a) Verification interface as *proof obligations* and *commitments*
   (b) The notion of *obligation discharging schedule*
2. **Modeling adequacy and soundness**
   (a) Correctness conditions: *Safety*, *Monotonicity*, *Completion*
   (b) Employing the notion of *linking strategy* to articulate correctness
   (c) *Formal verification* of Proof Linking for Java bytecode typechecking
3. **Implementation feasibility**
   (a) Reference implementation of Proof Linking in the *Aegis VM*
   (b) *Stand-alone bytecode verifier*
   (c) *Pluggable Verification Modules* as an extensible protection mechanism