Software Security

Compartmentalisation

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Today

- Compartmentilisation

  within a process

  – supported by the programming language (eg Java)

  – supported by hardware (eg Intel SGX)

- Why compartmentalisation is a great idea! ☺
- But: compartmentalisation can fail or simply not be used ☹

Modularisation

&

Compartmentalisation / Sandboxing

Modularisation

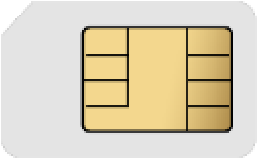
which includes

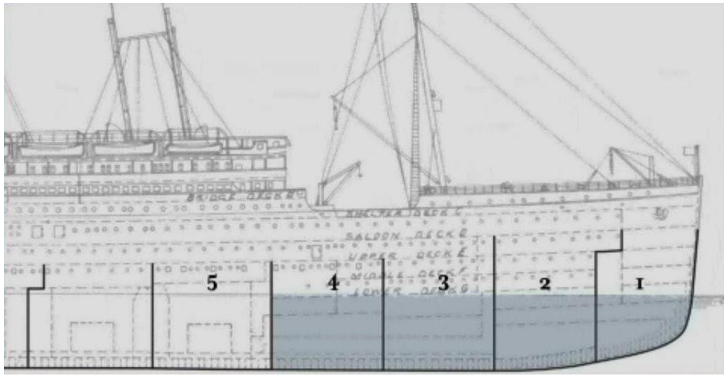
Compartmentalisation

which includes

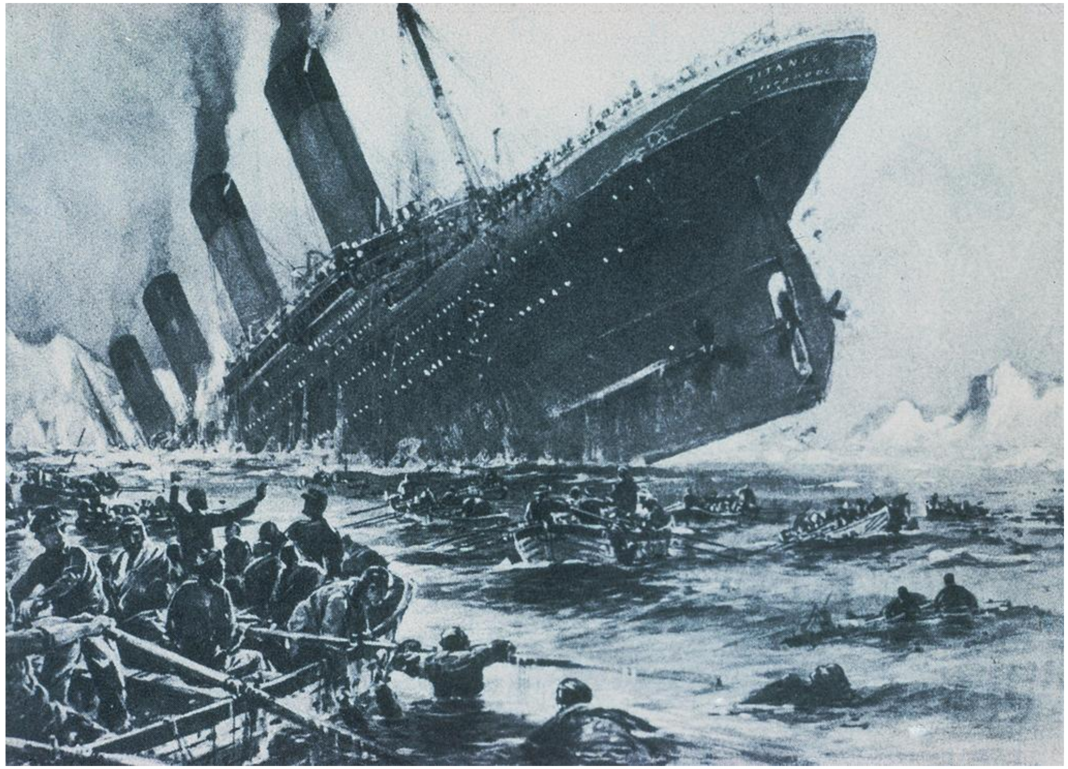
Sandboxing

Examples





Titanic



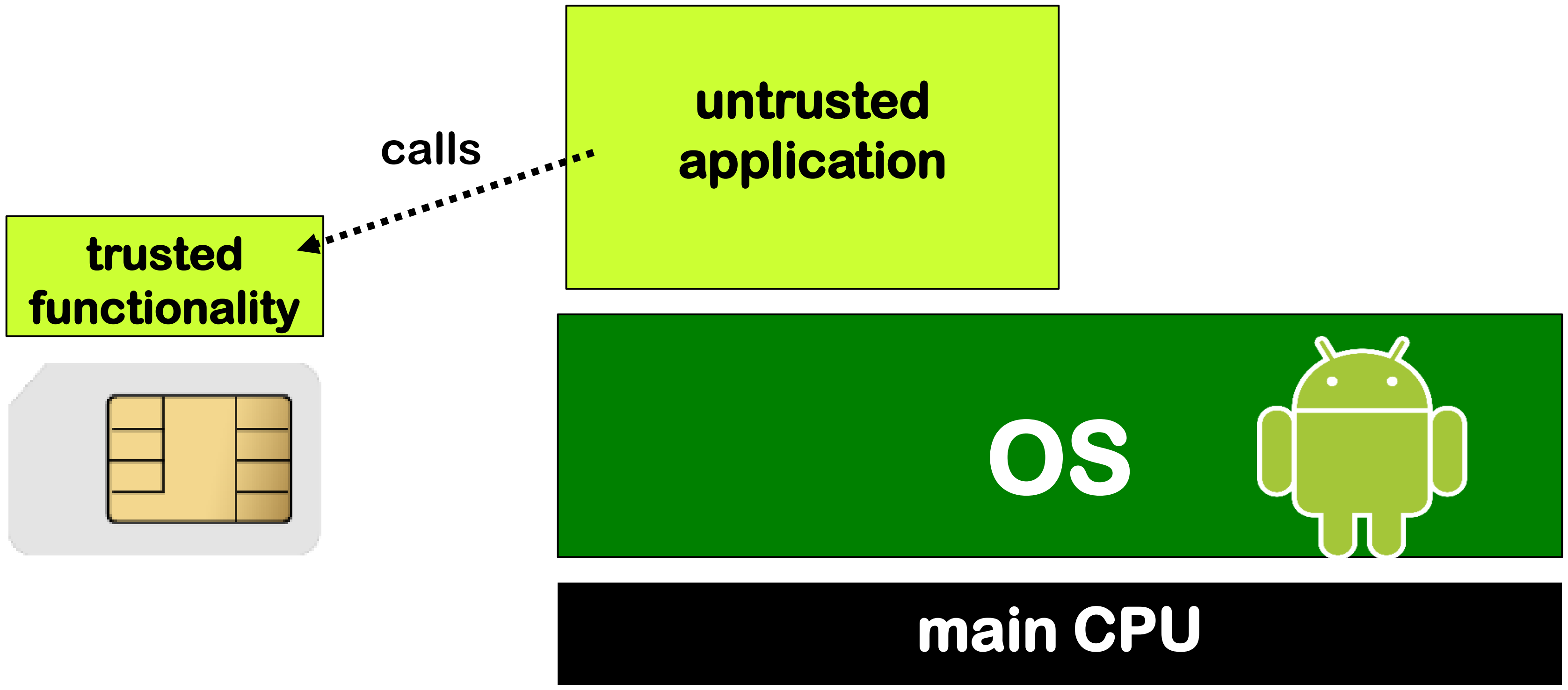
Does this mean compartmentalising is a bad idea?

No, but the attacker model was wrong.

- **Making vessel double-hulled would have been a better form of compartmentalising.**

Compartmentalisation example: SIM card in phone

A SIM provides some trusted functionality (with a small TCB) to a larger untrusted application (with a larger TCB)



Compartmentalisation examples

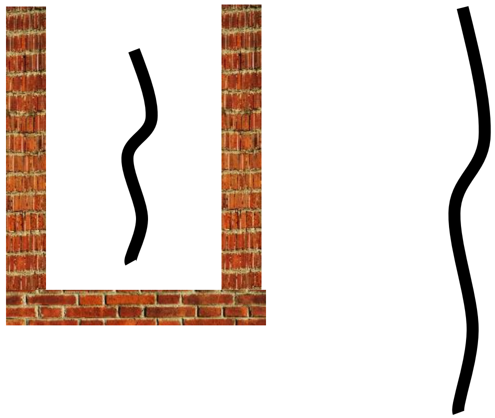
Compartmentalisation can be applied on many levels

- In an organisation
  - eg terrorist cells in Al Qaida or extreme animal rights group
- In an IT system
  - eg different machines for different tasks
- On a single computer, eg
  - different processes for different tasks
  - different user accounts for different task
  - use virtual machines to isolate tasks
  - partition your hard disk & install two OSs
- Inside a program / application / app / process
  - different ‘modules’ with different tasks

Focus of today

Isolation vs CIA (Confidentiality, Integrity & Availability)

Isolation is a very useful security property for programs and processes (i.e. program in execution)



'isolation' can be understood in **CIA** terms, as

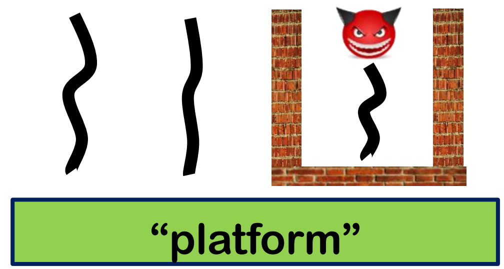
confidentiality and integrity of both data and code,

but conceptually less clear

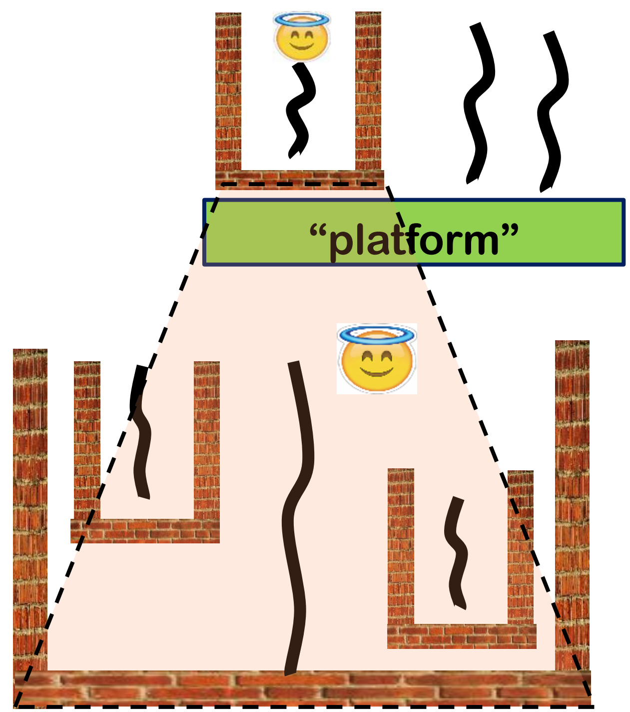
Two use cases for compartments

Compartmentalisation is good to isolate different trust levels

1. to contain a untrusted process from attacking others
   - aka sandboxing



2. to protect a trusted process from outside attacks



   - Here, it makes sense to apply it recursively

Compartmentalisation

Important questions to ask about any form of compartmentalisation

- What is the Trusted Computing Base (TCB) ?
  - Compartmentalising critical functionality inside a trusted process reduces the TCB for that functionality inside that process, but increases the TCB with the TCB of the enforcement mechanism
- Can the compartmentalisation be controlled by policies?
  - How expressive & complex are these policies?
  - Expressivity can be good, but resulting complexity can be bad…
- What are input & output channels?
  - We want exposed interfaces to be as simple, small, and just powerful enough
- Are there any hidden channels? Eg timing behaviour
  - These can be used deliberately, as covert channels, or exist by accident, as side channels

Access control

Some compartments offer access control that can be configured

It involves

1. Rights/permissions
2. Parties (eg. users, processes, components)
3. Policies that give rights to parties

   – specifying who is allowed to do what
4. Runtime monitoring to enforce policies,
   which becomes part of the TCB

Compartmentalisation for security design

1. Divide systems into chunks – aka compartments, components,…

   Different compartments for different tasks

2. Give minimal access rights to each compartment

   aka principle of least privilege

3. Have strong encapsulation between compartments

   so flaw in one compartment cannot corrupt others

4. Have clear and simple interfaces between compartments

   exposing minimal functionality

Benefits:

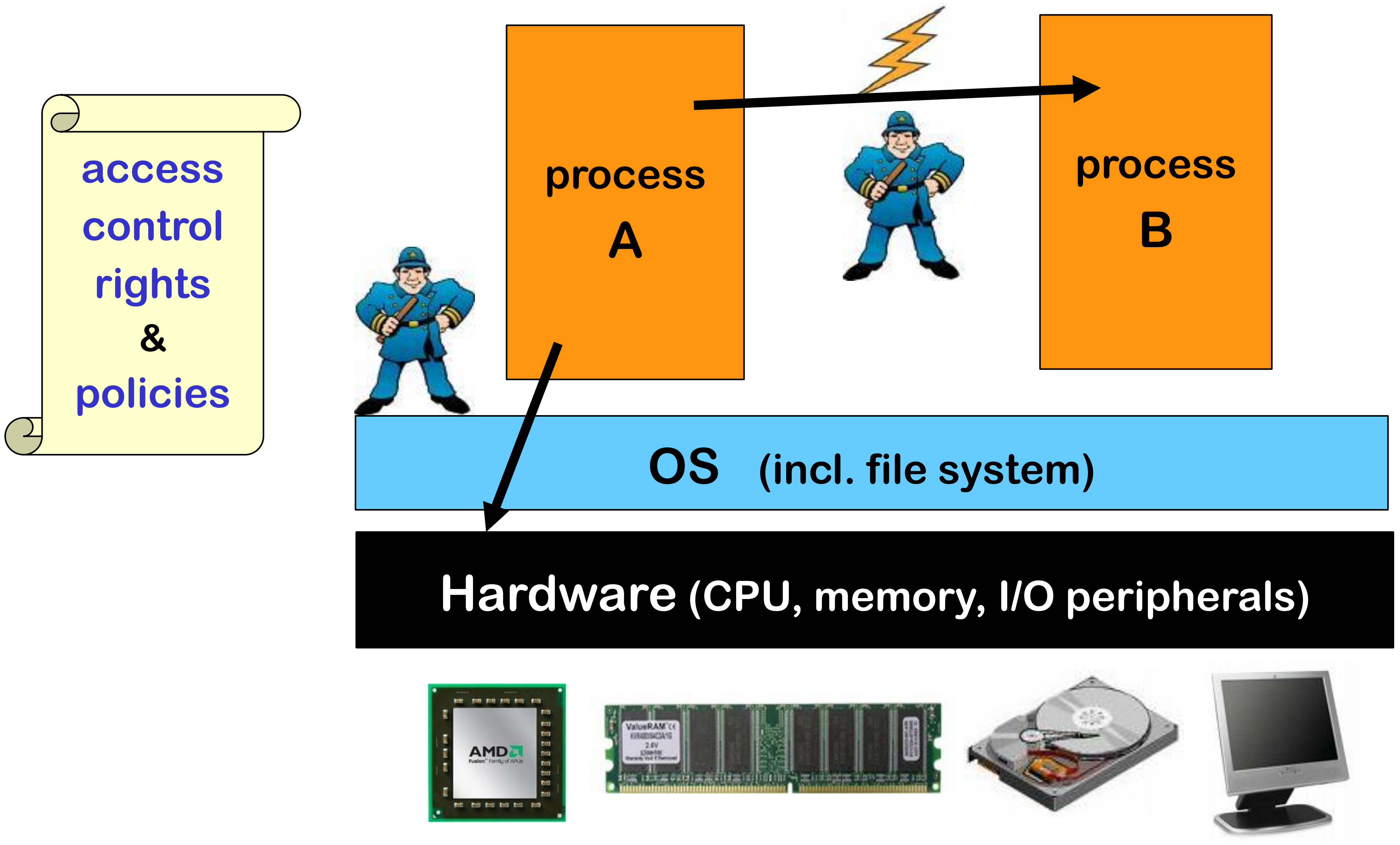
a. Reduces TCB for certain security-sensitive functionality

b. Reduces the impact of any security flaws.

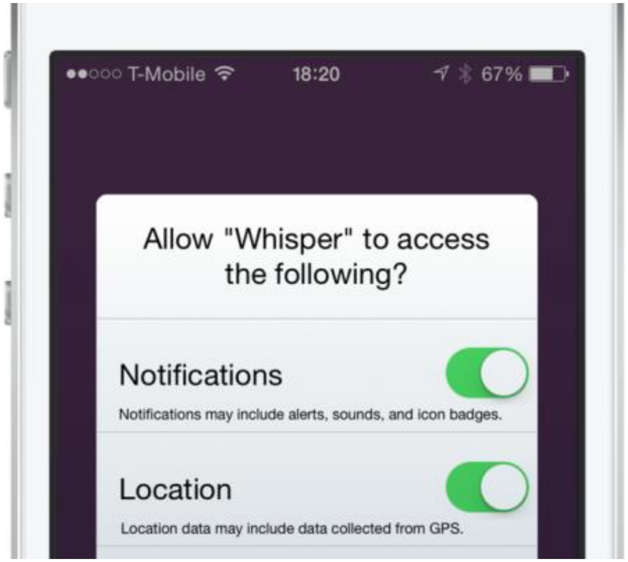
Operating System (OS) Access Control

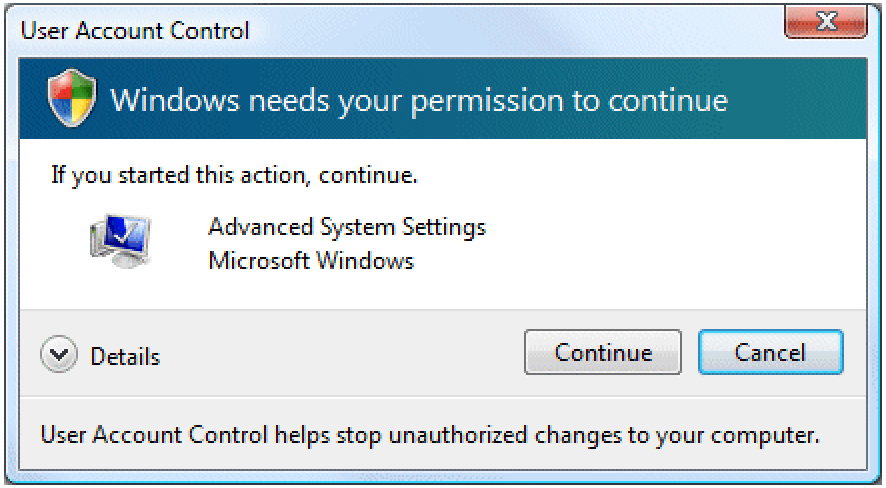
See also Chapter 2 of the lecture notes

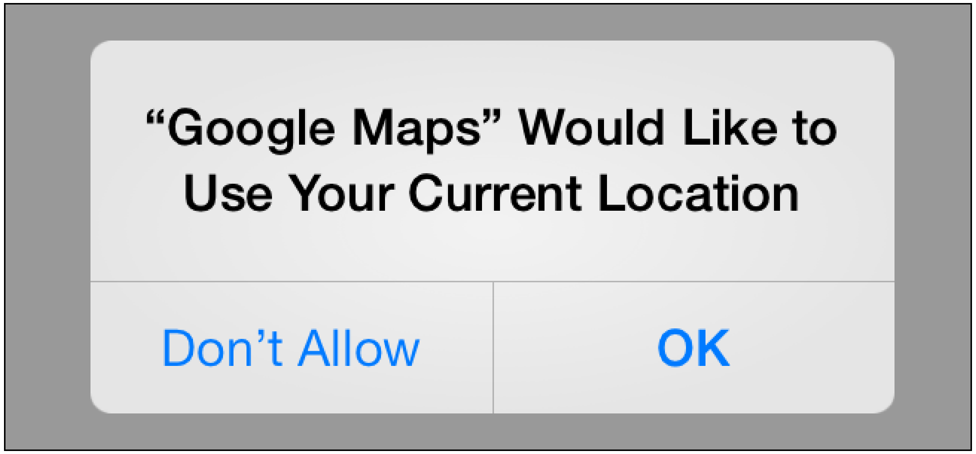
Classical OS-based security (reminder)



Signs of OS access control







Problems with OS access control

1. Size of the TCB
   The Trusted Computing Base for OS access control is **huge**
   so there *will* be security flaws in the code.

   The only safe assumption: a malicious user process on a typical OS (Linux, Windows, BSD, iOS, Android, ...) *will* be able to get root rights.

2. Too much complexity
   The languages to express access control policy are very complex, so people *will* make mistakes

3. Not enough expressivity / granularity
   Eg the OS cannot do access control *within* process, as processes as the 'atomic' units

Note: fundamental conflict between the need for expressivity

and the desire to keep things simple

Example: complexity (resulting in *privilege escalation)*

UNIX access control uses 3 permissions (`rwx`) for 3 categories of users (`owner,group,others`), for files & directories.

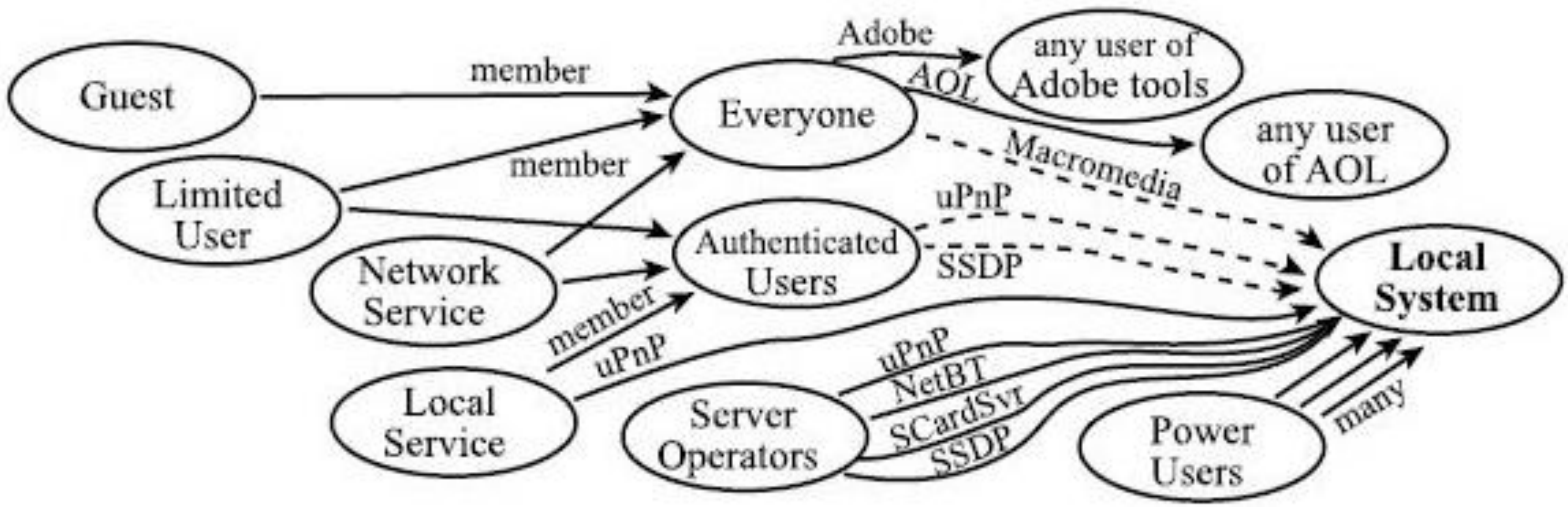
Windows XP uses 30 permissions, 9 categories of users, and 15 kinds of objects.

Example common configuration flaw in XP access control, in 4 steps:

1. Windows XP uses `Local Service` or `Local System` services for privileged functionality (where UNIX uses `setuid` binaries)
2. The permission `SERVICE_CHANGE_CONFIG` allows *changing the executable* associated with a service (say a printer driver)
3. But... it *also* allows to change *the account under which it runs*, incl. to `Local System`, which gives maximum root privileges.
4. Many configurations mistakenly grant `SERVICE_CHANGE_CONFIG` to all `Authenticated Users`...

Privilege escalation in Windows XP

Unintended privilege escalation due to misconfigured access rights of standard software packages in Windows XP:



[S. Govindavajhala and A.W. Appel, Windows Access Control Demystified, 2006]

Moral of the story (1) : KEEP IT SIMPLE

Moral of the story (2) : If it is not simple, check the details

`chroot` jail

`chroot` - change root - is nice example of compartmentalisation (of file system) in UNIX/Linux. It is coarse but simple.

- restricts access of a process to a subset of file system, ie. changes the root of file system for that process
- Eg running an application you just downloaded with

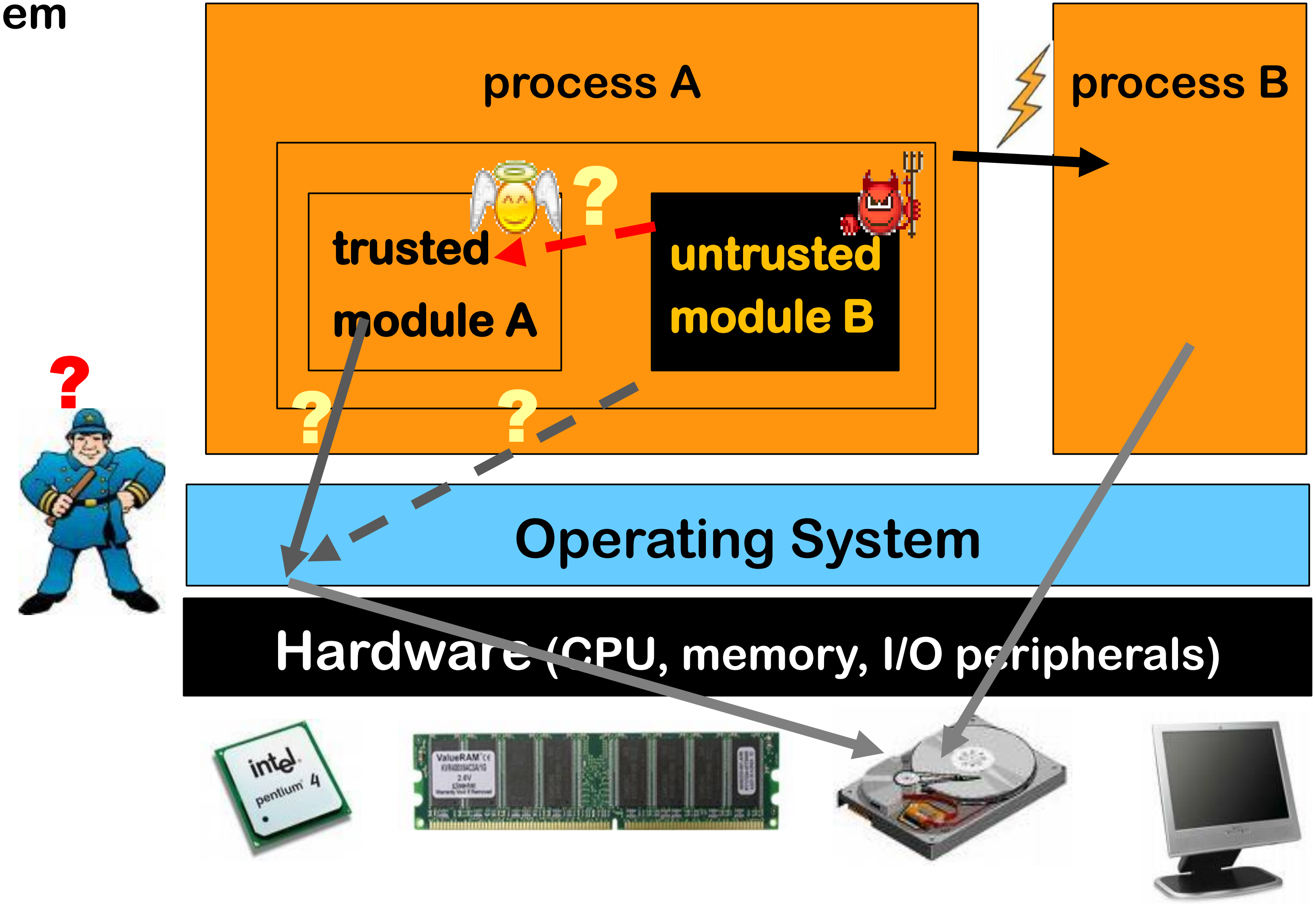
```
chroot /home/sos/erik/trial ; /tmp
```

  restricts access to just these two directories

- Using traditional OS access control permissions for this would be very tricky! It would require getting permissions right all over the file system.

Limits in granularity

OS can't distinguish components *within* process, so can't differentiate access control for them, or do access control between them



Limitation of classic OS access control

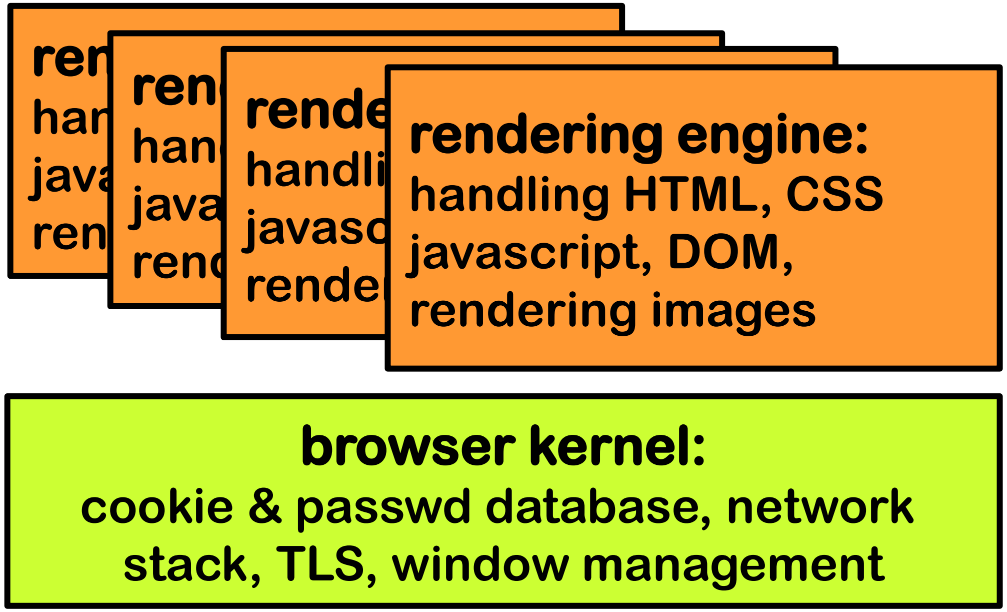
- A process has a fixed set of permissions. Usually, all permissions of the user who started it
- Execution with reduced permission set may be needed temporarily when executing untrusted or less trusted code. For this OS access control may be too coarse.

Remedies/improvements

- Allowing users to drop rights when they start a process
- Asking user approval for additional permissions at run-time
- Using different user accounts for different applications, as Android does
- Split a process into multiple processes with different access rights

Example: compartmentalisation in Chrome

Chrome browser process was split into multiple OS processes



One rendering engine per tab, plus one for trusted content (eg HTTPS certificate warnings)

No access to local file system and to each other

One browser kernel with *full user privileges*

- (Complex!) rendering engine is black box for browser kernel
- Running a new process per domain can enforce the restrictions of the SOP (Same Origin Policy)
- *Advantage: TCB for certain operations drastically reduced*

More compartmentalisation in browsers

There are more forms of compartmentalisation and sandboxing inside browsers, namely in the HTML content do

- **SOP (Same Origin Policy)**
- **and optionally even inside the HTML content displayed**
  - **CSP (Content Security Policy)**
  - **Sandboxing for iframes**

Microsoft Edge introduced Super Duper Secure Mode (SDSM) in 2021 to remove some complexity, eg disabling JIT, and to enable some additional memory protection mechanisms, eg CET (Control flow Enforcement Technology)

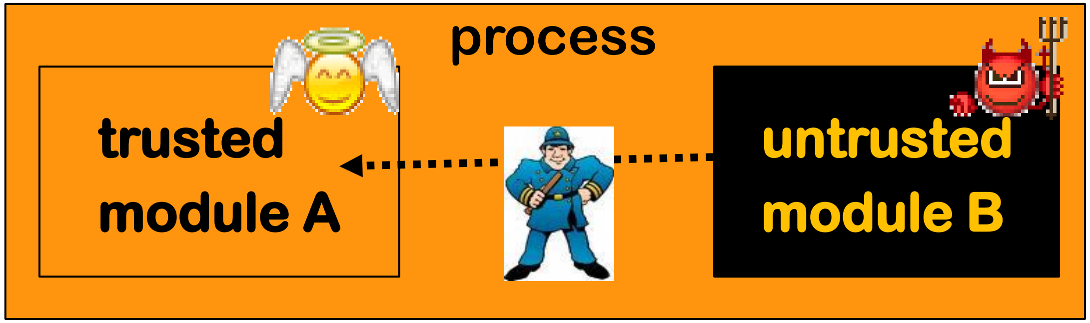
https://microsoftedge.github.io/edgevr/posts/Super-Duper-Secure-Mode/

Language-level access control

Chapter 4 of the lecture notes

Access control at the language level

In a safe programming language, access control can be provided *within* a process, at language-level, because interactions between components can be restricted & controlled



This makes it possible to have security guarantees in the presence of untrusted code (which could be malicious or just buggy)

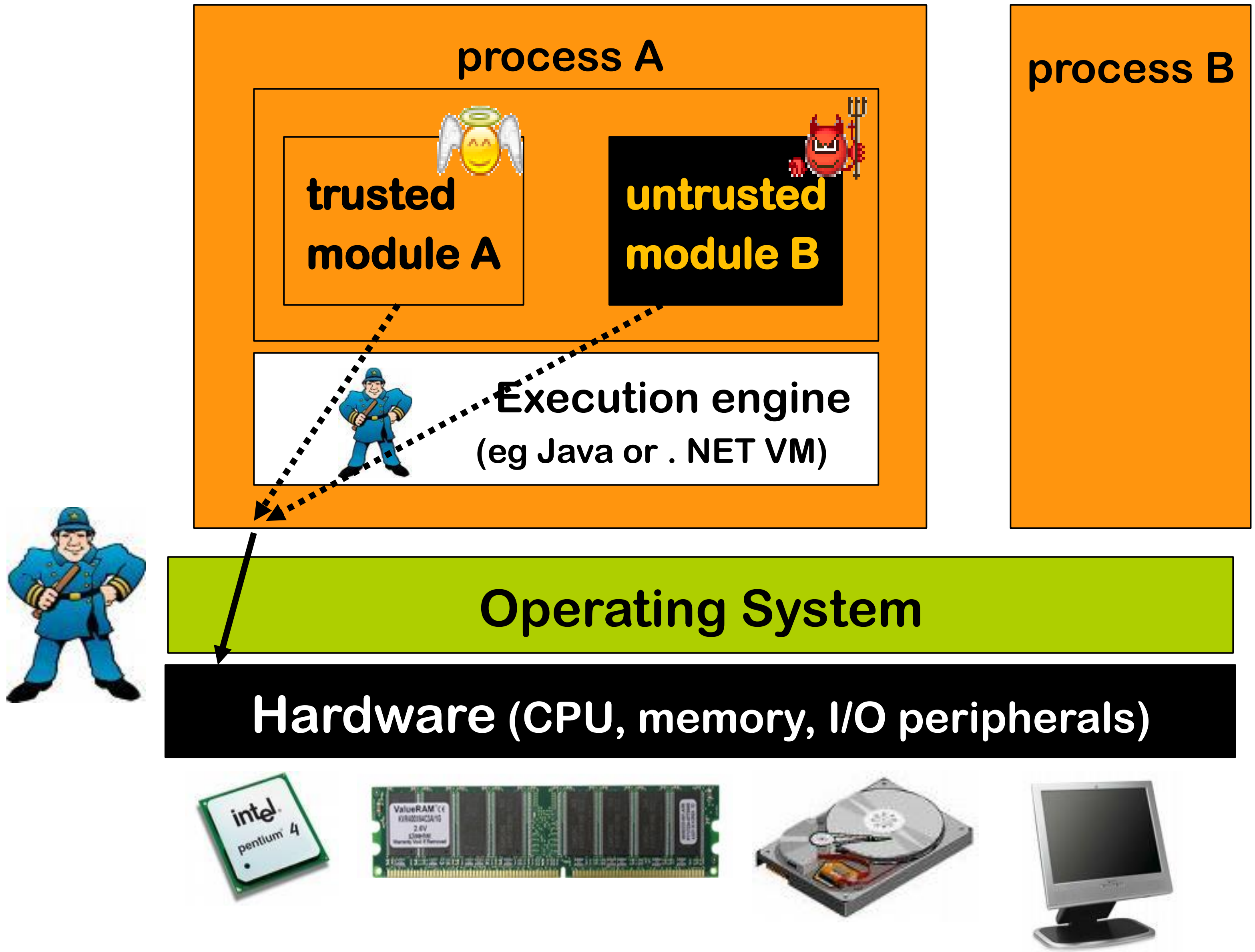
- *Without memory-safety, this is impossible. Why?*

  Because B can access any memory used by A

- *Without type-safety, it is hard. Why?*

  Because B can pass ill-typed arguments to A's interface

Language-level sandboxing on top of OS sandboxing



Sand-boxing with code-based access control

Use cases

- using code from some untrusted or less trusted library
  - ie protection from supply chain attacks
- concentrating security-sensitive functionality is small module
  - smaller code base => smaller chance of bugs
  - put best programmers on this module
  - do more quality assurance for this module
    (more design reviews, more testing, more code reviews, ...)

Sand-boxing with code-based access control

Language platforms such as Java and .NET provide code-based access control

- this treats different parts of a program differently
- on top of the user-based access control of the OS

Ingredients for this access control, as for any form of access control

1. permissions
2. components (aka protection domains)
   - in traditional OS access control, this is the user ID
3. policies
   - which gives permissions to components, ie. *who* is allowed to do *what*

Code-based access control in Java

Example configuration file that expresses a policy

```
grant
 codebase "http://www.cs.ru.nl/ds", signedBy "Radboud",
 { permission
      java.io.FilePermission "/home/ds/erik","read";
 };

grant
 codebase "file:/.*"
 { permission
      java.io.FilePermission "/home/ds/erik","write";
 }
```

protection domains

Protection domains

- Protection domains based on evidence

  1. Where did it come from?
     - where on the local file system (hard disk) or where on the internet
  2. Was it digitally signed and if so by who?
     - using a standard PKI

- When loading a component, the Virtual Machine (VM) consults the security policy and remembers the permissions

Permissions

- Permissions represent a right to perform some actions. Examples:
  - `FilePermission(name, mode)`
  - `NetworkPermission`
  - `WindowPermission`
- Permissions have a set semantics, so one permission can be a superset of another one.
  - E.g. `FilePermission("*", "read")` includes `FilePermission("some_file.txt", "read")`
- Developers can define new custom permissions.

Last week: code-based access control in Java

Example configuration file that expresses a policy

```
grant
 codebase "http://www.cs.ru.nl/ds", signedBy "Radboud",
 { permission
     java.io.FilePermission "/home/ds/erik","read";
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```
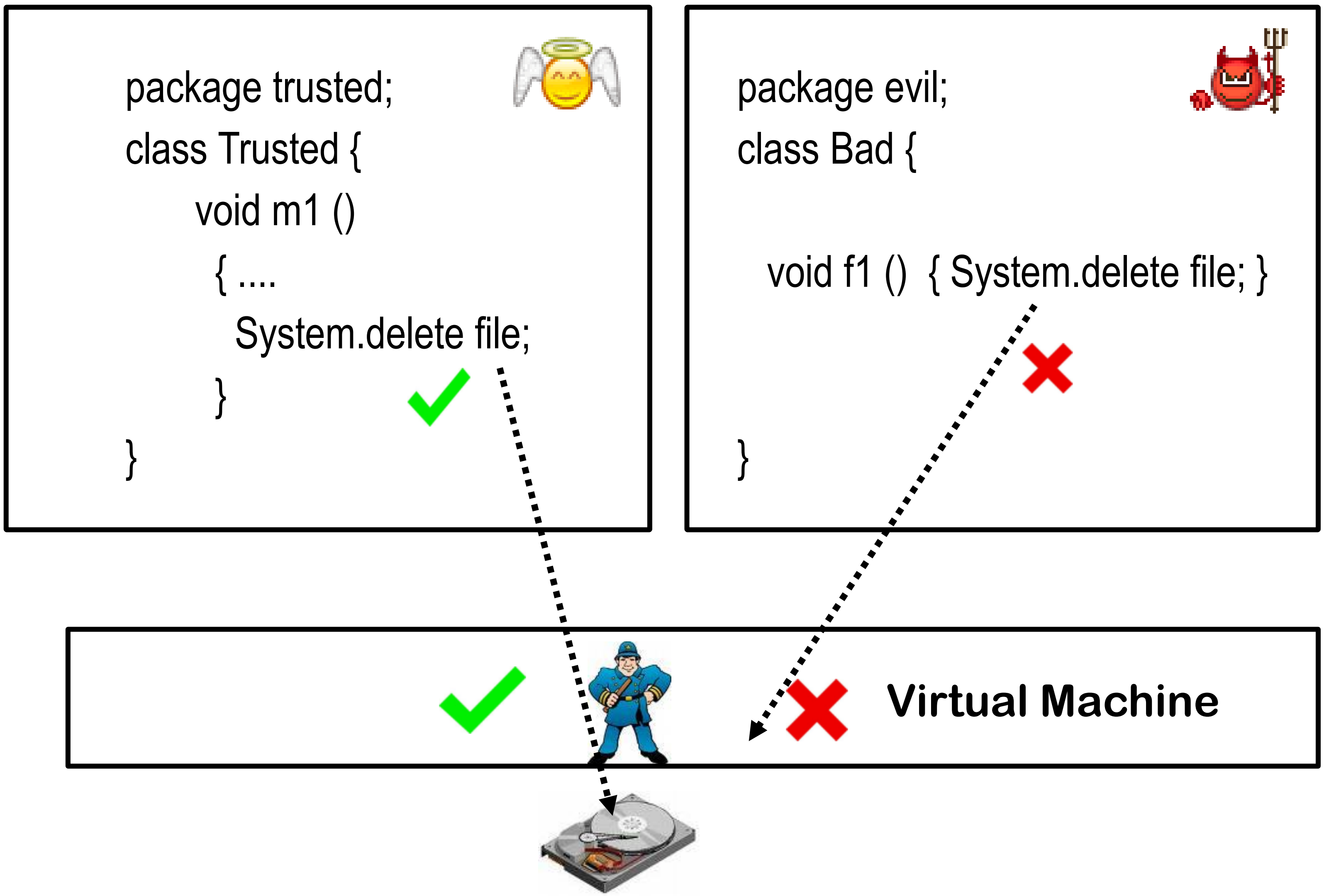
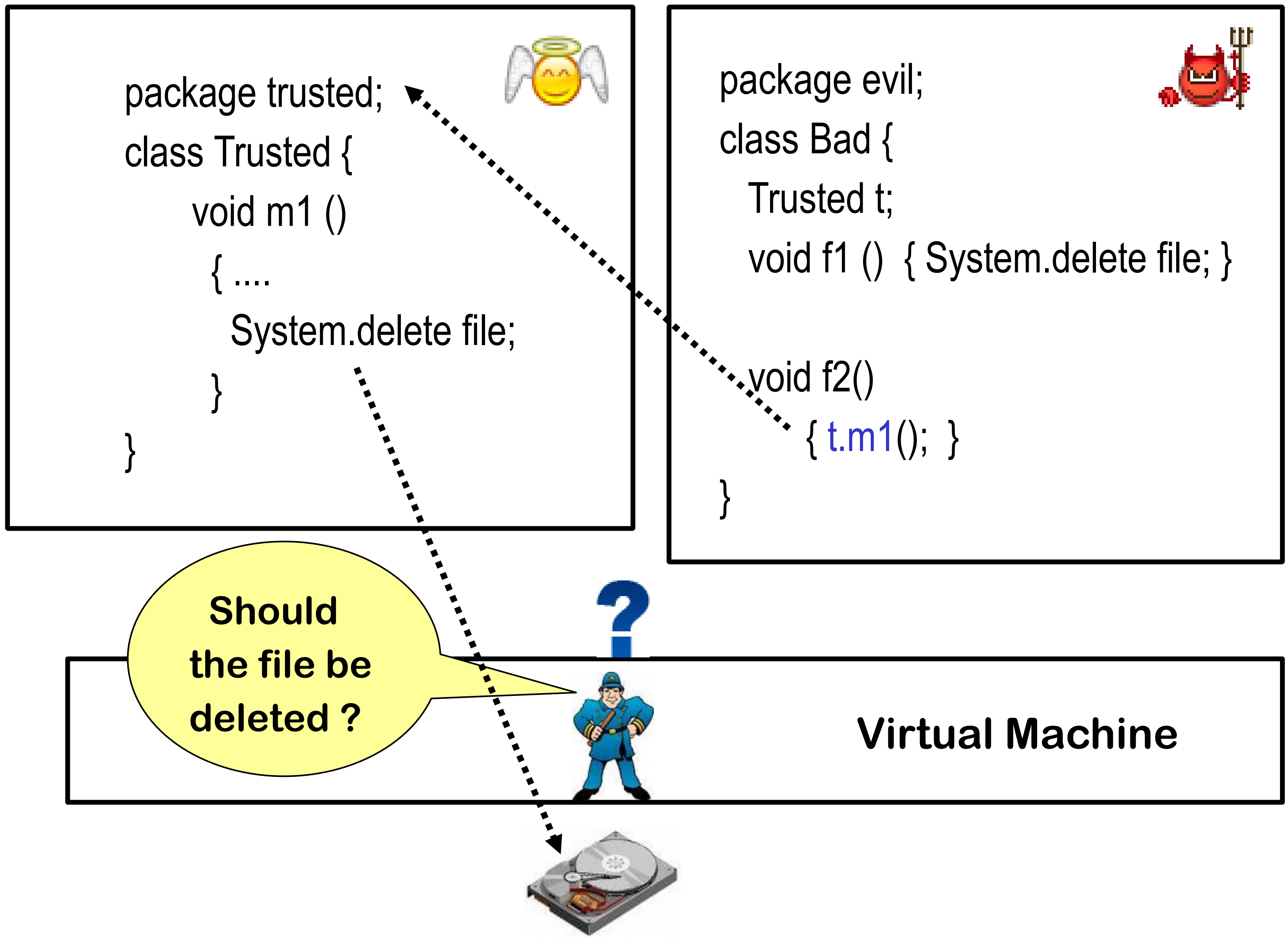

protection domains


package trusted;
class Trusted {
void m1 ()
{ ....
System.delete file;
}
}
package evil;
class Bad {
void f1 () { System.delete file; }
}
Virtual Machine

Complication: methods calls



Complication: method calls

There are different possibilities here

1. allow action if top frame on the stack has permission
2. only allow action if all frames on the stack have permission
3. ....

Pros? Cons?

1. is very dangerous: a class may accidentally expose dangerous functionality

2. is very restrictive: a class may want to, and need to, expose some dangerous functionality, but in a controlled way

More flexible solution: stackwalking aka stack inspection

Exposing dangerous functionality, (in)securely

```
Class Trusted{
  public void unsafeMethod(File f){
     delete f; } // Could be abused by evil caller
  public void safeMethod(File f) {
        .... // lots of checks on f;
     if all checks are passed, then delete f;}
         // Cannot be abused, assuming checks are bullet-proof
  public void anotherSafeMethod(){
     delete "/tmp/bla"; }
         // Cannot be abused, as filename is fixed.
         //  Assuming this file is not important..
}
```

Using visibility to control access?

```
Class Trusted{
  private void unsafeMethod(File f){
     delete f; } // Could be abused by ev
  public void safeMethod(File f) {
        .... // lots of checks on f;
     if all checks are passed, then delete
          // Cannot be abused, assuming checks are bullet-proof
  public void anotherSafeMethod(){
     delete "/tmp/bla"; }
          // Cannot be abused, as filename is fixed.
          //  Assuming this file is not important..
}
```

Making the unsafe method private & hence *invisible* to untrusted code helps, but is error-prone. Some public method may call this private method and indirectly expose access to it

Hence: stackwalking

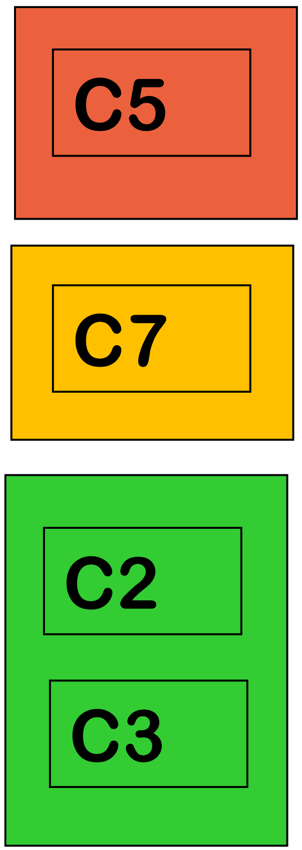
Stack walking

- Every resource access or sensitive operation protected by a demandPermission(P) call for an appropriate permission P
  - no access without asking permission!
- The algorithm for granting permission is based on *stack inspection* aka *stack walking*

Stack inspection first implemented in Netscape 4.0,

then adopted by Internet Explorer, Java, .NET

Stack walking: basic concepts



Stack for thread T:
C5 called by C7
called by C2 and C3

Suppose thread T tries to access a resource

Basic algorithm:

access is allowed iff

ALL components on the call stack have the right to access the resource

ie

- rights of a thread is the *intersection* of rights of all outstanding method calls

Stack walking

Basic algorithm is *too restrictive* in some cases

E.g.

- Allowing an untrusted component to delete some specific files
- Giving a partially trusted component the right to open specially marked windows (eg. security pop-ups) without giving it the right to open arbitrary windows
- Giving an app the right to phone certain phone numbers (eg. only domestic ones, or only ones in the mobile's phonebook)

Stack walk modifiers

- Enable_permission(P):
  - means: don't check my callers for this permission, I take full responsibility
  - This is essential to allow *controlled* access to resources for less trusted code

- Disable_permission(P):
  - means: don't grant me this permission, I don't need it
  - This allows applying the *principle of least privilege* (ie. only givie or ask the privileges *really* needed, and *only when* they are really needed)

Stack walking: algorithm

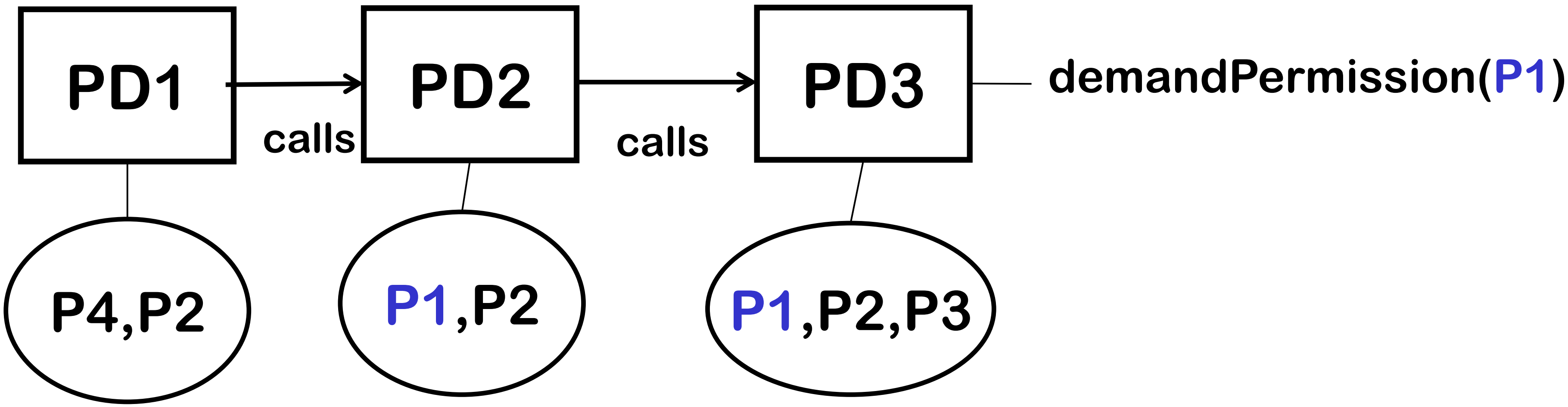
On creating new thread:

new thread inherit access control context of creating thread

DemandPermission(P) algorithm:

1. for each caller on the stack, from top to bottom:
   if the caller
   a) lacks Permission P: throw exception
   b) has disabled Permission P: throw exception
   c) has enabled Permission P: return
2. check inherited access control context

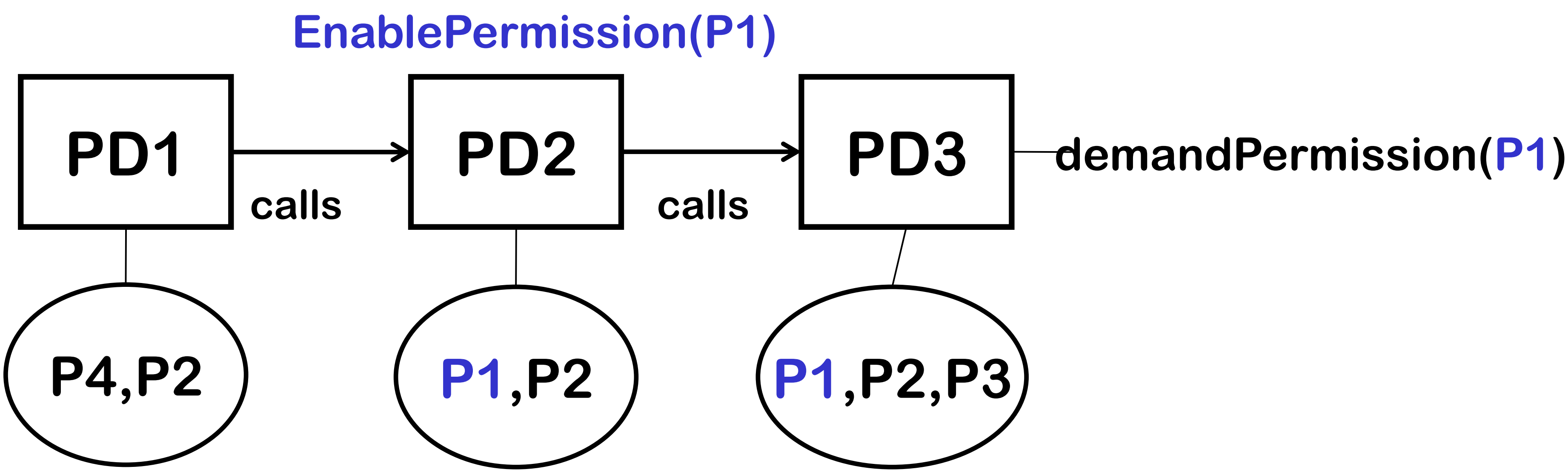
Stack walk modifiers: examples



Will DemandPermission(P1) succeed ?

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

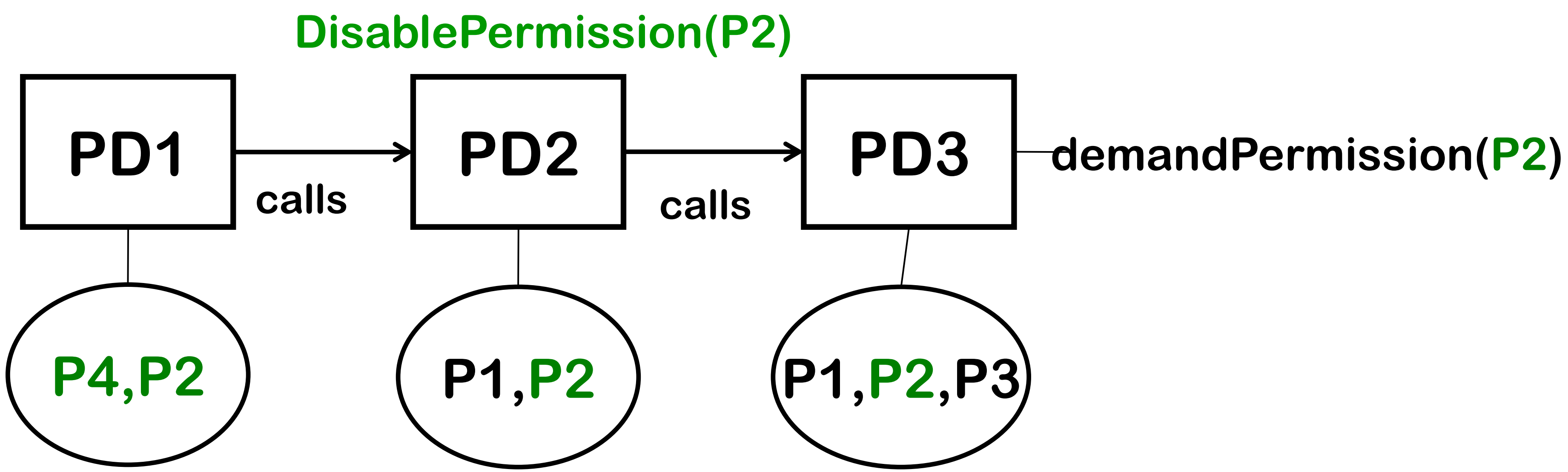
Stack walk modifiers: examples



Will DemandPermission(P1) succeed ?

DemandPermission(P1) succeeds

Stack walk modifiers: examples



Will DemandPermission(P2) succeed ?

DemandPermission(P2) fails

Using stack walking to restrict access to functionality

```
Class Trusted{
   public void unsafeMethod(File f){
      delete f; }
   public void safeMethod(File f) {
      ... // lots of checks on f;
      enablePermission (FileDeletionPermission);
      delete f;}
   public void anotherSafeMethod(){
      enablePermission (FileDeletionPermission);
      delete "/tmp/bla"; }
}
```

"I take full responsibility for my callers"

Typical programming pattern

The typical programming pattern in privileged components, esp. in public methods accessible by untrusted code:

```
public methodExposingScaryFunctionality (A a, B b){
    ....; do security checks on arguments a and b
    enable privileges (P1,P2);
    do the dangerous stuff that needs these privileges;
    disable privileges (P1,P2);
    .... }
```

in keeping with the principle of least privilege

Spot the security flaw?

```
Class Good{
  public void m1 (String filename) {
      lot of checks on filename;
      enablePermission (FileDeletionPermission);
      delete filename;}

   public void m2(byte[] filename){
      lot of checks on filename;
      enablePermission (FileDeletionPermission);
      delete filename;}
}
```

TOCTOU attack (Time of Check, Time of Use)

```
Class Good{
  public void m1 (String filename) {
       lot of checks on filename;
       enablePermission (FileDeletionPermission);
       delete filename;}

   public void m2( byte[] filename){
       lot of checks on filename;
       enablePermission (FileDeletionPermission);
       delete filename;}
}
```

m1 is secure, because Strings are immutable
(assuming there are no TOCTOU vulnerabilities in the underlying file systems, eg due to symbolic links)

m2 is insecure, because byte arrays are mutable; attackers can could change the value of filename after the checks, in a multi-threaded setting

Need for privilege elevation

Note the similarity between

- Methods which enable some permissions
  - which temporarily raise privileges
- Linux `setuid root` programs or Windows Local System Services
  - which can be started by any user, but then run in admin mode
- OS system calls invoked from a user program
  - which cause a switch from user to kernel model

All are trusted services that elevate the privileges of their clients

- hopefully in a secure way...
- if not: privilege escalation attacks

In any code review, such code obviously requires extra attention!

Security flaw in code signing check (Magic Coat)

Implementation of the class `Class` in JDK1.1.1

```
package java.lang;

public class Class {

  private String[] signers;

  /** Obtain list of signers of given class */

  public String[] getSigners()

      { return signers;   }
```

What is the bug ?

How can it be fixed ?

Could it be prevented at language-level ?

Security flaw in code signing check (Magic Coat)

Implementation of the class `Class` in JDK1.1.1

```
package java.lang;

public class Class {

  private String[] signers;

  /** Obtain list of signers of given class */

  public String[] getSigners()

      { return signers;   }
```

What is the bug ? *`getSigners` leaks reference to internal data structure*

How can it be fixed ? *`getSigners` should clone the array and return a clone*

Could it be prevented at language-level ? *By having immutable arrays, or type system for alias control*

Java safety & security guarantees

- memory safety
- strong typing
- visibility restrictions (`public`, `private`,...)
- immutable fields using `final`
- unextendable classes using `final`
- immutable objects, eg `String`, `Boolean`, `Integer`, `URL`
- sandboxing based on stackwalking

This allows security guarantees to be made even if part of the code is untrusted – or simply buggy

Similar guarantees for Microsoft .NET/C#, Scala, …