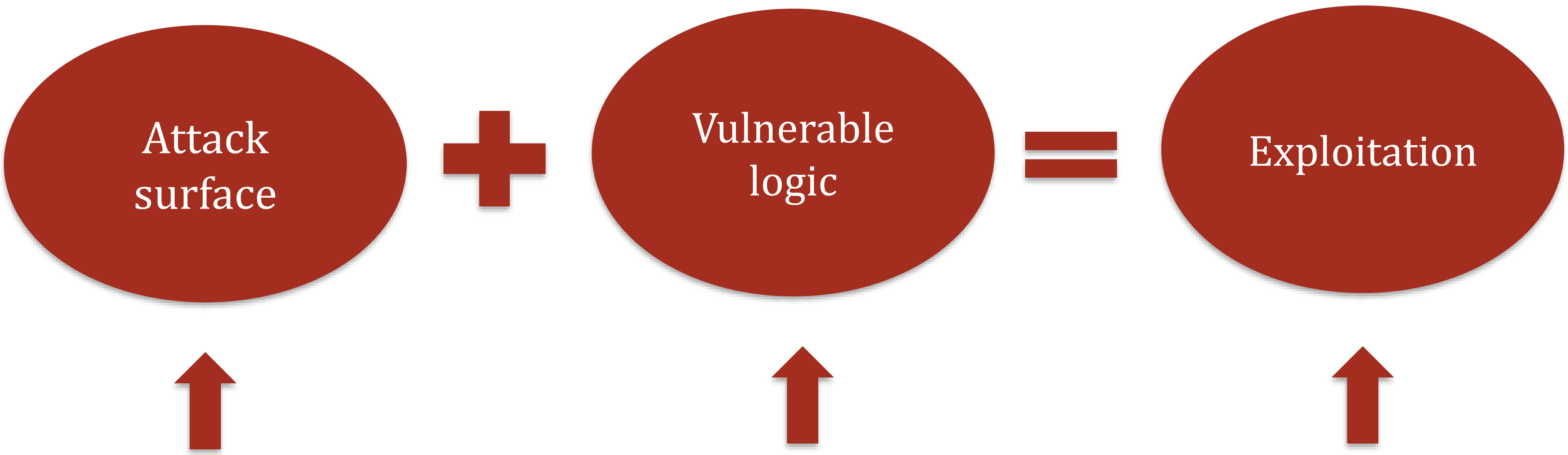
CS165 – Computer Security

Control Flow Integrity and Software Fault Isolation
Nov 16, 2021

Our story so far…

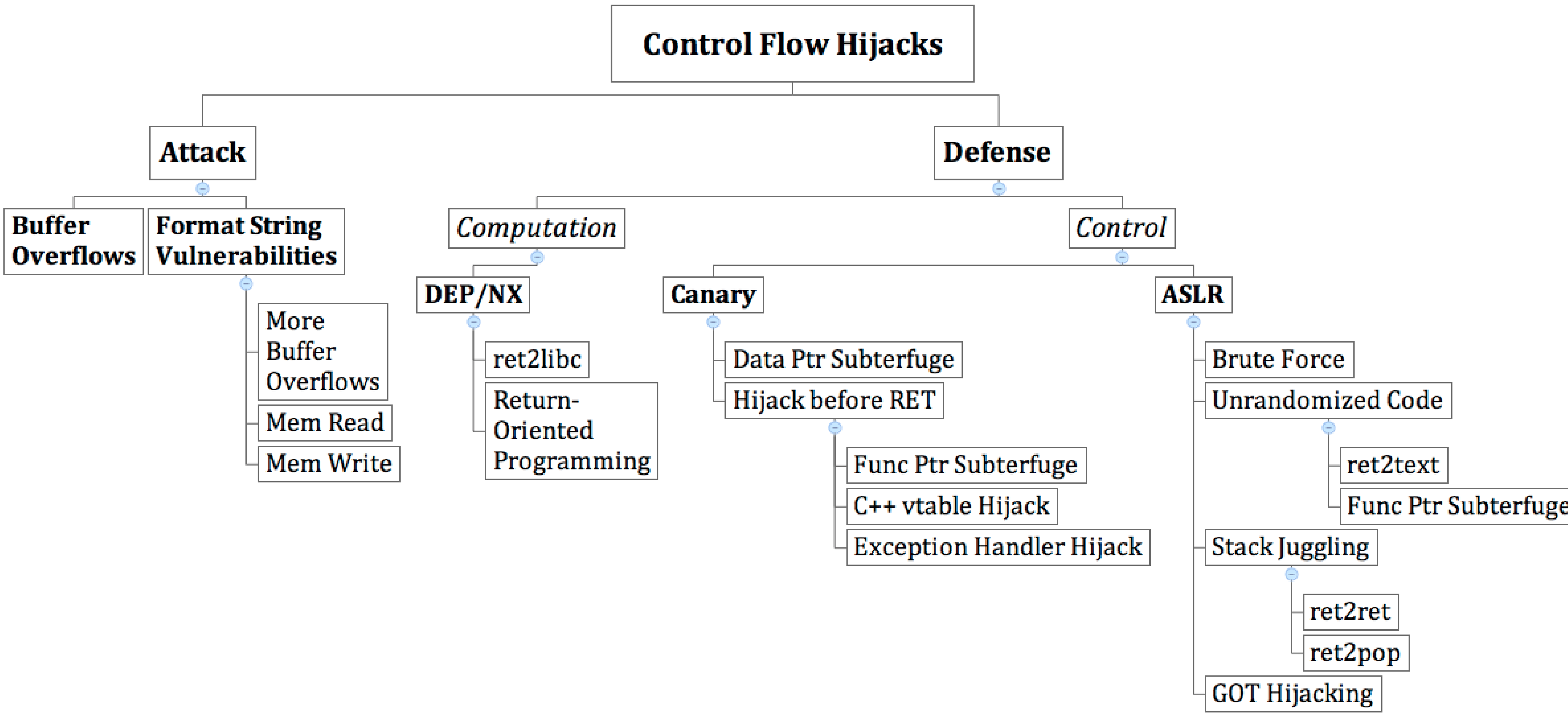


Access control

Bug finding via
(1) Static analysis
(2) Dynamic analysis

Prevention/mitigation techniques?

Our story so far…



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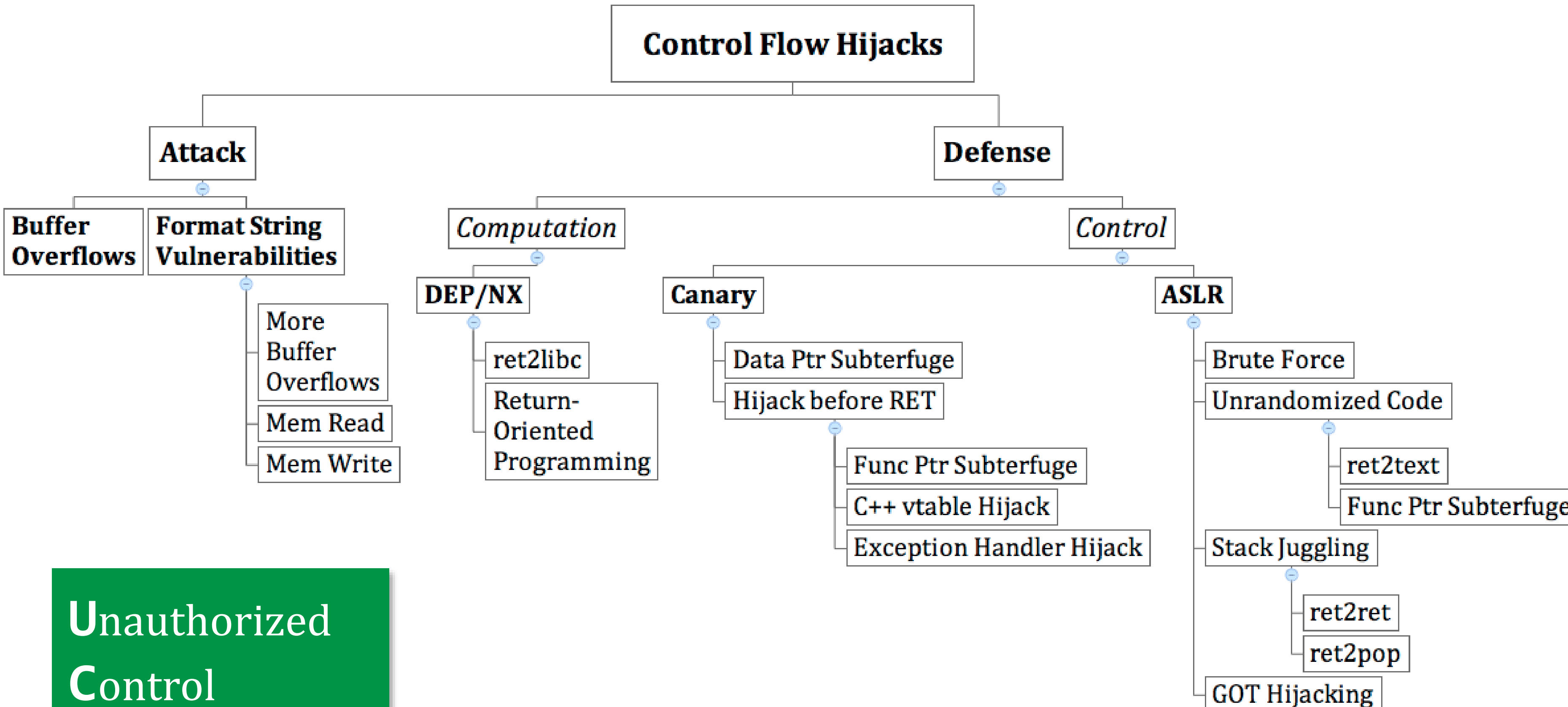

Unauthorized
Control
Information
Tampering

Control Flow Hijack: Always control + computation

shellcode (aka payload)	padding	&buf

computation + ***control***

Stack buffer overflow, return-to-libc
ROP, functional pointer subterfuge:
Hijacking the control

Can we prevent control manipulation?

Control Flow Integrity!

Agenda

Reference Monitors

Control Flow Integrity

Software Fault Isolation

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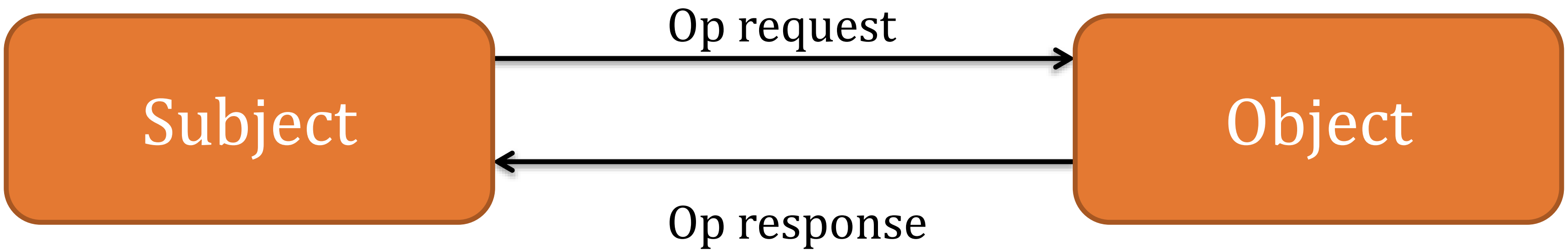
Reference Monitors

NEXT

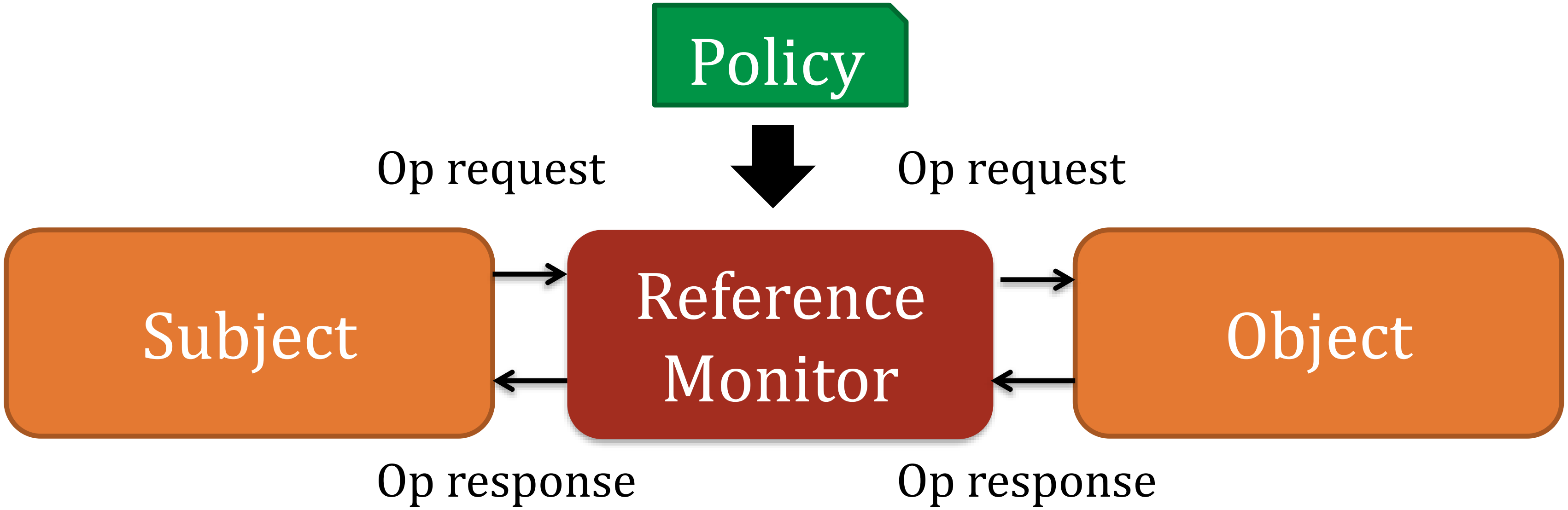
Control Flow Integrity

Software Fault Isolation



People
Processes
Computer Operations

Files
Sockets
Computer Operations



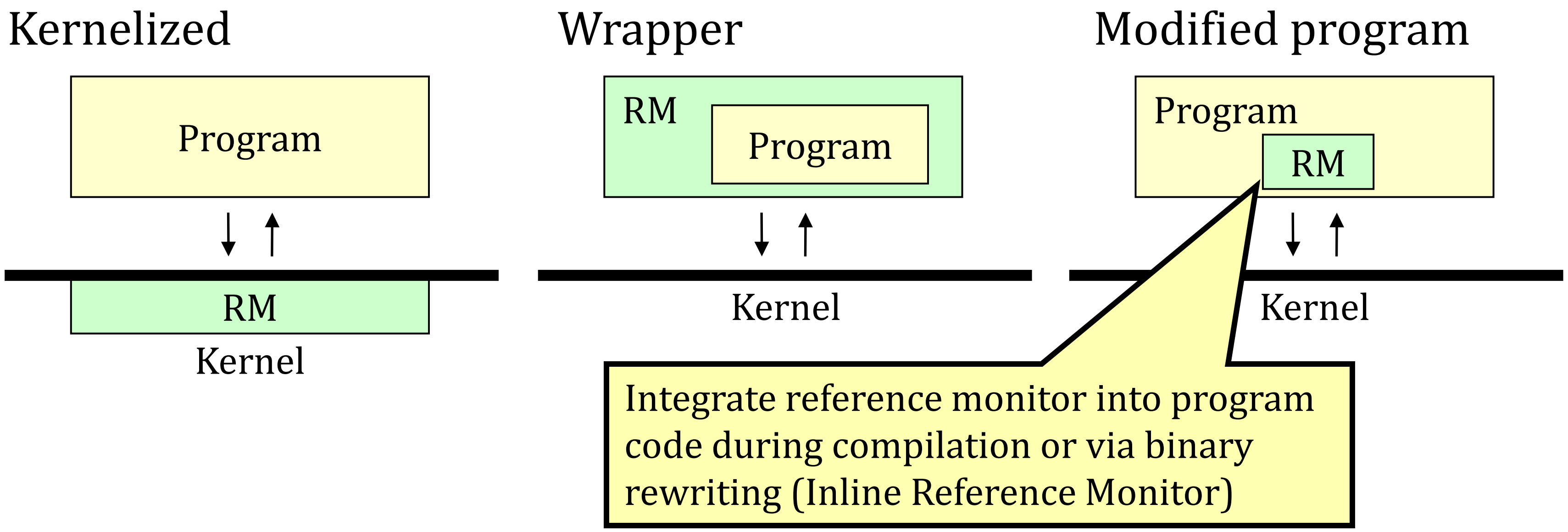
Principles:

1. Complete Mediation: The reference monitor must always be invoked
2. Tamper-proof: The reference monitor cannot be changed by unauthorized subjects or objects
3. Verifiable: The reference monitor is small enough to thoroughly understand, test, and ultimately, verify.

OS As a Reference Monitor

- OS enforces a variety of policies
  - File accesses are checked against file's Access Control List (ACL)
  - Process cannot write into memory of another process
  - Some operations require superuser privileges
    - But may need to switch back and forth (e.g., setuid in Unix)
  - Enforce CPU sharing, disk quotas, etc.

Reference Monitor Implementation

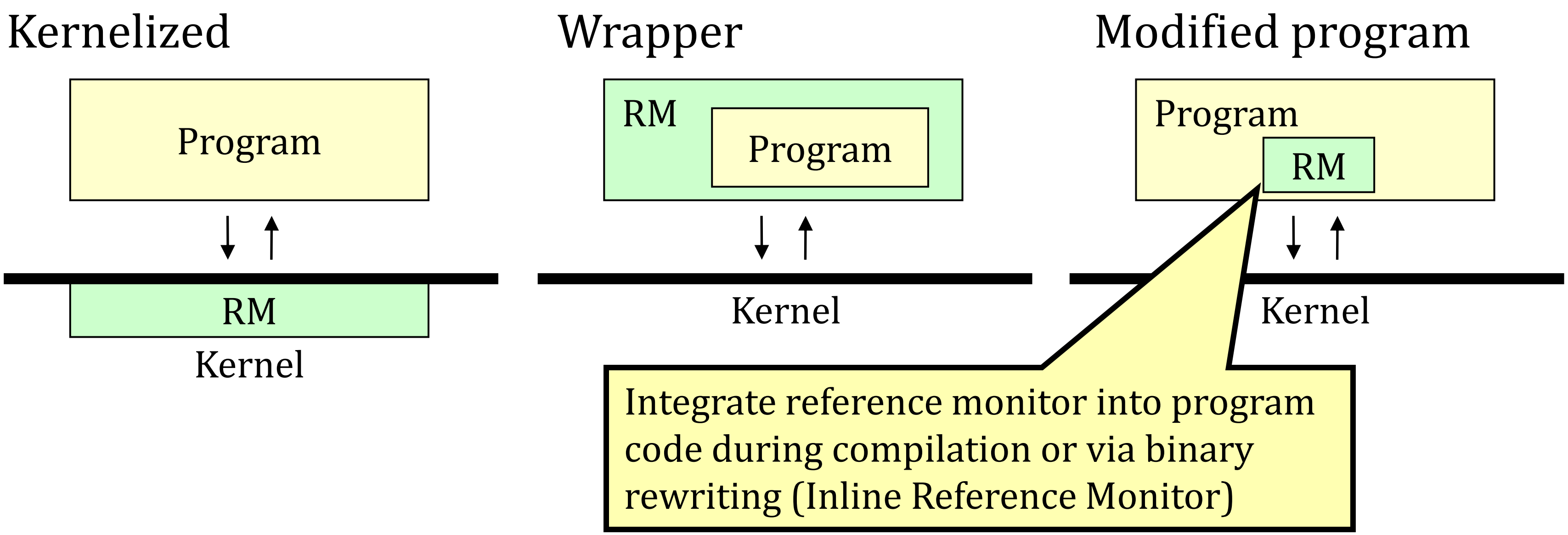


Today's Example: Inlining a control flow policy into a program

What Makes a Process itself Safe?

- Memory safety: all memory accesses are "correct"
  - Respect array bounds, separation of code and data
- Type safety: all function calls and operations have arguments of correct type
- Control-flow safety: all control transfers are envisioned by the original program
  - No arbitrary jumps, no calls to library routines that the original program did not call

Reference Monitor Implementation



- Policies can depend on application semantics
- Enforcement doesn't require context switches in the kernel
- Lower performance overhead

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Control Flow Integrity NEXT

Software Fault Isolation

Control Flow Integrity

Assigned Reading:

Control-Flow Integrity: Principles, Implementation and Applications
by Abadi, Budiu, Erlingsson, and Ligatti

Control Flow Integrity

Control Flow Integrity

- **protects against powerful adversary**
  - with <u>full</u> control over <u>entire</u> data memory

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CFI Adversary Model

CAN

- Overwrite any data memory at any time
  - stack, heap, data segs
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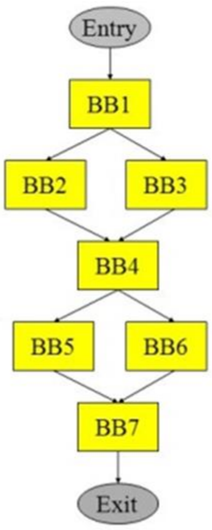
CANNOT

- Execute Data
  - NX takes care of that
- Modify Code
  - text seg usually read-only
- Write to %ip
  - true in x86
- Overwrite registers in other contexts
  - kernel will restore regs

CFI Overview

Invariant: Execution must follow a path in a control flow graph (CFG) created ahead of run time.

“static”



Most control flow transfer targets are hard-coded

jnz	**short loc_18002C19E**	**0F 85 B4 00 00 00**
call	**__scrt_initialize_crt**	**EB 12 0B 00 00**

But what about indirect jumps and ret?

e.g., func pointer, ret address

CFI Overview

Method to check indirect control transfers:

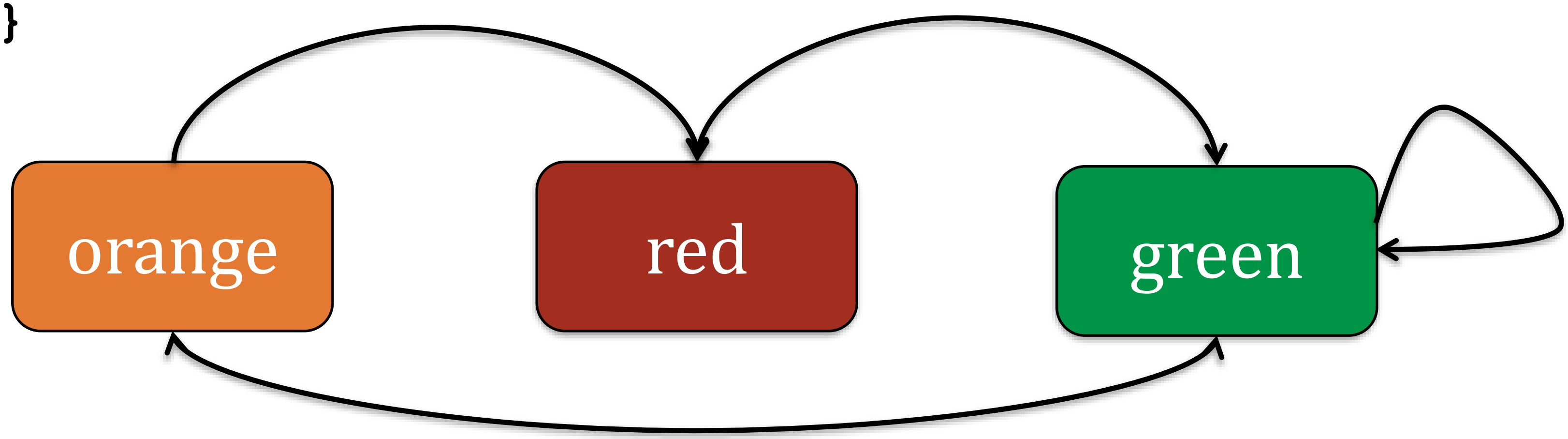
- build CG and CFG statically, e.g., at compile time
  - **call, jmp, ret** instructions
- instrument (rewrite) binary, e.g., at install time
  - add IDs and ID checks; maintain ID uniqueness
- verify CFI instrumentation at load time
  - indirect jump targets, presence of IDs and ID checks, ID uniqueness
- perform ID checks at run time
  - indirect jumps have matching IDs

Call Graph – Checking **Return Address**

```
void orange()
{
1.  red(1);
2.  red(2);
3.  green();
}
```

```
void red(int x)
{
green();
...
}
```

```
void green()
{
   green();
   orange();
}
```



- Upon return (e.g., red)

ret →

```
mov ecx, [esp]  //check ret addr
cmp [ecx], AABBCCDDh
jne error_label
jmp ecx+4
```

- At the caller (e.g., orange)

call
...
→

```
0x00   call red
0x04   AABBCCDDh #read-only data
0x08   ...
```

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void green()
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  green();
  orange();
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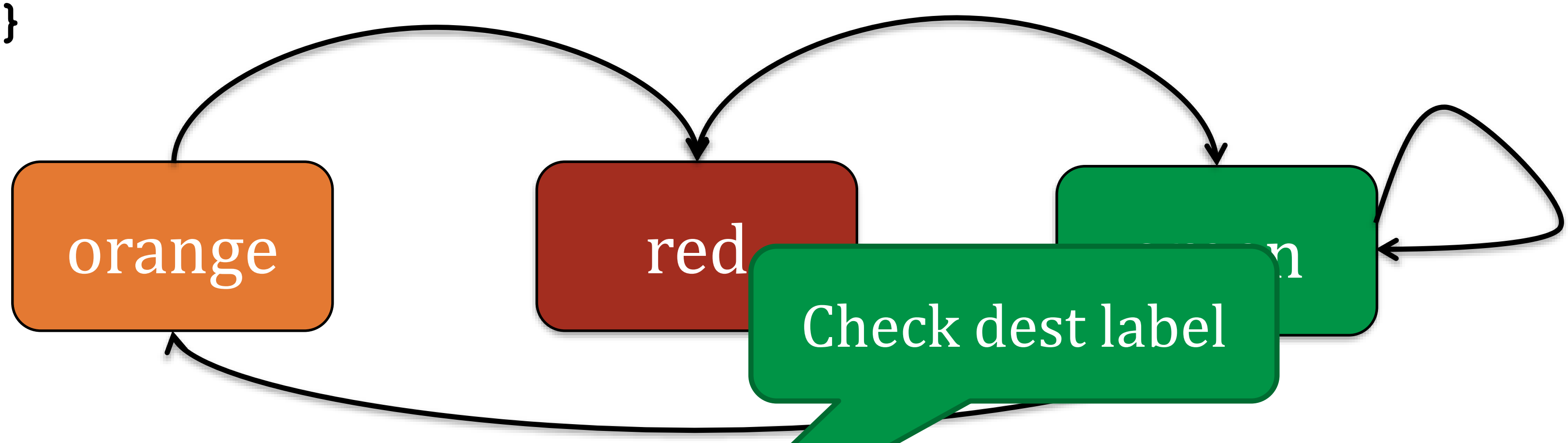

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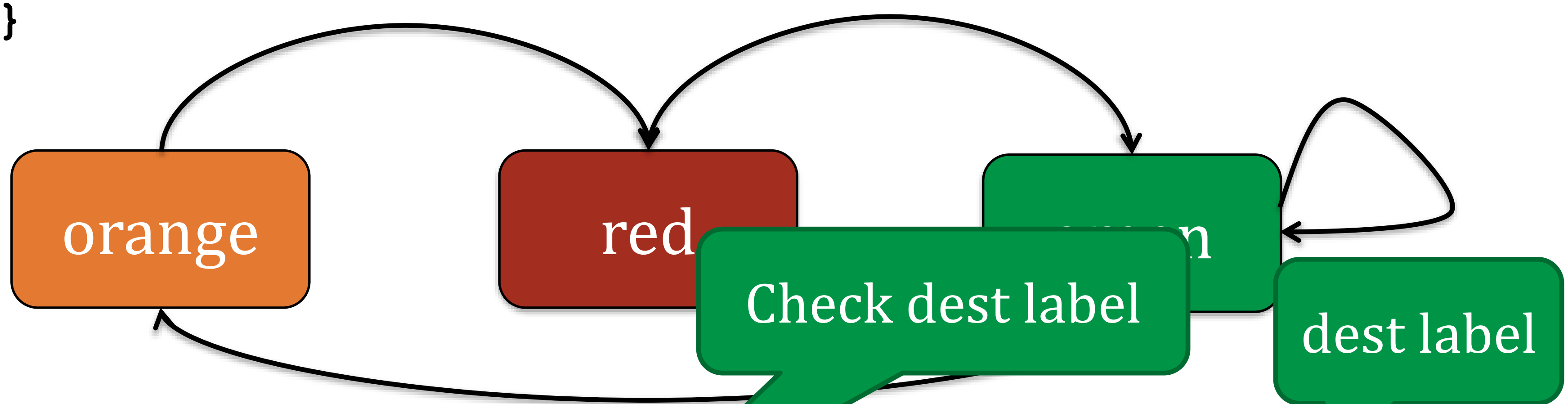

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Checking **Function Pointer** Deference

```
FF 53 08                   call   [ebx+8]            ; call a function pointer
```

is instrumented using `prefetchnta` destination IDs, to become:

```
8B 43 08                   mov   eax, [ebx+8]        ; load pointer into register
3E 81 78 04 78 56 34 12    cmp   [eax+4], 12345678h  ; compare opcodes at destination
75 13                      jne   error_label         ; if not ID value, then fail
FF D0                      call eax                  ; call function pointer
3E 0F 18 05 DD CC BB AA    prefetchnta [AABBCCDDh]   ; label ID, used upon the return
```

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```

Check dest label

Performance

Size: increase 8% avg

Time: increase 0-45%; 16% avg

– I/O latency helps hide overhead

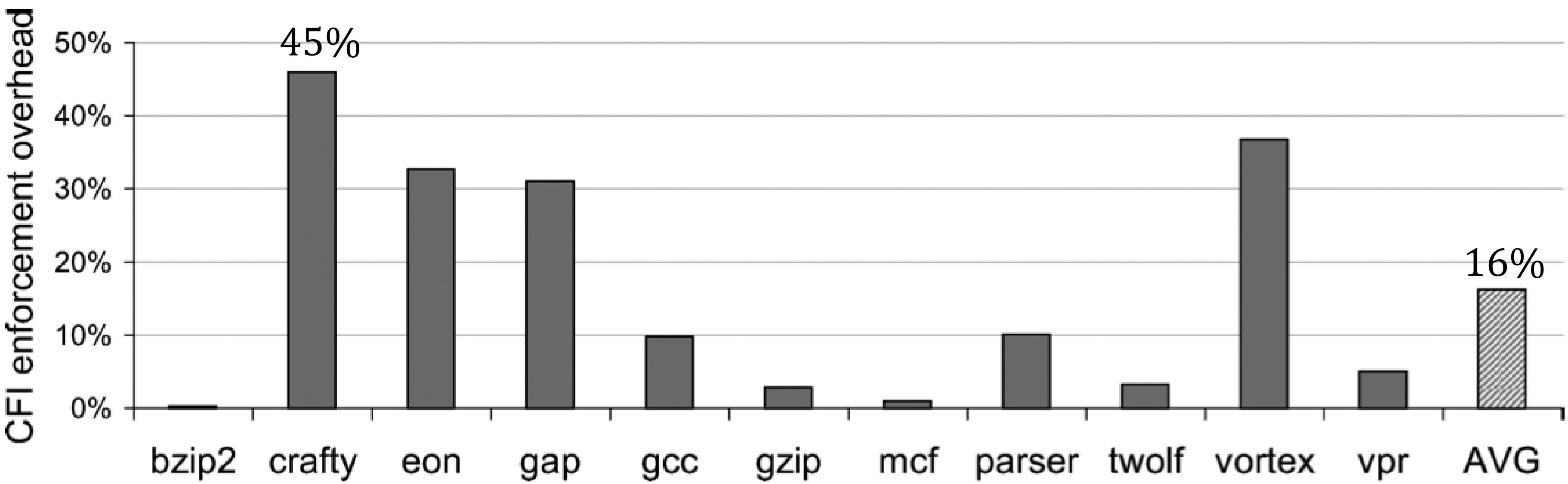
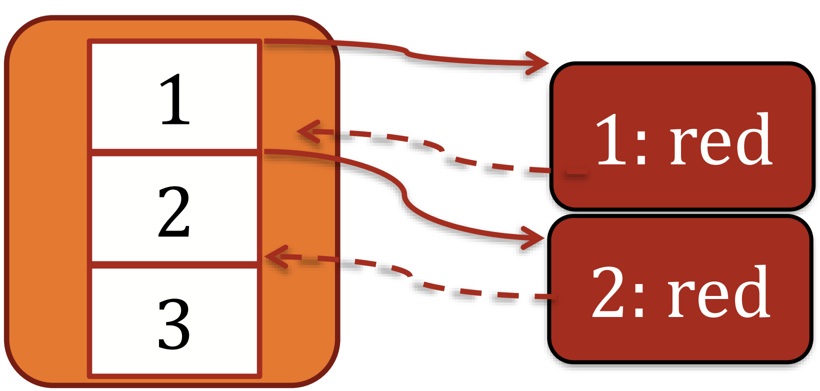


Fig. 6. Execution overhead of inlined CFI enforcement on SPEC2000 benchmarks.

Context-Sensitive CFI

- Previous assumption: destination is fixed (a single target or a group)

```
void orange()      void red(int x)      void green()
{                  {                    {
1. red(1);         ..                     green();
2. red(2);         }                      orange();
3. green();                             }
}
```



A *more precise* CFI for orange lines 1 and 2.

Context-Sensitive CFI

Whether different calling contexts are distinguished

```
void orange()
{
1.  red(1);
2.  red(2);
3.  green();
}
```

```
void red(int x)
{
..
}
```

```
void green()
{
  green();
  yellow();
}
```

Context sensitive distinguishes 2 different calls to red(-)

Context Sensitive Example

```
a = id(4);
                void id(int z)
                { return z; }
b = id(5);
```

Context-Sensitive
(color denotes matching call/ret)

Context sensitive can tell one call returns 4, the other 5

```
a = id(4);
                void id(int z)
                { return z; }
b = id(5);
```

Context-Insensitive
(note merging)

Context insensitive will say both calls return {4,5}

Context Sensitivity Problems

Suppose A and B both call C.

- CFI uses same return label in A and B.

How to prevent C from returning to B when it was called from A?

- **Solultion: Shadow Call Stack**
  - a protected memory region for call stack
  - each call/ret instrumented to update shadow
  - CFI ensures instrumented checks will be run

Security Guarantees

Effective against attacks based on illegitimate control-flow transfer

- buffer overflow, ret2libc, ROP, pointer subterfuge, etc.

Any check becomes non-circumventable.

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Any check becomes non-circumventable.

Allow data-only attacks since they respect CFG!

- incorrect usage (e.g. printf can still dump mem)
- substitution of data (e.g. replace file names)

CFI an active area of research

CCS 2015:

- Per-Input Control-Flow Integrity
- Practical Context-Sensitive CFI
- CCFI: Cryptographically Enforced Control Flow Integrity
- Losing Control: On the Effectiveness of Control-Flow Integrity under Stack Attacks

CFI Summary

Control Flow Integrity ensures that control flow follows a path in CFG

- Accuracy of CFG determines level of enforcement
- Can build other security policies on top of CFI
- Simple version now deployed in Windows 10 (a slow but continuing trend)

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Reference Monitors ✔

Control Flow Integrity ✔

Software Fault Isolation

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Software Fault Isolation

Optional Reading:
Efficient Software-Based Fault Isolation
by Wahbe, Lucco, Anderson, Graham

Motivation: Running untrusted code

- We often need to run buggy/unstrusted code:
  - programs from untrusted Internet sites:
    - toolbars, viewers, codecs for media player
  - old or insecure applications: ghostview, outlook
  - legacy daemons: sendmail, bind
  - honeypots
- Goal: if application "misbehaves," kill it

Isolation Mechanisms

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- Hardware
  - Memory Protection (virtual address translation, x86 segmentation)

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Software Fault Isolation
≈
Memory Protection
in Software

Software Fault Isolation

- SFI ensures that a module only accesses memory within its region by adding ***checks*** (also a type of Inline Reference Monitor)
  - e.g., a plugin can accesses only its own memory

```
if(module_lower < x < module_upper)
    z = load[x];
```

SFI Check

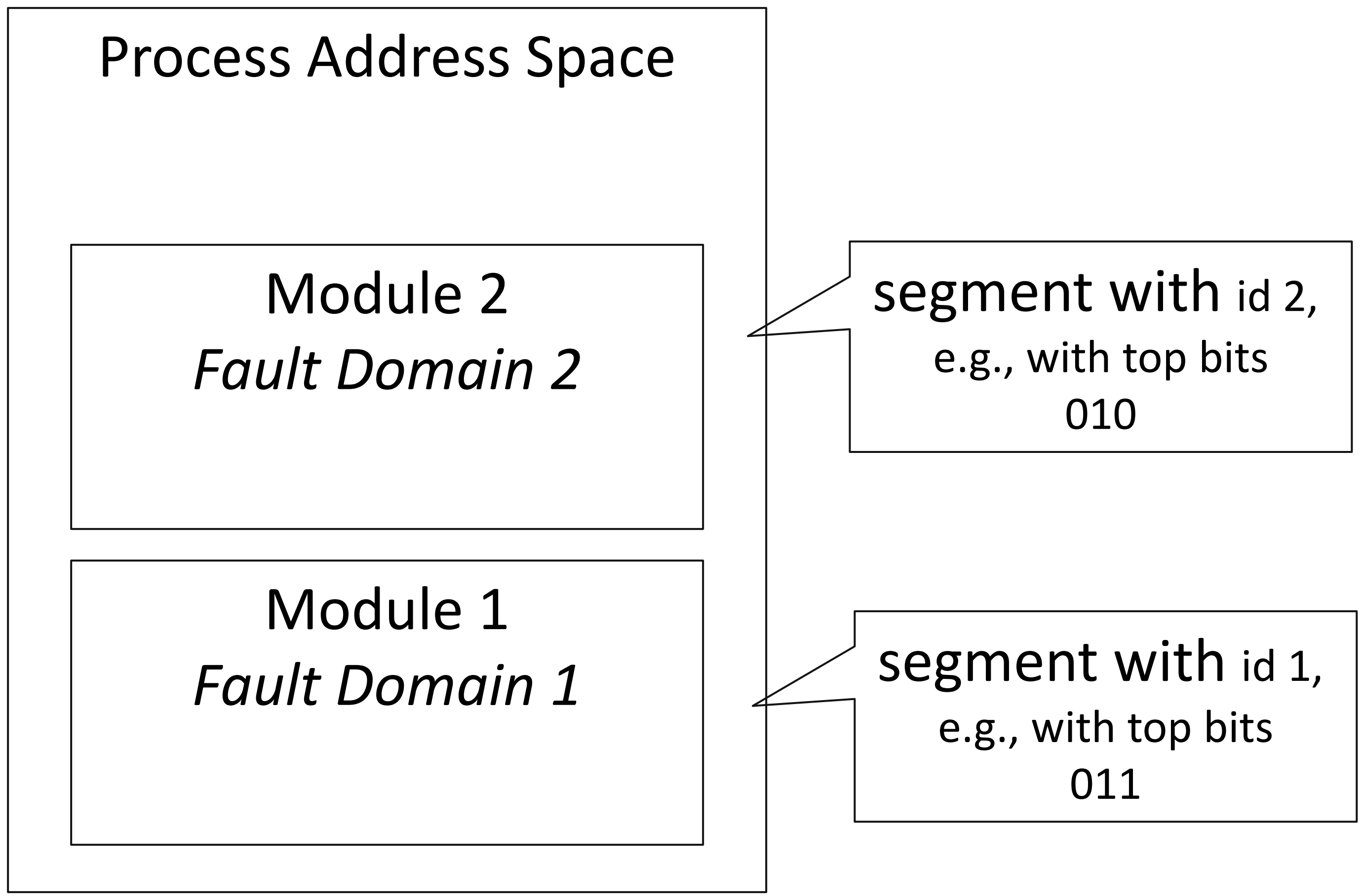
- CFI as a building block can ensure inserted memory checks are executed

SFI Goals

- Confine faults inside distrusted extensions
  - codec shouldn't compromise media player
  - device driver shouldn't compromise kernel
  - plugin shouldn't compromise web browser

- Allow for efficient cross-domain calls
  - numerous calls between media player and codec
  - numerous calls between device driver and kernel

Main Idea


Process Address Space
Module 2
Fault Domain 2
Module 1
Fault Domain 1
segment with id 2, e.g., with top bits 010
segment with id 1, e.g., with top bits 011

SFI Example

```
int compute_sum( int a[], int len )
{
    int sum = 0;
    for(int i = 0; i < len; ++i) {
        sum += a[i];
    }
    return sum;
}
```

```
      ...
      mov  ecx, 0h              ; int i = 0
      mov  esi, [esp+8]         ; a[] base ptr
LOOP: and  esi, 20FFFFFFh       ; SFI masking
      add  eax, [esi+ecx*4]     ; sum += a[i]
      inc  ecx                  ; ++i
      cmp  ecx, edx             ; i < len
      jl   LOOP
```

Optimizing SFI using CFI

```c
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Questions