Control-Flow Integrity (CFI)

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Language-based Security

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Motivation

- Goal: Enforce uncircumventable “control-flow integrity” policy
  - Must prevent untrusted code from “jumping over” guard code
  - Must prevent untrusted code from overwriting guard code
  - Must prevent untrusted code from corrupting security state data
- Two policies to enforce:
  - Control-flow Integrity (constrain jumps)
  - Memory safety (constrain writes)
- Why are these two policies harder to enforce for compiled native code languages than for bytecode-based languages like Java?

Software Fault Isolation

- Enforce control-flow safety and memory safety
- Control-flow policy:
  - All reachable, in-module instructions appear in a static, fall-thru disassembly
  - Inter-module flows target exported function entrypoints
  - No jumps into middle of “chunks”
- Example Implementations:
  - PittSFIeld [McCamant, Morrisett, USENIX Security ’06]
  - Google NaCl [Yee, Sehr, Dardyk, Chen, Muth, Ormandy, Okasaka, Narula, Fullagar, S&P ’09]
  - Reins [Wartell, Mohan, Hamlen, ACSAC ’12]

Main Problem: Computed Jumps

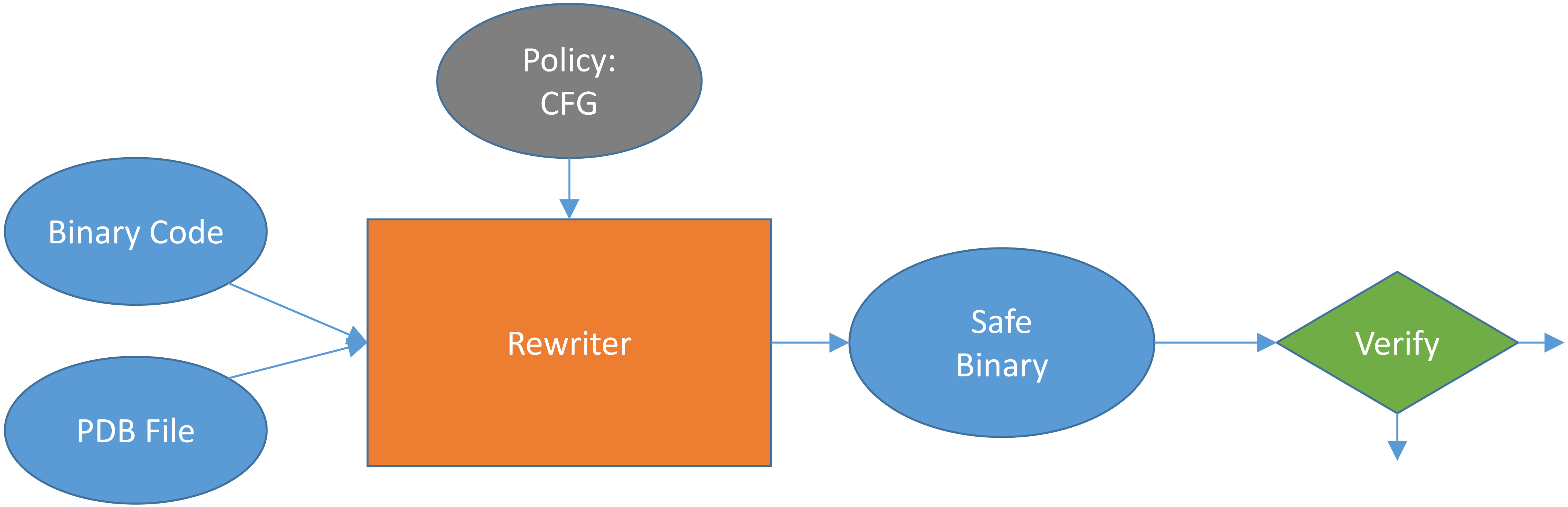
- Many jump instructions compute their destinations at runtime – can potentially go *anywhere!*
- Examples:
  - jmp eax // start executing bytes at the address stored in eax
  - call eax // call a subroutine at address stored in eax
  - ret // load an address off the stack and jump to it
- Defense cannot safely impose guard code before dangerous operations if *any computed jump in the entire program* might jump over the guard code directly to the dangerous operation.

Problem #2: Writable Code, Executable Data

- By default, native code can write to any bytes in the address space – including its own code!
  - Cannot protect dangerous operations if any memory-write in the entire program might replace the guard code.
- By default, native code can jump to any bytes in the address space – including its data segment!
  - Cannot protect dangerous operations in runtime-generated code, since no guard code lives there.
- Hardware solution: Set code pages non-writable (NW) and data pages non-executable (NX)
  - How to prevent untrusted code from unsetting the protection bits?

CFI Workflow

CFI:



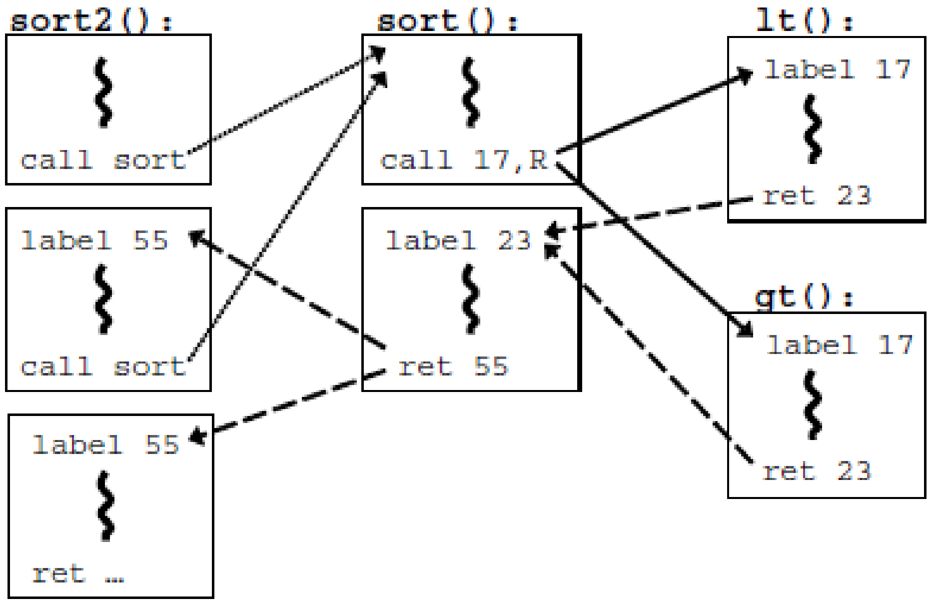
Control-Flow Integrity Policy

- Static Control-Flow Graph (CFG)
  - Derivable from application source code
  - Derivable from debug symbols (PDB file) yielded by Microsoft compilers
    - Avoids disclosure of full source code
    - Limits one to Microsoft-compiled code in practice
    - Requires code-producer cooperation!
- Example:

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



Enforce the CFG

- Label jump targets with unique binary IDs
- Guard jumps with ID-checks

Source / **Destination**

```
Source                                                           Destination
Opcode bytes          Instructions                               Opcode bytes    Instructions
FF E1                 jmp  ecx              ; computed jump      8B 44 24 04     mov  eax, [esp+4]    ; dst
                                                                 ...
```

can be instrumented as (a):

```
81 39 78 56 34 12     cmp  [ecx], 12345678h ; comp ID & dst      78 56 34 12     ; data 12345678h     ; ID
75 13                 jne  error_label      ; if != fail         8B 44 24 04     mov  eax, [esp+4]    ; dst
8D 49 04              lea  ecx, [ecx+4]     ; skip ID at dst     ...
FF E1                 jmp  ecx              ; jump to dst
```

or, alternatively, instrumented as (b):

```
B8 77 56 34 12        mov  eax, 12345677h   ; load ID-1          3E 0F 18 05     prefetchnta          ; label
40                    inc  eax              ; add 1 for ID       78 56 34 12        [12345678h]       ;    ID
39 41 04              cmp  [ecx+4], eax     ; compare w/dst      8B 44 24 04     mov  eax, [esp+4]    ; dst
75 13                 jne  error_label      ; if != fail         ...
FF E1                 jmp  ecx              ; jump to label
```

Requirements/Limitations

- Unique IDs
  - Must be able to find enough unique binary IDs not appearing in code
  - Not usually a problem in practice, but some tricky engineering problems
- Non-writable code
  - Use page-level write-protection
  - Runtime code self-modification not supported
- Non-executable data
  - Use Data Execution Prevention (DEP) NX-bit
  - Just-In-Time (JIT) compilation not supported (rules out many interpreters)

Limits of Static CFG Policies

- Call-return matching policy not expressible as CFG!

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
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sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
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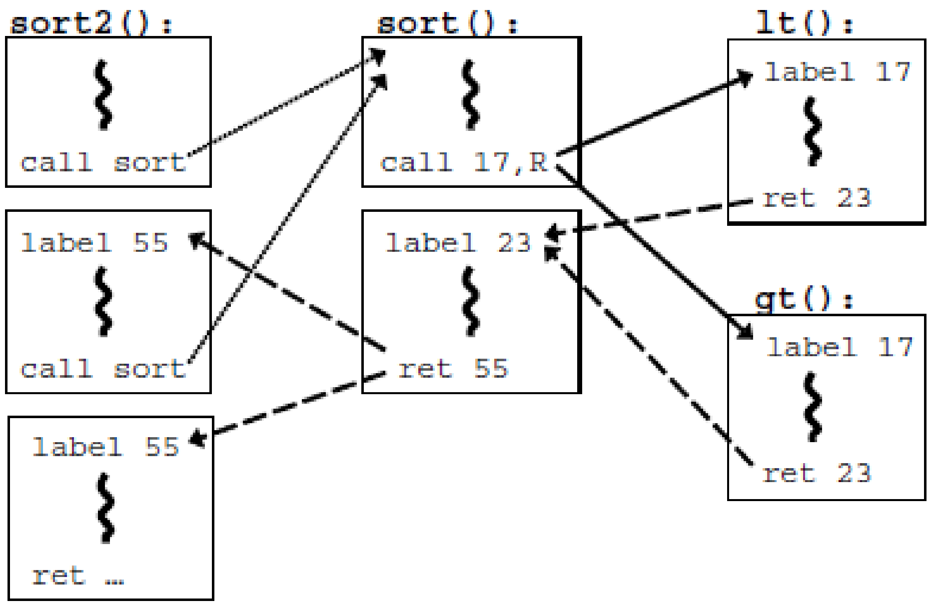


Enforcing Call-Return Matching

- Enforce CFG to get uncircumventable guard code
- Use guard code to implement memory safety (SMAC)
- Use memory safety to implement a protected shadow-stack
    - Copy of the call stack that contains only the return addresses pushed by calls
    - Only protected guard code may write to it
- Reference shadow-stack to enforce call-return matching

Software Memory Access Control (SMAC)

- Goal: Write-protect certain memory regions from subsets of the code
  - Memory region is process-writable (e.g., so guard code can write to it)
  - But prohibit non-guard code from writing to it (e.g., integrity enforcement)
- Enforcement Strategy
  - Mask write-addresses
    - and eax, 0x0000FFFF
    - mov [eax], <data>
  - CFG-policy prevents circumvention of masking instruction
- Now we can implement secure data structures
  - Only writable by guard code

Call-return Matching

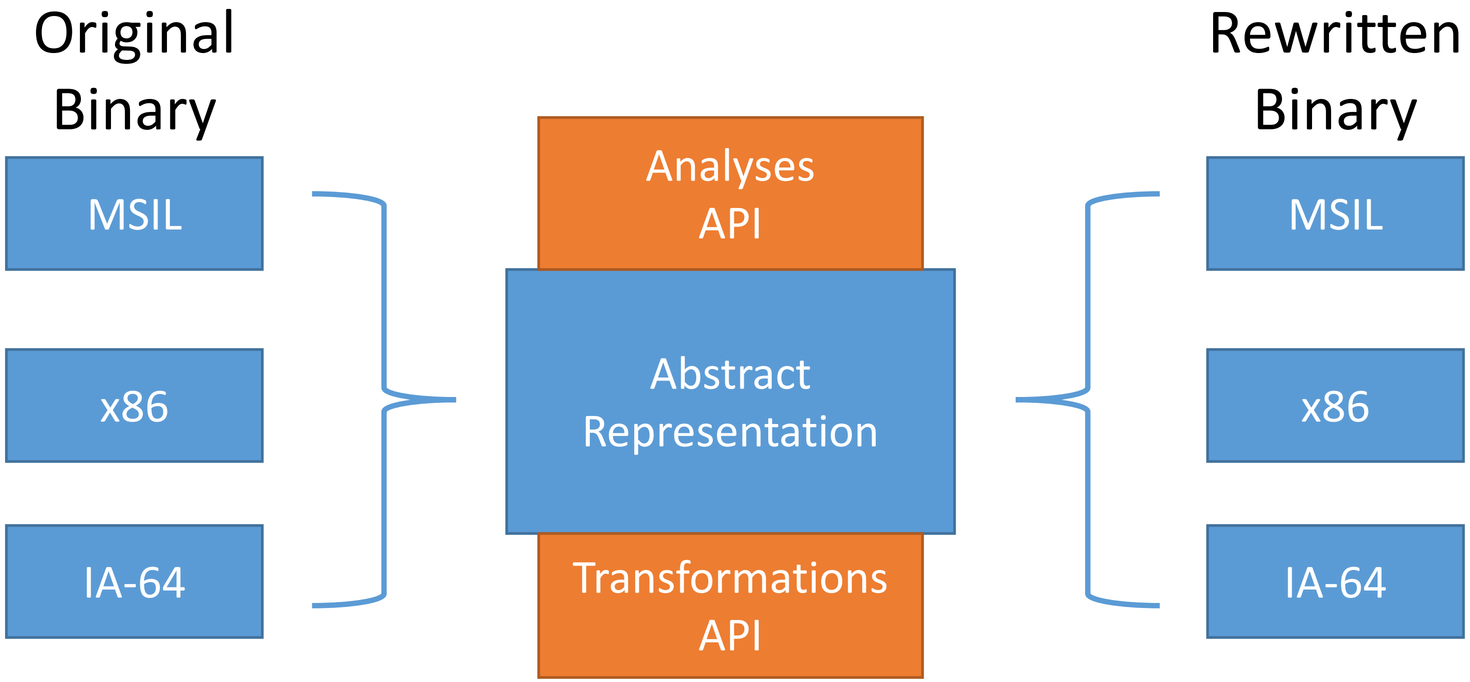
- Secure data structure: Shadow-stack
  - call L1
  - …
  - L1: mov [shadow_stack], [esp]
  - inc shadow_stack_ptr
- Check shadow stack on returns
  - mov [esp], [shadow_stack]
  - dec shadow_stack_ptr
  - ret

Impact

- What happens if attacker exploits a buffer-overflow vulnerability to smash the stack?
- Caveat: Our experience is that most legacy Windows binaries *do not obey call-return matching!*
  - Tail-recursive calls
  - Exception-handling
  - Weird binary optimizations that don’t correspond to any source-level features

Microsoft's Rewriting System

- Microsoft Vulcan
  - Multi-architecture rewriting
  - Requires .pdb file to accurately disassemble and analyze binary



Discussion

- What attacks continue to succeed against CFI?
- What attacks are thwarted?
- What are the challenges for widespread adoption?
- Compelling usage scenarios?