Control-Flow Integrity (CFI)

M. Abadi, M. Budiu, U. Erlingsson, and J. Ligatti

Language-based Security
Dr. Kevin W. Hamlen
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, Dardy, 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

Policy: CFG

Rewriter

Safe Binary

Verify

CFI:

Binary Code

PDB File
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:

```c
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

<table>
<thead>
<tr>
<th>Opcode bytes</th>
<th>Source Instructions</th>
<th>Destinations</th>
<th>Address bytes</th>
<th>Source Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF E1</td>
<td>jmp ecx</td>
<td></td>
<td>8B 44 24 04</td>
<td>mov eax, [esp+4]</td>
</tr>
<tr>
<td></td>
<td>; computed jump</td>
<td></td>
<td></td>
<td>; dst</td>
</tr>
<tr>
<td>81 39 72 56 34 12 cmp [ecx], 12345672h; cmp ID &amp; dst</td>
<td>78 56 34 12</td>
<td>; data 12345672h; ID</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 13         jne error_label ; if != fail</td>
<td>8B 44 24 04</td>
<td>mov eax, [esp+4] ; dst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8D 49 04      lea ecx, [ecx+4] ; skip ID at dst</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FF E1         jmp ecx</td>
<td>; jump to dst</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3 77 56 34 12 mov eax, 12345677h; load ID-1</td>
<td>3E 0F 18 05</td>
<td>prefetchnta ; label</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40            inc eax</td>
<td>; add 1 for ID</td>
<td>78 56 34 12</td>
<td>[12345672h] ; ID</td>
<td></td>
</tr>
<tr>
<td>39 41 04      cmp [ecx+4], eax ; compare w/dst</td>
<td>8B 44 24 04</td>
<td>mov eax, [esp+4] ; dst</td>
<td></td>
<td></td>
</tr>
<tr>
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</table>
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!
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

Original Binary
- MSIL
- x86
- IA-64

Rewritten Binary
- MSIL
- x86
- IA-64

Analyses API
Abstract Representation
Transformations API
Discussion

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