Control Flow Integrity

Outline

• CFI – Control Flow Integrity at Source Code Level
• BinCFI – CFI for Binary Executables
• BinCC – Binary Code Continent
• vfGuard – CFI Policy for Virtual Function Calls
M. Abadi, M. Budiu, U. Erlingsson, J. Ligatti

Control-Flow Integrity:
Principles, Implementations, and Applications

(CCS 2005)

• Main idea: pre-determine control flow graph (CFG) of an application
  • Static analysis of source code
  • Static binary analysis ← CFI
  • Execution profiling
  • Explicit specification of security policy
• Execution must follow the pre-determined control flow graph
CFI: Binary Instrumentation

- Use binary rewriting to instrument code with runtime checks (similar to SFI)
- Inserted checks ensure that the execution always stays within the statically determined CFG
  - Whenever an instruction transfers control, destination must be valid according to the CFG
- Goal: prevent injection of arbitrary code and invalid control transfers (e.g., return-to-libc)
  - Secure even if the attacker has complete control over the thread’s address space

CFG Example

```c
bool lt(int x, int y) {
    return x < y;
}
bool gt(int x, int y) {
    return x > y;
}
int sort2(int a[], int b[], int len) {
    sort(a, len, lt);
    sort(b, len, gt);
}
```
CFI: Control Flow Enforcement

- For each control transfer, determine statically its possible destination(s)
- Insert a **unique bit pattern at every destination**
  - Two destinations are equivalent if CFG contains edges to each from the same source
  - This is imprecise (why?)
  - Use same bit pattern for equivalent destinations
- Insert binary code that at runtime will check whether the bit pattern of the target instruction matches the pattern of possible destinations

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CFI: Example of Instrumentation

**Original code**

<table>
<thead>
<tr>
<th>Opcode bytes</th>
<th>Source Instructions</th>
<th>Destination Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF E1</td>
<td>jmp ecx</td>
<td>mov eax, [esp+4] ; dst</td>
</tr>
</tbody>
</table>

**Instrumented code**

<table>
<thead>
<tr>
<th>Opcode bytes</th>
<th>Source Instructions</th>
<th>Destination Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>88 77 56 54 12</td>
<td>mov eax, 12345678H</td>
<td>cmp [eax], esp+4 ; dst</td>
</tr>
<tr>
<td>48</td>
<td>add eax</td>
<td>test eax, 12345678H ; label</td>
</tr>
<tr>
<td>39 41 04</td>
<td>cmp [eax], esp+4 ; dst</td>
<td>mov eax, [esp+4] ; dst</td>
</tr>
<tr>
<td>76 19</td>
<td>jnz esp+4</td>
<td>jnz esp+10</td>
</tr>
<tr>
<td>FF E1</td>
<td>jmp esp+10</td>
<td>; jump to label</td>
</tr>
</tbody>
</table>

Jump to the destination only if the tag is equal to “12345678”

Abuse an x86 assembly instruction to insert “12345678” tag into the binary
CFI: Preventing Circumvention

- Unique IDs
  - Bit patterns chosen as destination IDs must not appear anywhere else in the code memory except ID checks
- Non-writable code
  - Program should not modify code memory at runtime
    - What about run-time code generation and self-modification?
- Non-executable data
  - Program should not execute data as if it were code
- Enforcement: hardware support + prohibit system calls that change protection state + verification at load-time

Improving CFI Precision

- Suppose a call from A goes to C, and a call from B goes to either C, or D (when can this happen?)
  - CFI will use the same tag for C and D, but this allows an “invalid” call from A to D
  - Possible solution: duplicate code or inline
  - Possible solution: multiple tags
- Function F is called first from A, then from B; what’s a valid destination for its return?
  - CFI will use the same tag for both call sites, but this allows F to return to B after being called from A
  - Solution: shadow call stack
CFI: Security Guarantees

• Effective against attacks based on illegitimate control-flow transfer
  • Stack-based buffer overflow, return-to-libc exploits, pointer subterfuge
• Does not protect against attacks that do not violate the program’s original CFG
  • Incorrect arguments to system calls
  • Substitution of file names
  • Other data-only attacks

Performance Overhead

Figure 4: Execution overhead of inlined CFI enforcement on SPEC2000 benchmarks.
Performance Overhead (2)

Figure 8: Enforcement overhead for CFI with a protected shadow call stack on SPEC2000 benchmarks.

Control-Flow Integrity For COTS Binaries

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Motivation for this work

• Many previous works closely related to CFI
  • CFI [Abadi et al 05, Abadi et al 2009, Zhang et al 2013]
  • Instruction bundling [MaCamant et al 2008, Yee et al 2009]
  • Indexed Hooks [2011], Control-flow locking [Bletsch et al 2011]
  • MoCFI [Davi et al 2012], Reins [Wartell et al 2012]...
• Require compiler support, or binaries that contain relocation, symbol, or debug info
• Do not provide complete protection
  • Binary code, libraries, loader.

Key Challenges

• Disassembly and Static analysis of COTS binaries
• Robust static binary instrumentation
  • Without breaking low-level code
  • Transparency for position-independent code, C++ exceptions, etc.
• Modular instrumentation
  • Applied to executables and libraries
  • Enables sharing libraries across multiple processes
• Assess compatibility/strength tradeoff
Disassembly Errors

- Disassembly of non-code
  - Tolerate these errors by leaving original code in place
- Incorrect disassembly of legitimate code
  - Instruction decoding errors (not a real challenge)
  - Instruction boundary errors
- Failure to disassemble (we avoid this)

Disassembly Algorithm

1. Linear disassembly
2. Error detection
   - invalid opcode
   - direct jump/call outside module address
   - direct control into insn
3. Error correction
   - Identify “gap:” data/padding disassembled as code
     - Scan backward to preceding unconditional jump
     - Scan forward to next direct or indirect target
     - Indirect targets obtained from static analysis
4. Mark “gap,” repeat until no more errors
Static Analysis

Code pointers are needed:
• to correct disassembly errors
• to constrain indirect control flow (ICF) targets

We classify code pointers into categories:
• Code Pointer Constants (CK)
• Computed Code Pointers (CC)
• Exception handlers (EH)
• Exported symbols (ES)
• Return addresses (RA)

Static Analysis

• Code pointer constraints
  • Scan for constants:
    • At any byte offset within code and data segments
    • Fall within the current module
    • Point to a valid instruction boundary

• Computed code pointers
  • Does not support arbitrary arithmetic, but targets jump tables
  • Use static analysis of code within a fixed-size window proceeding indirect jump
Instrumented Module

- Translating function pointers
  - Appear as constants in code, but can’t statically translate
  - Solution: Runtime address translation
- Full transparency: all code pointers, incl. dynamically generated ones, target original code
  - Important for supporting unusual uses of code pointers
    - To compute data addresses (PIC-code, data embedded in code)
    - C++ exception handling

Static Instrumentation for CFI

- Goal: constrain branch targets to those determined by static analysis
  - Direct branches: nothing to be done
  - Indirect branches: check against a table of (statically computed) valid targets
- Key observation
  - CFI enforcement can be combined with address translation
Modularity

**Intra-module** control transfer: MTT

executeble

```
.new_text:
func_entry:
  Text
  jmp retjmp_lkup
  push L_next
  jmp call_lkup
...
```

```
call_lkup ......
data MTT1
retjmp_lkup ......
data MTT2
```

What if the target is out side of the module?

Modularity

**Inter-module** control transfer: GTT

executeble

```
...new_text:
```

```
call_lkup ......
data MTT1
retjmp_lkup ......
data MTT2
```

```
call_lkup_glbl
retjmp_lkup_glbl
```

```
...libfunc:
  ...
  #return
  jmp retjmp_lkup
```

```
libc.so.6
```

```
Global Table
GTT
(initialized by ld.so)
exe
libc
```

```
libc.so.6
```

```
Global Table
GTT
(initialized by ld.so)
exe
libc
```

```
libc.so.6
```

```
call_lkup ......
data MTT1
retjmp_lkup ......
data MTT2
```

update of GTT is done in ld.so
Modularity

Code injection: null GTT entry

GTT only maps code!

Basic version of CFI

- return: target next of call
- call/jmp: target any function whose address is taken
  - Obtainable from relocation info (“reloc-CFI”)
    - matches implementation described in [Abadi et al 2005]

- How to cope with missing relocation info?
  - Use static analysis to over-approximate function addresses taken
- “Strict-CFI”
CFI Real-World Exceptions

- special returns
  - as indirect jumps (lazy binding in ld.so)
  - going to function entries (setcontext(2))
  - not going just after call (C++ exception)
- calls used to get PC address
- jump as a replacement of return

Measuring “Protection Strength”

- Average Indirect target Reduction (AIR)
  - $T$: number of possible targets of $j$th ICF branch
  - $S$: all possible target addresses (size of binary)
  \[
  \frac{1}{n} \sum_{j=1}^{n} \left(1 - \frac{|T_j|}{S}\right)
  \]
- AIR is a general metric that can be applied to other control-flow containment approaches
Coarser versions of CFI

bundle-CFI:
- all ICF targets aligned on 2-byte boundary,
  \( n = 4 \) (PittSField) or 5 (Native Client)

instr-CFI: the most basic CFI
- all ICFs target instruction boundaries

<table>
<thead>
<tr>
<th>Name</th>
<th>Reloc CFI</th>
<th>Strct CFI</th>
<th>Bin CFI</th>
<th>Bundle CFI</th>
<th>Inst CFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>perlbench</td>
<td>98.49%</td>
<td>98.44%</td>
<td>97.89%</td>
<td>95.41%</td>
<td>67.33%</td>
</tr>
<tr>
<td>bzip2</td>
<td>99.55%</td>
<td>99.49%</td>
<td>99.37%</td>
<td>95.65%</td>
<td>78.59%</td>
</tr>
<tr>
<td>gcc</td>
<td>98.73%</td>
<td>98.71%</td>
<td>98.34%</td>
<td>95.86%</td>
<td>80.63%</td>
</tr>
<tr>
<td>gobmk</td>
<td>99.40%</td>
<td>99.40%</td>
<td>99.20%</td>
<td>97.75%</td>
<td>89.08%</td>
</tr>
<tr>
<td>......</td>
<td>......</td>
<td>......</td>
<td>......</td>
<td>......</td>
<td>......</td>
</tr>
<tr>
<td>average</td>
<td>99.13%</td>
<td>99.08%</td>
<td>98.86%</td>
<td>96.04%</td>
<td>79.27%</td>
</tr>
</tbody>
</table>

- Loss due to use of static analysis is negligible
- Loss due to binCFI relaxation is very small
Evaluation

Disassembly testing
Real world program testing
Gadget elimination

Disassembly Testing

<table>
<thead>
<tr>
<th>Module</th>
<th>Package</th>
<th>Size</th>
<th>Instruction#</th>
<th>errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>libxul.so</td>
<td>firefox-5.0</td>
<td>26M</td>
<td>4.3M</td>
<td>0</td>
</tr>
<tr>
<td>gimp-console-2.6</td>
<td>gimp-2.6.5</td>
<td>7.7M</td>
<td>385K</td>
<td>0</td>
</tr>
<tr>
<td>libc.so</td>
<td>glibc-2.13</td>
<td>8.1M</td>
<td>301K</td>
<td>0</td>
</tr>
<tr>
<td>libnss3.so</td>
<td>firefox-5.0</td>
<td>4.1M</td>
<td>235K</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>......</td>
<td></td>
<td>......</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>58M</td>
<td>5.84M</td>
<td>0</td>
</tr>
</tbody>
</table>

“diff” compiler generated assembly and our disassembly
Real world program testing

<table>
<thead>
<tr>
<th>Application Name</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>firefox 5 (no JIT)</td>
<td>open web pages</td>
</tr>
<tr>
<td>acroread9</td>
<td>open 20 pdf files; scroll; print; zoom in/out</td>
</tr>
<tr>
<td>gimp-2.6</td>
<td>load jpg picture, crop, blur, sharpen, etc.</td>
</tr>
<tr>
<td>Wireshark v1.6.2</td>
<td>capture packets on LAN for 20 minutes</td>
</tr>
<tr>
<td>lyx v2.0.0</td>
<td>open a large report; edit; convert to pdf/dvi/ps</td>
</tr>
<tr>
<td>mplayer 4.6.1</td>
<td>play an mp3 file</td>
</tr>
<tr>
<td>......</td>
<td>..........</td>
</tr>
<tr>
<td>Total:</td>
<td>12 real world programs</td>
</tr>
</tbody>
</table>

Gadget Elimination