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

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Control-Flow Integrity:
Principles, Implementations, and Applications

(CCS 2005)

CFI: Control-Flow Integrity

[Abadi et al.]

- 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

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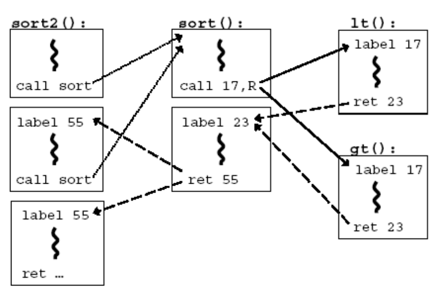
CFG Example

```
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 );
}
```



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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

Source

```
Opcode bytes          Instructions
FF E1                 jmp   ecx                  ; computed jump
```

Destination

```
Opcode bytes          Instructions
8B 44 24 04           mov   eax, [esp+4]         ; dst
```

Instrumented code

```
B8 77 56 34 12        mov   eax, 12345677h       ; load ID-1
40                    inc   eax                  ; add 1 for ID
39 41 04              cmp   [ecx+4], eax         ; compare w/dst
75 13                 jne   error_label          ; if != fail
FF E1                 jmp   ecx                  ; jump to label
```

```
3E 0F 18 05           prefetchnta                ; label
78 56 34 12               [12345678h]            ;     ID
8B 44 24 04           mov   eax, [esp+4]         ; dst
...
```

Jump to the destination only if the tag is equal to "12345678"

Abuse an x86 assembly instruction to insert "12345678" tag into the binary

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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

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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

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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

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Performance Overhead

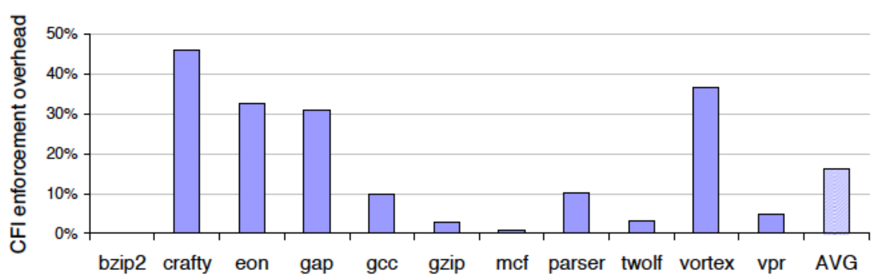

Figure 4: Execution overhead of inlined CFI enforcement on SPEC2000 benchmarks.

Performance Overhead (2)

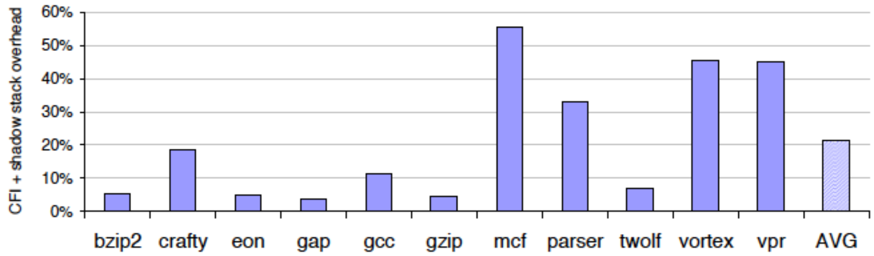

Figure 8: Enforcement overhead for CFI with a protected shadow call stack on SPEC2000 benchmarks.

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

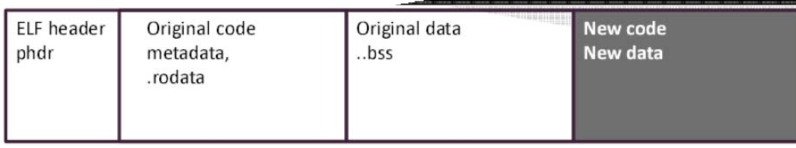
We classify code pointers into categories:

- Code Pointer Constants (CK)
- Computed Code Pointers (CC)
- Exception handlers (EH)
- Exported symbols (ES)
- Return addresses (RA)

Static Analysis

- Code pointer constaints
  - 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



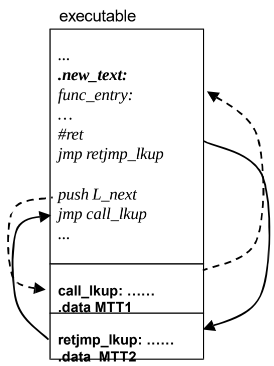
- Translating function pointers
  - Appear as constants in code, but can't statically translate
  - Solution: Runtime address translation
- Full transparency: all code pointers, incl. dynamically generated ones, target original code
  - Important for supporting unusual uses of code pointers
    - To 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

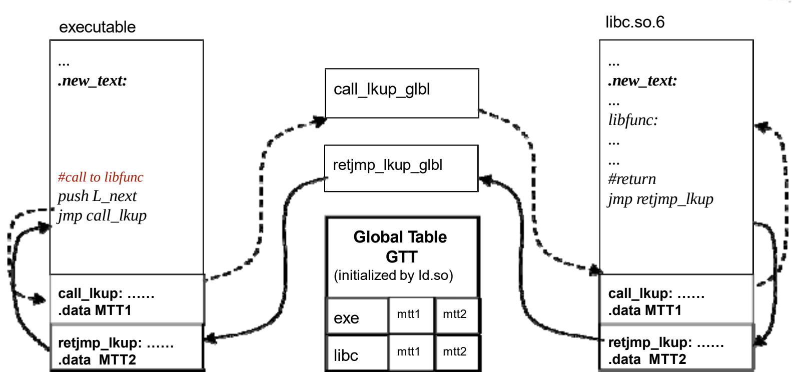
Intra-module control transfer: MTT



What if the target is out side of the module ?

Modularity

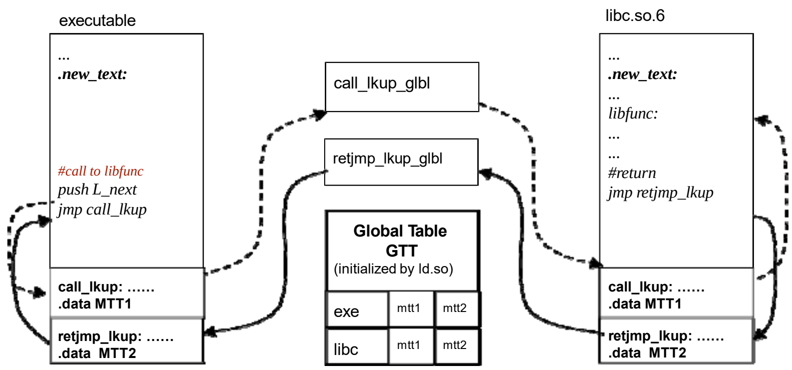
Inter-module control transfer: GTT



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
  - a. *as indirect jumps (lazy binding in ld.so)*
  - b. *going to function entries (setcontext(2))*
  - c. *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)
  - a. *T : number of possible targets of jth ICF branch*
  - b. *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 ICFTs target instruction boundaries**

AIR metric (single module)

Name	Reloc CFI	Strict CFI	**Bin CFI**	Bundle CFI	Instr CFI
perlbench	98.49%	98.44%	**97.89%**	95.41%	67.33%
bzip2	99.55%	99.49%	**99.37%**	95.65%	78.59%
gcc	98.73%	98.71%	**98.34%**	95.86%	80.63%
gobmk	99.40%	99.40%	**99.20%**	97.75%	89.08%
……	……	……	**……**	……	……
average	**99.13%**	**99.08%**	**98.86%**	**96.04%**	**79.27%**

- **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

Module	Package	Size	Instruction#	errors
libxul.so	firefox-5.0	26M	4.3M	0
gimp-console-2.6	gimp-2.6.5	7.7M	385K	0
libc.so	glibc-2.13	8.1M	301K	0
libnss3.so	firefox-5.0	4.1M	235K	0
……	……	……	……	……
Total		58M	5.84M	0

"diff" compiler generated assembly and our disassembly

Real world program testing

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

Gadget Elimination