Control Flow Integrity

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18-732

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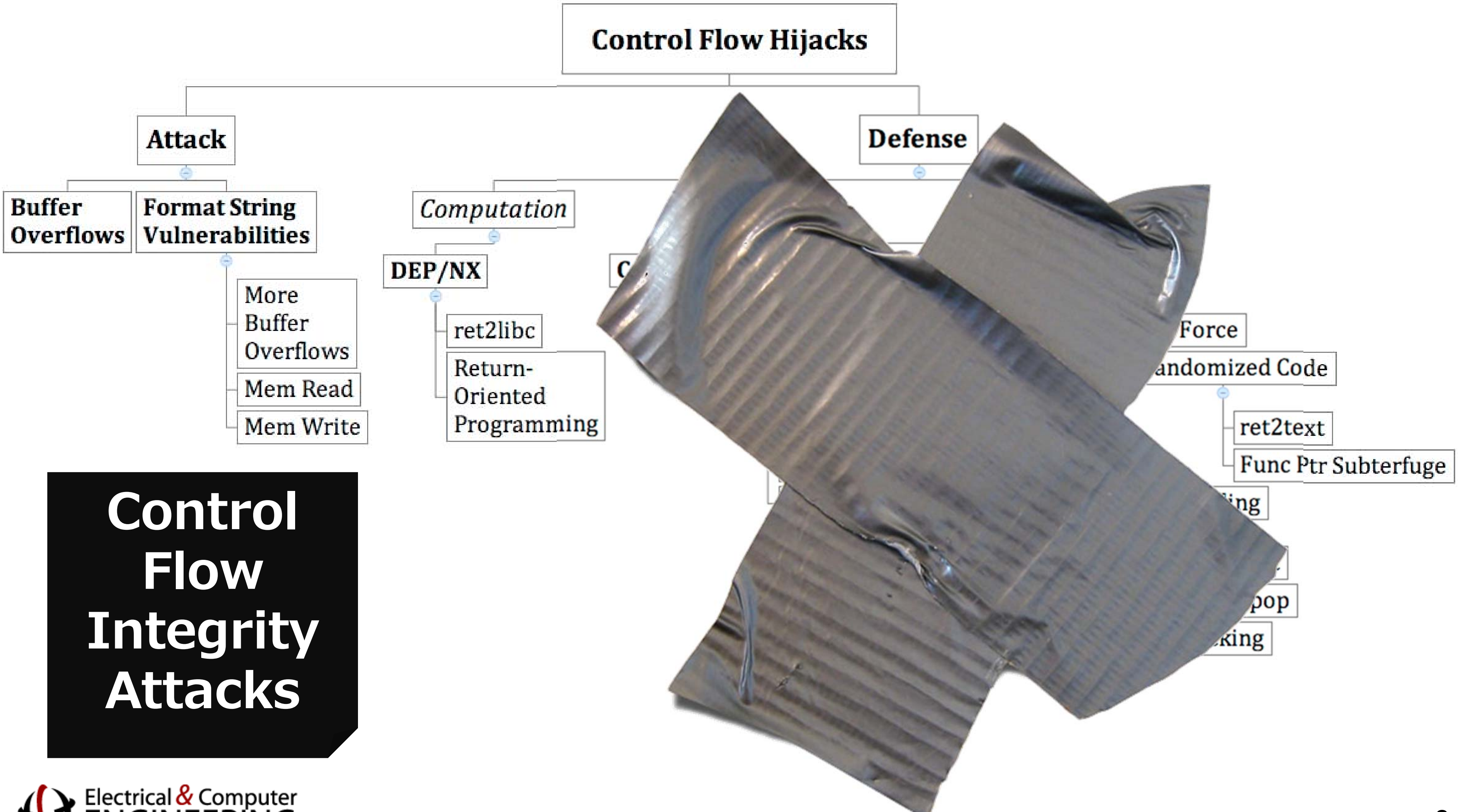
Control Hijacking Arms Race



Control Flow Integrity Attacks

http://propercourse.blogspot.com/2010/05/i-believe-in-duct-tape.html

CFI: Goal

Provably correct mechanisms that prevent **powerful attackers** from succeeding by protecting **against all control flow integrity attacks**

CFI: Idea

During program execution, whenever a machine-code instruction transfers control, it targets a valid destination, as determined by a *Control Flow Graph (CFG) created ahead of time*

Attack Model

Powerful Attacker: Can at any time arbitrarily overwrite any data memory and (most) registers

- Attacker cannot directly modify the PC
- Attacker cannot modify reserved registers

Assumptions:

- **Data memory is Non-Executable**
- **Code memory is Non-Writable**

Lecture Outline

- **CFI: Goal**
- **Background: Control Flow Graph**
- **CFI: Approach**
- **Building on CFI**
  - IRM, SFI, SMAC, Protected Shadow Call Stack
- **Formal Study**

Basic Block

A consecutive sequence of instructions / code such that

- the instruction in each position always executes before (dominates) all those in later positions, and
- no outside instruction can execute between two instructions in the sequence

control is "straight"
(no jump targets except at the beginning,
no jumps except at the end)

1. x = y + z
2. z = t + i

3. x = y + z
4. z = t + i
5. jmp 1

6. jmp 3

1. x = y + z
2. z = t + i
3. x = y + z
4. z = t + i
5. jmp 1

CFG Definition

A static *Control Flow Graph* is a graph where

- each vertex v_i is a basic block, and
- there is an edge (v_i, v_j) if there ***may*** be a transfer of control from block v_i to block v_j

Historically, the scope of a "CFG" is limited to a function or procedure, i.e., intra-procedural

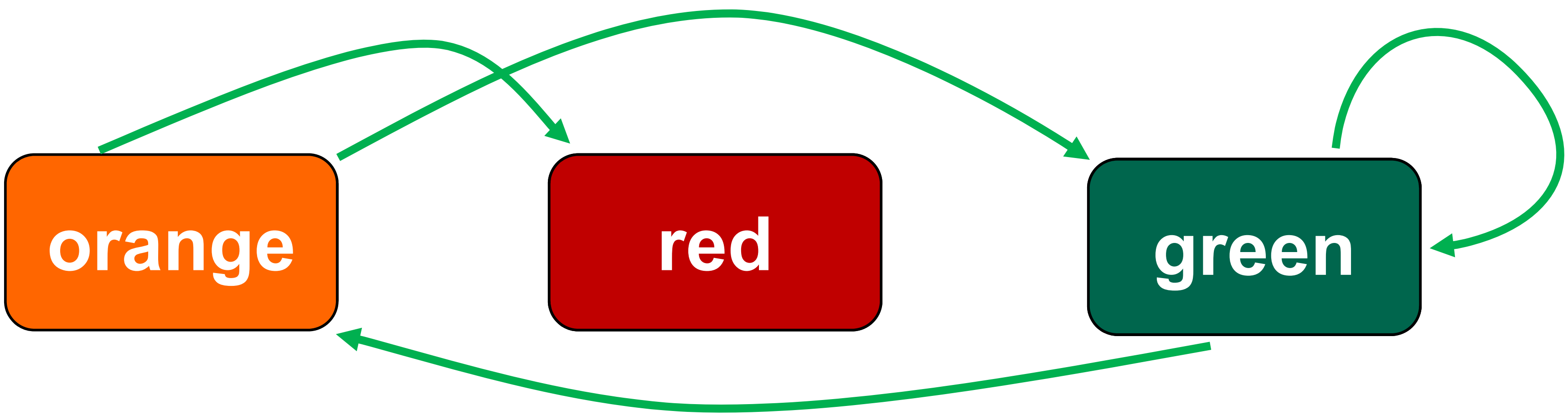
Call Graph

- Nodes are functions
- There is an edge (v_i, v_j) if function v_i calls function v_j

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

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

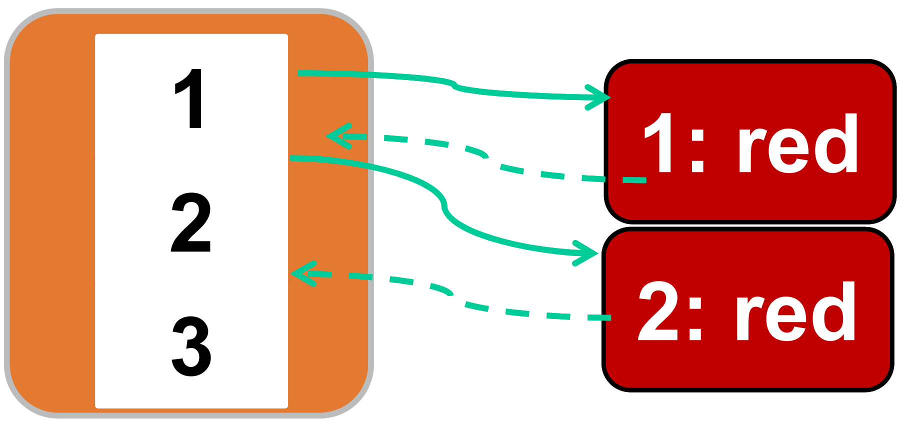
```
void green()
{
  green();
  orange();
}
```



Super Graph

- Superimpose CFGs of all procedures over the call graph

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



A context sensitive super-graph for orange lines 1 and 2

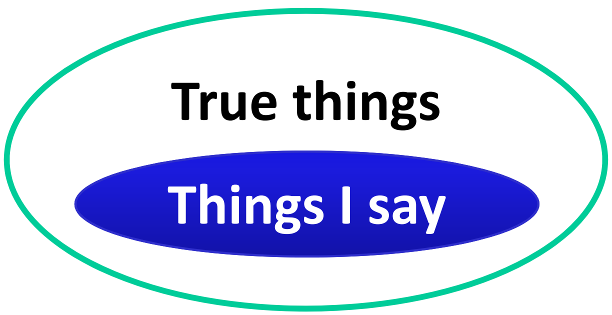
Precision

The more precise the analysis, the more accurately it reflects the "real" program behavior

- Limited by ***soundness/completeness*** tradeoff
- Depends on forms of ***sensitivity*** of analysis

Soundness

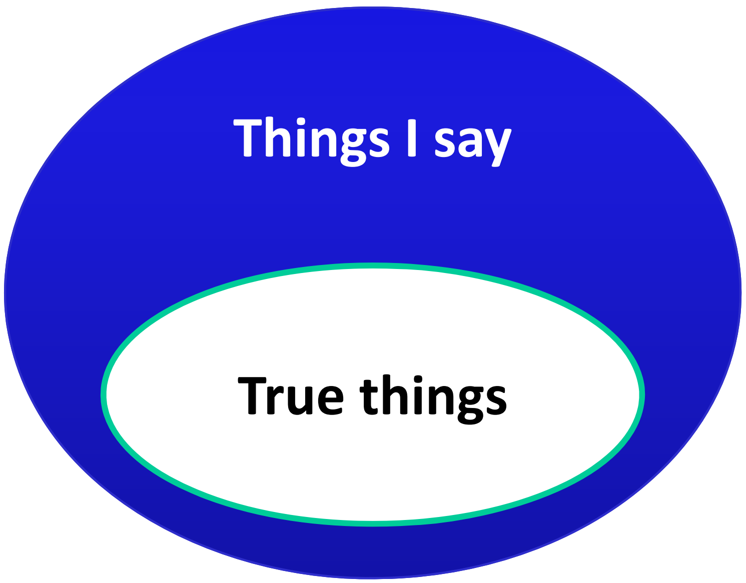
If analysis says X is true, then X is true



Trivially sound: Say nothing

Completeness

If X is true, then analysis says X is true



Trivially complete: Say everything

Sound and Complete: Say exactly the set of true things!

Context Sensitivity

Different calling contexts are distinguished

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

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

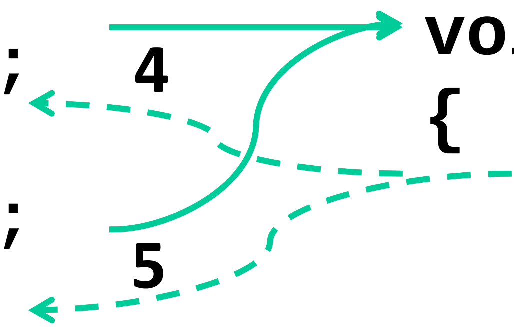
```
void green()
{
  green();
  orange();
}
```

Context sensitive distinguishes 2 different calls to red()

Context Sensitive Example

```
a = id(4);

b = id(5);
```

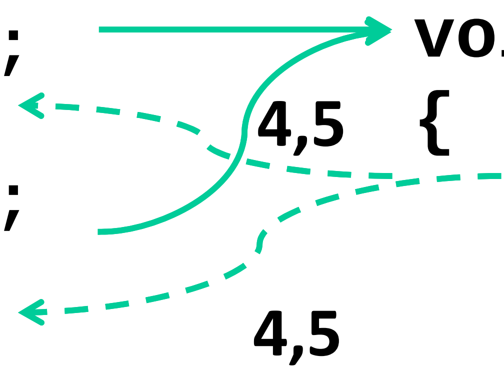



```
void id(int z)
{ return z; }
```

Context-Sensitive

```
a = id(4);

b = id(5);
```




```
void id(int z)
{ return z; }
```

Context-Insensitive (note merging)

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CFI Overview

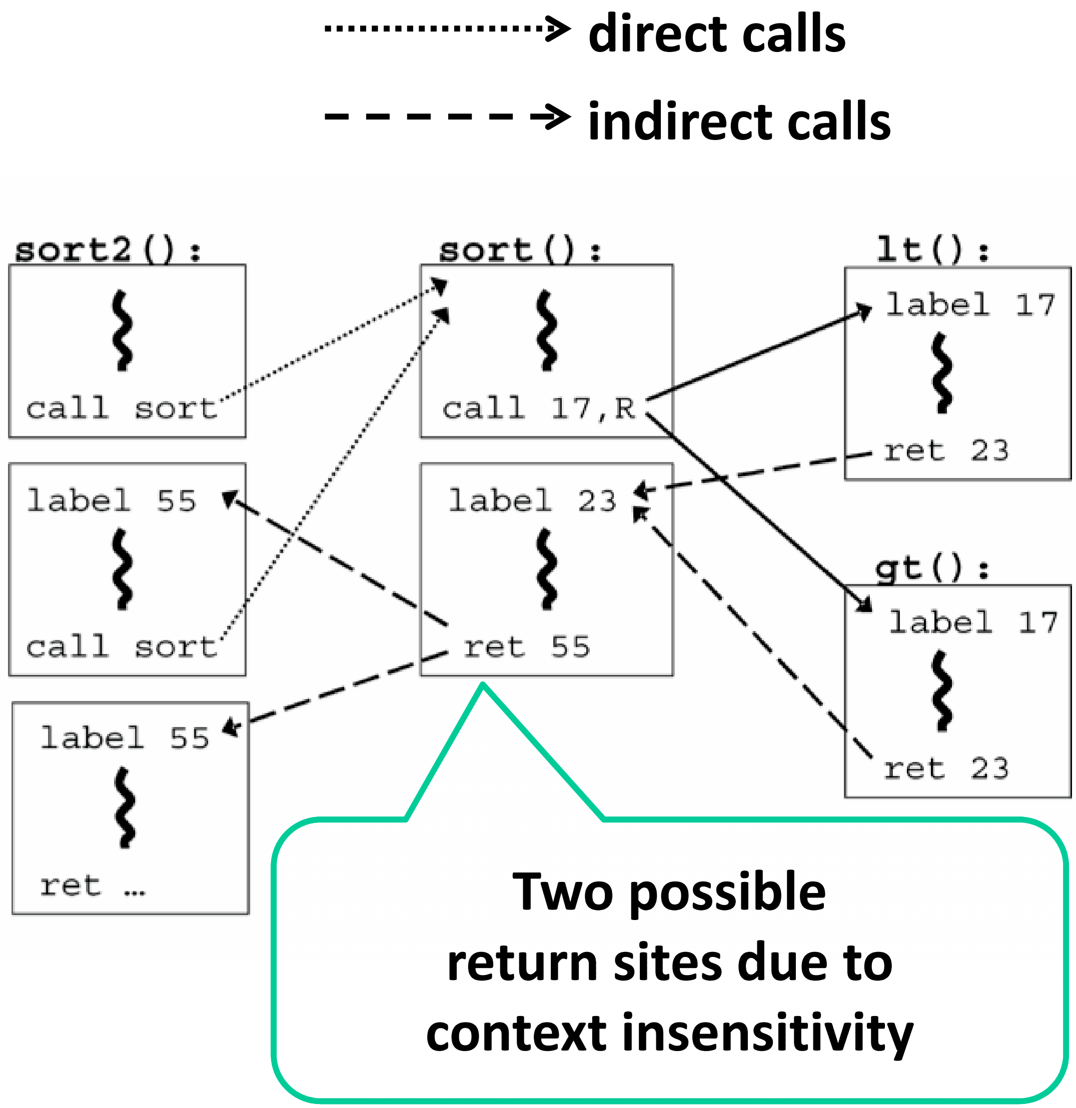
Invariant: Execution must follow a path in a control flow graph (CFG) created ahead of run time

Method:
- **Build CFG statically, e.g., at compile time**
- **Instrument (rewrite) binary, e.g., at install time**
  - Add IDs and ID checks; maintain ID uniqueness
- **Verify CFI instrumentation at load time**
  - Direct jump targets, presence of IDs and ID checks, ID uniqueness
- **Perform ID checks at run time**
  - Indirect jumps have matching IDs

Security Principle: Minimal Trusted Computing Base — Trust simple verifier, not complex rewriter

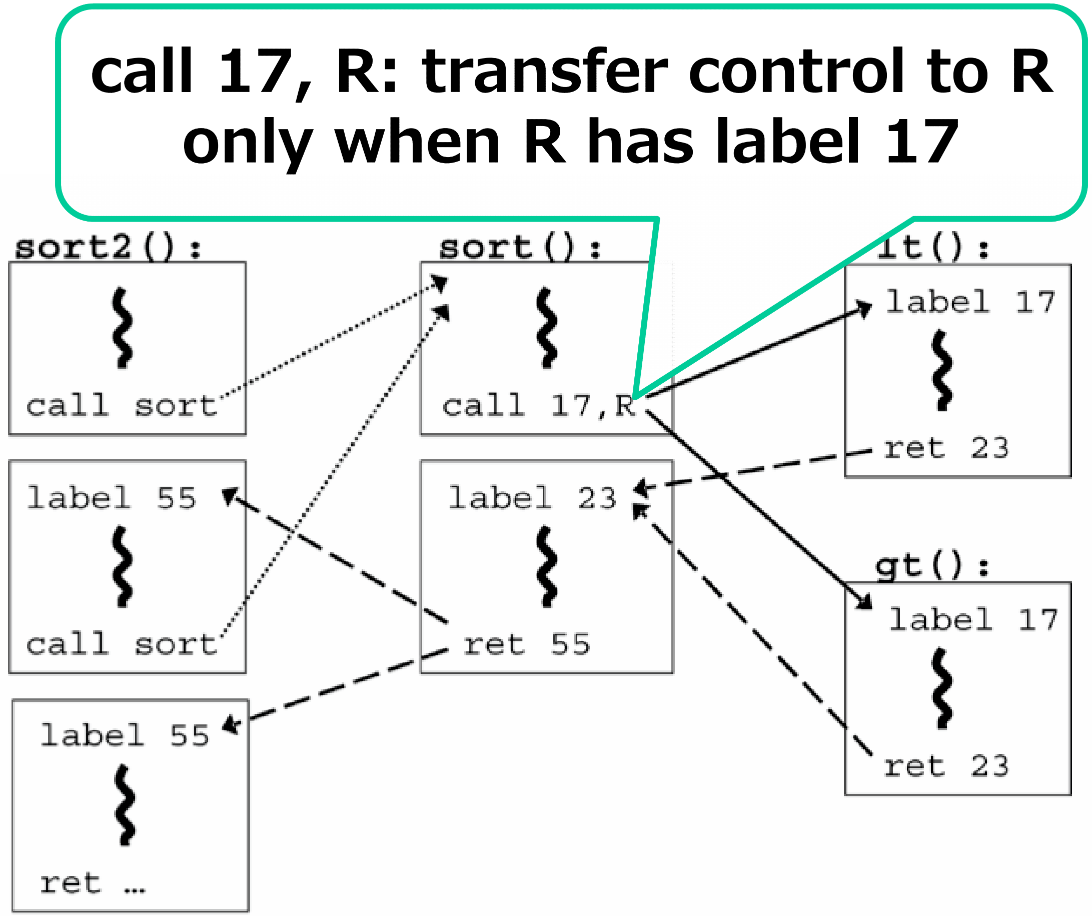
Build CFG

```
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 );
}
```



Instrument Binary

```
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 );
}
```



- Insert a unique number at each destination
- Two destinations are equivalent if CFG contains edges to each from the same source

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

Verify CFI Instrumentation

- **Direct jump targets (e.g., call 0x12345678)**
  - Are all targets valid according to CFG?
- **IDs**
  - Is there an ID right after every entry point?
  - Does any ID appear in the binary by accident?
- **ID checks**
  - Is there a check before every control transfer?
  - Does each check respect the CFG?

Trust simple verifier, not complex rewriter

Revisiting Assumptions

- **UNQ: Unique IDs**
  - Required to preserve CFG semantics
- **NWC: Non-Writable Code**
  - Otherwise attacker can overwrite CFI dynamic check
  - Not true if code dynamically loaded or generated
- **NXD: Non-Executable Data**
  - Otherwise attacker could cause the execution of data labeled with expected ID

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**
  - Data-only attacks
  - Incorrect arguments to system calls
  - Substitution of file names
  - Incorrect logic in implementation

Evaluation

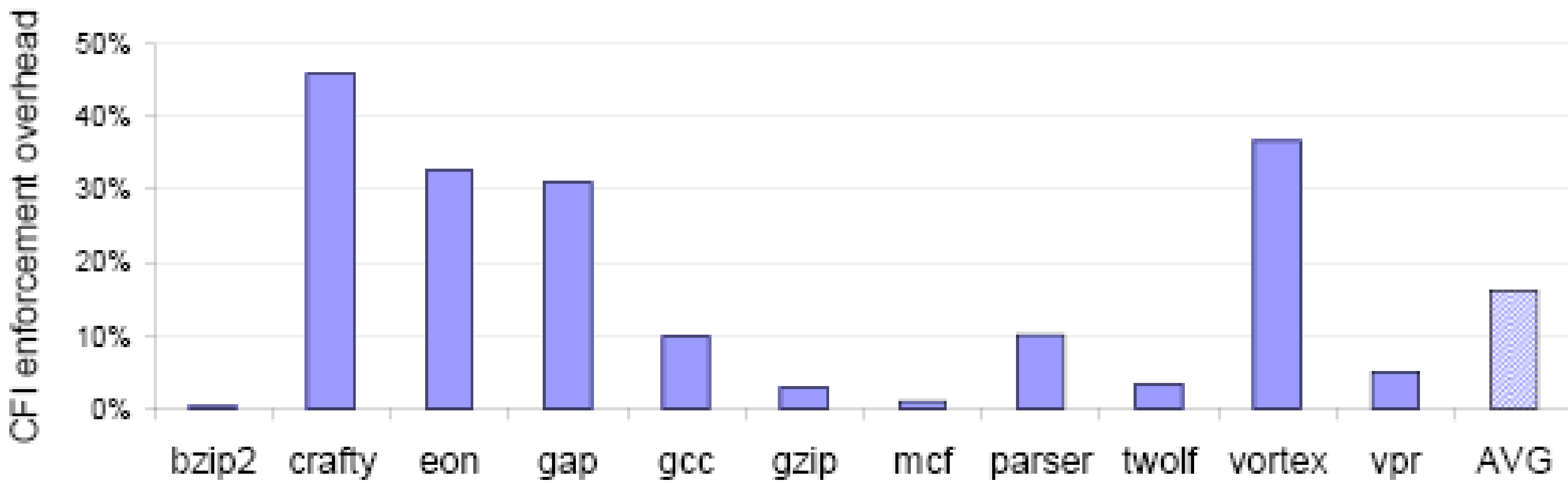


Fig. 6. Execution overhead of inlined CFI enforcement on SPEC2000 benchmarks.

x86 Pentium 4, 1.8 GHz, 512MB RAM; average overhead: 16%; range: 0-45%

Evaluation

- **CFG construction + CFI instrumentation: ~10s**
- **Increase in binary size: ~8%**
- **Relative execution overhead:**
  - crafty: CFI – 45%
  - gcc: CFI < 10%

- **Security-related experiments**
  - CFI protects against various specific attacks (read Section 4.3)

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SFI

- **CFI implies *non-circumventable sandboxing* (i.e., safety checks inserted by instrumentation before instruction X will always be executed before reaching X)**
- **SFI: Dynamic checks to ensure that target memory accesses lie within a certain range**
  - CFI makes these checks non-circumventable

SMAC: Generalized SFI

- **SMAC: Different access checks at different instructions in the program**
  - Isolated data memory regions that are only accessible by specific pieces of program code (e.g., library function)
  - SMAC can remove NX data and NW code assumptions of CFI
  - CFI makes these checks non-circumventable

Example: CFI + SMAC

```
call   eax                    ; call a function pointer (destination address)
```

with CFI, and SMAC discharging the NXD requirement, can become:

```
and   eax, 40FFFFFFh          ; mask to ensure address is in code memory
cmp   [eax+4], 12345678h      ; compare opcodes at destination
jne   error_label             ; if not ID value, then fail
call eax                      ; call function pointer
prefetchnta [AABBCCDDh]       ; label ID, used upon the return
```

- **Non-executable data assumption no longer needed since SMAC ensures target address is pointing to code**

CFI as a Foundation for Non-circumventable IRMs

- **Inlined Reference Monitors (IRM) work correctly assuming:**
  - Inserted dynamic checks cannot be circumvented by changing control flow – enforced using CFI
  - IRM state cannot be modified by attacker – enforced by SMAC

CFI with Context Sensitivity

- **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 1: duplicate code (or even inline everything)
  - Solution 2: use a shadow call stack
    - place stack in SMAC-protected memory region
    - only SMAC instrumentation code at call and return sites modify stack by pushing and popping values
    - Statically verify that instrumentation code is correct

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Security Proof Outline

1. Define machine code semantics
2. Model a powerful attacker
3. Define instrumentation algorithm
4. Prove security theorem

Weakness of Abadi et al. work:
Formal study uses a simple RISC-style assembly language, not the x86 ISA
(cf. McCamant and Morrisett's PittSFIeld 2006)

Machine Model

Execution State:

- **Mc (code memory): maps addresses to words**
- **Md (data memory): maps addresses to words**
- **R (registers): maps register nos. to words**
- **pc (program counter): a word**

Operational Semantics

For each instruction, operational semantics defines how the instruction affects state

Operational Semantics (normal)

- Semantics of *add rd, rs, rt*

$$(M_c|M_d, R, pc) \rightarrow_{\mathrm{n}} (M_c|M_d, R\{r_d \mapsto R(r_s) + R(r_t)\}, pc + 1)$$

when $M_c(pc)$ holds $add\ r_d, r_s, r_t$ and $pc + 1$ is in the domain of M_c

$\rightarrow_{\mathrm{n}}$ **: Binary relation on states that expresses normal execution steps**

Operational Semantics (attacker)

- **Idea: Attacker may arbitrarily modify data memory and most registers at any time**
- **Formally, attacker transition captured by binary relation on states**

$$\rightarrow_a$$

$$(M_c|M_d, R, pc) \rightarrow_a (M_c|M_d', R, pc)$$

Transitions $\rightarrow$ are either normal transitions $\rightarrow_n$ or attacker transitions $\rightarrow_a$

Instrumentation Algorithm

- **I(Mc): Code memory Mc is well-instrumented according to the CFI-criteria**

- **Example:**
  - Every computed jump instruction is preceded by a particular sequence of instructions, which depends on a given CFG

Definition of CFG and instrumentation algorithm in paper

CFI Security Theorem

Let S_0 be a state with code memory M_c such that $I(M_c)$ and $pc = 0$, and let $S_1, \ldots, S_n$ be states such that $S_0 \to S_1 \to \ldots \to S_n$. Then, for all $i \in 0..(n-1)$, either $S_i \to_a S_{i+1}$ or the pc at S_{i+1} is one of the allowed successors for the pc at S_i according to the given CFG.

- **Requires definition of transition relation →, instrumentation algorithm I(Mc), and CFG.**
- **Property holds in the presence of attacker steps**
- **Proof is by induction on execution sequences**

CFI Summary

Small Trusted Computing Base:
Trust simple verifier, not complex rewriter

Method:

- **Build CFG statically, e.g., at compile time**
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Connections to Other Lectures

- **Software analysis methods assume CFG accurately reflects possible executions of program**
  - Software model checking (ASPIER, MOPS)
  - Static analysis (Coverity Prevent)
- **Language-based methods**
  - Type systems guarantee memory and control flow safety for programs written in that language (PCC, TAL)
  - No guarantees if data memory corrupted by another entity or flaw
- **Run-time enforcement methods can be circumvented if CFG not respected**
  - Software-based Fault Isolation (SFI)
  - Inlined Reference Monitors (IRMs)

Sources

- Abadi et al., Control-Flow Integrity: Principles, Implementations, and Applications, TISSEC 2009.
- Some slides from J. Ligatti, D. Brumley, A. Datta.