Memory safety, continued

With material from Mike Hicks, Dave Levin and Michelle Mazurek

http://images.myhardhatstickers.com/img/lg/H/Everybody-Safety-Hard-Hat-Label-HH-0115.gif

Today

- Return Oriented Programming
  - Yet another type of buffer overflow attack
  - Bypasses countermeasures discussed last time
- Control Flow Integrity
  - General countermeasure against buffer overflow attack
  - Can detect if logical flow of program is interrupted
- Other types of overflow attacks

Return oriented programming (ROP)

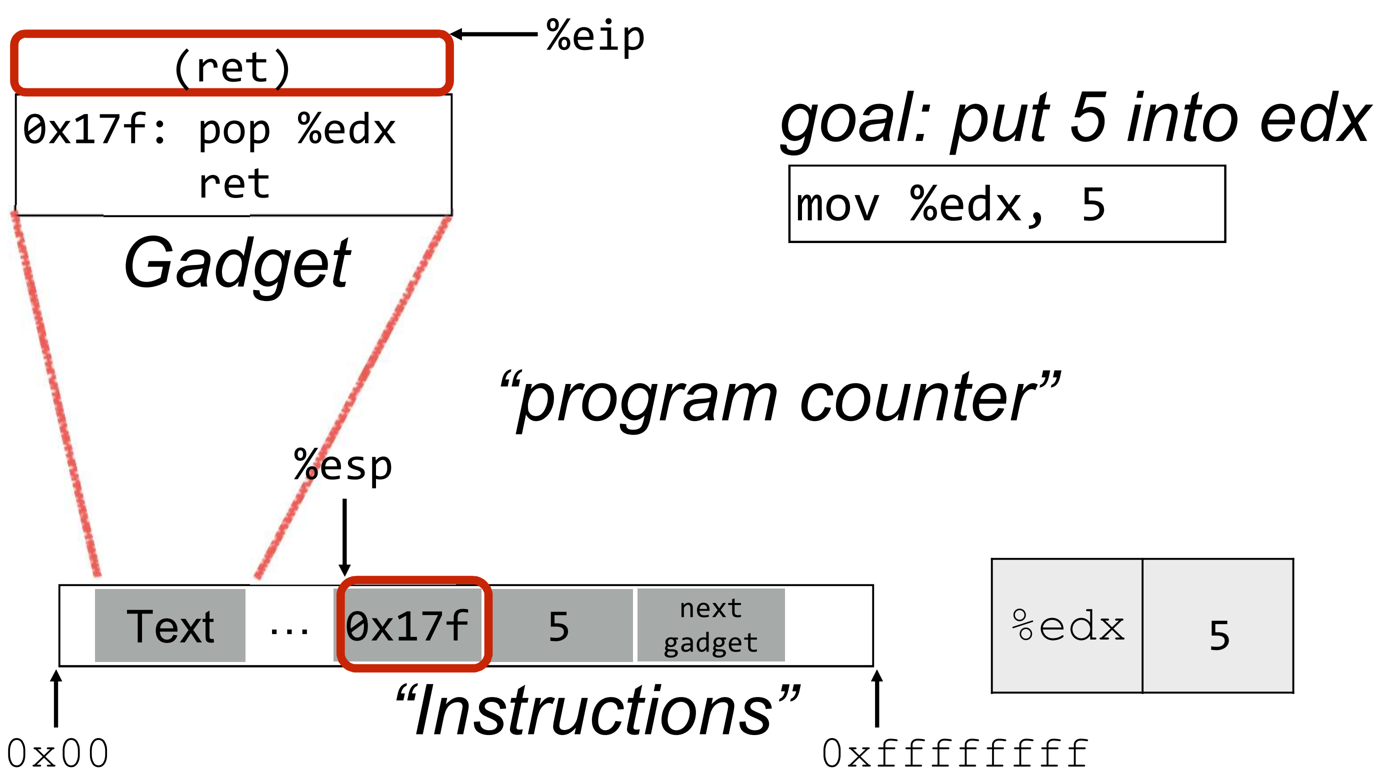
Return-oriented Programming

- Introduced by Hovav Shacham, CCS 2007
- Idea: rather than use a single (libc) function to run your shellcode, **string together pieces of existing code, called *gadgets***, to do it instead
- Challenges
  - **Find the gadgets** you need
  - **String them together**

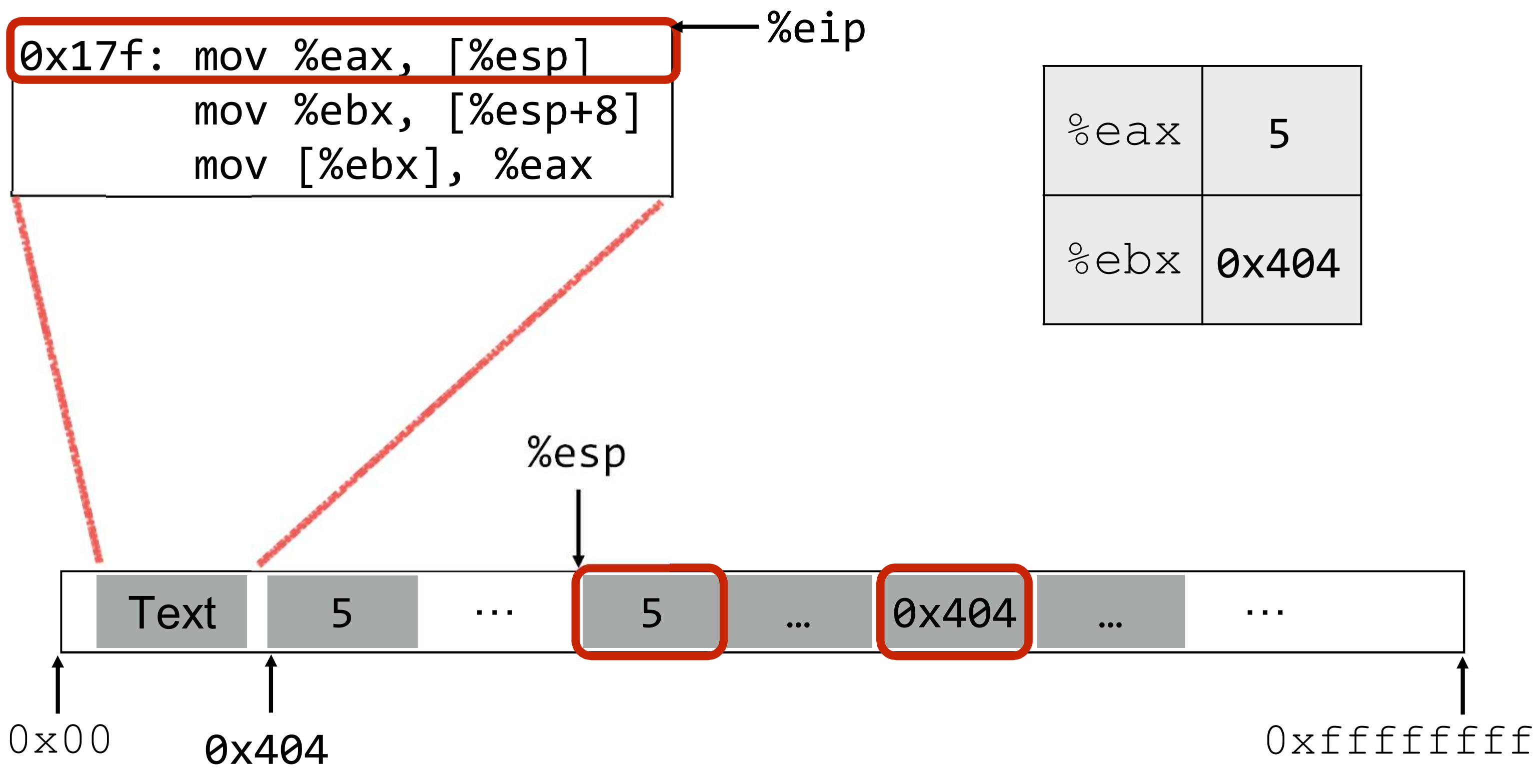
Approach

- Gadgets are instruction groups that end with `ret`
- Stack serves as the code
  - `%esp` = program counter
  - Gadgets invoked via `ret` instruction
  - Gadgets get their arguments via `pop`, etc.
    - Also on the stack

Simple example



Code sequence (no ROP)



Equivalent ROP sequence

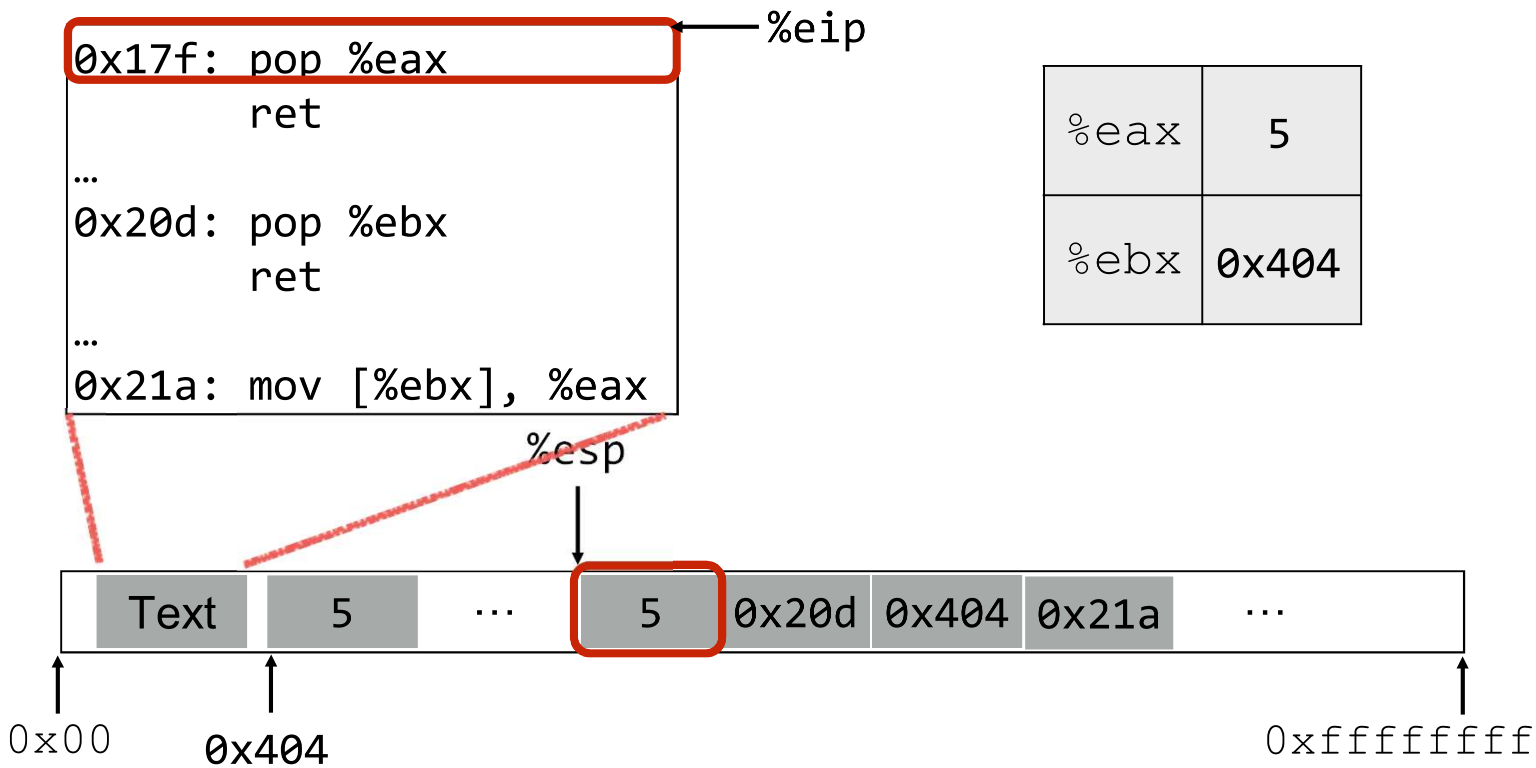


Image by Dino Dai Zovi

Whence the gadgets?

- How can we find gadgets to construct an exploit?
  - Automated search: look for `ret` instructions, work backwards
    - Cf. https://github.com/0vercl0k/rp
- Are there sufficient gadgets to do anything interesting?
  - For significant codebases (e.g., libc), **Turing complete**
    - Especially true on x86’s dense instruction set
  - Schwartz et al. (USENIX Sec’11) automated gadget shellcode creation, Turing complete not required

Control Flow Integrity

Behavior-based detection

- Stack canaries, non-executable data, ASLR make standard attacks harder / more complicated, but may not stop them
- Idea: **observe** the program's **behavior — is it doing what we expect it to?**
  - If not, might be compromised
- Challenges
  - Define "expected behavior"
  - Detect deviations from expectation efficiently
  - Avoid compromise of the detector

Control-flow Integrity (CFI)

- *Define "expected behavior":*

Control flow graph (CFG)

- *Detect deviations from expectation efficiently*

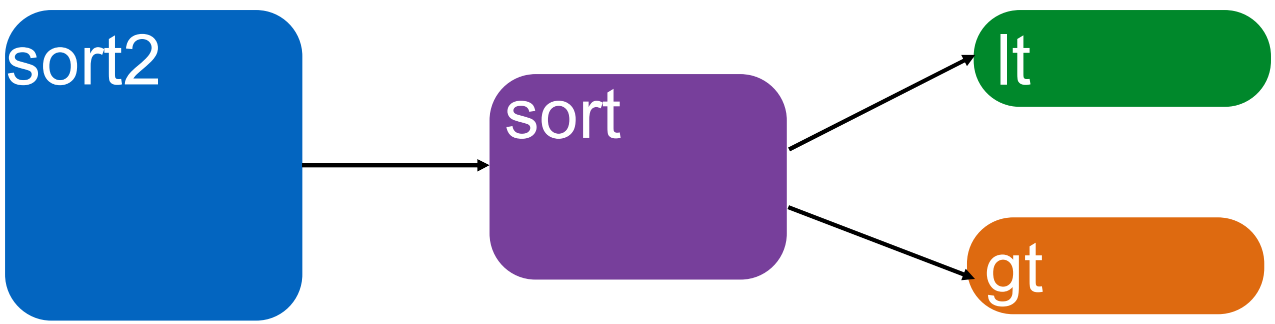
- *Avoid compromise of the detector*

Reference:
http://www.cs.columbia.edu/~suman/secure_sw_devel/p340-abadi.pdf

Call Graph

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

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



Which functions call other functions

Control Flow Graph

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

```
bool lt(int x, int y) {
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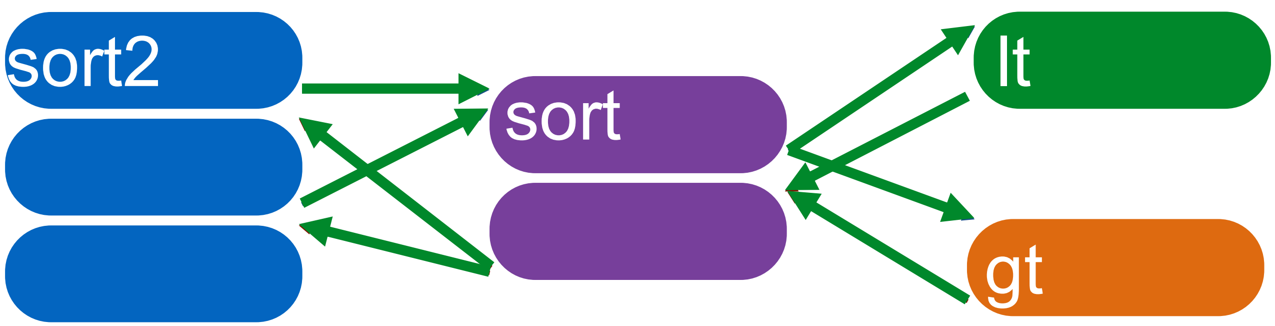

Break into ***basic blocks***

Distinguish ***calls*** *from* ***returns***

CFI: Compliance with CFG

- **Compute the call/return CFG** in advance
  - During compilation, or from the binary
- **Monitor the control flow** of the program and ensure that it only follows paths allowed by the CFG
- Observation: **Direct calls** need not be monitored
  - Assuming the code is immutable, the target address cannot be changed
- Therefore: **monitor only indirect calls**
  - `jmp`, `call`, `ret` with non-constant targets

Control Flow Graph

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sort2(int a[], int b[], int len)
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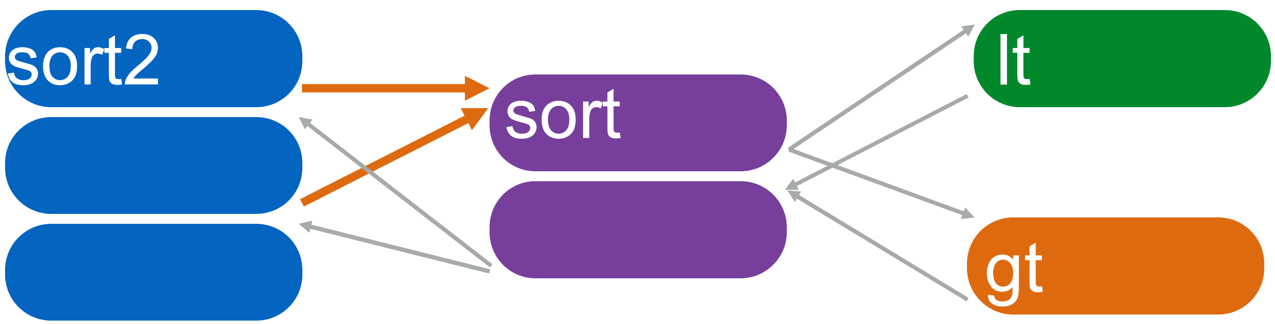

Direct calls *(always the same target)*

Control Flow Graph

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

```
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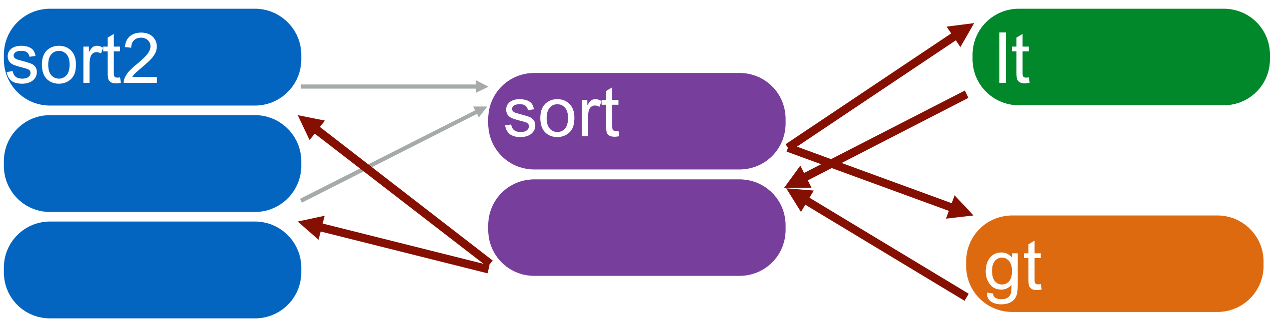


Indirect transfer *(*`call` *via register, or* `ret`*)*

Control-flow Integrity (CFI)

- *Define "expected behavior":*

  Control flow graph (CFG)

- *Detect deviations from expectation efficiently*

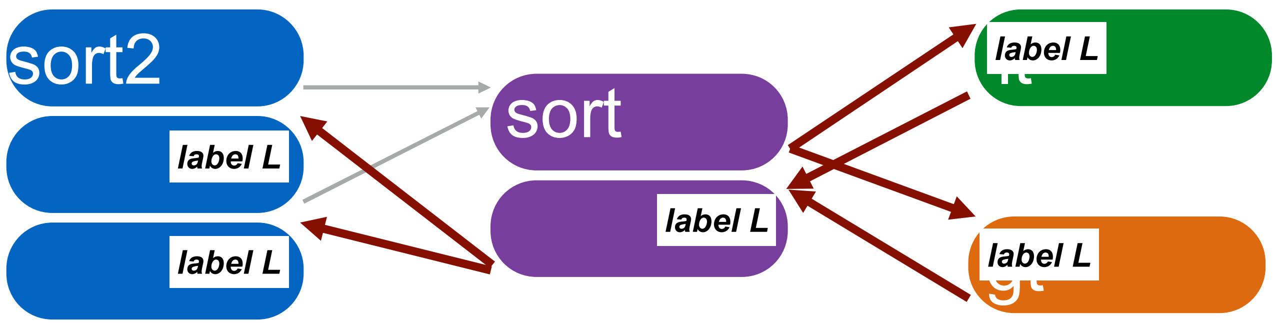
  In-line reference monitor (IRM)

- *Avoid compromise of the detector*

In-line Monitor

- Implement the monitor in-line, as a **program transformation**
- Insert a **label just before the target address** of an indirect transfer
- Insert **code to check the label of the target** at each indirect transfer
  - Abort if the label does not match
- The **labels are determined by the CFG**

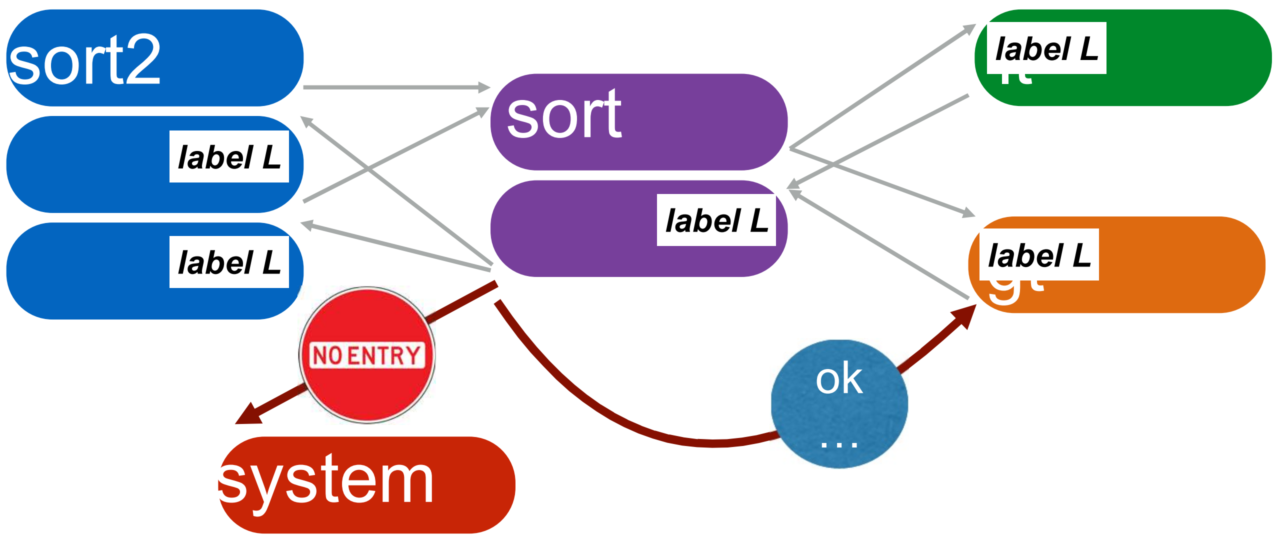
Simplest labeling



Use the same label at all targets: *label just means it's OK to jump here.*

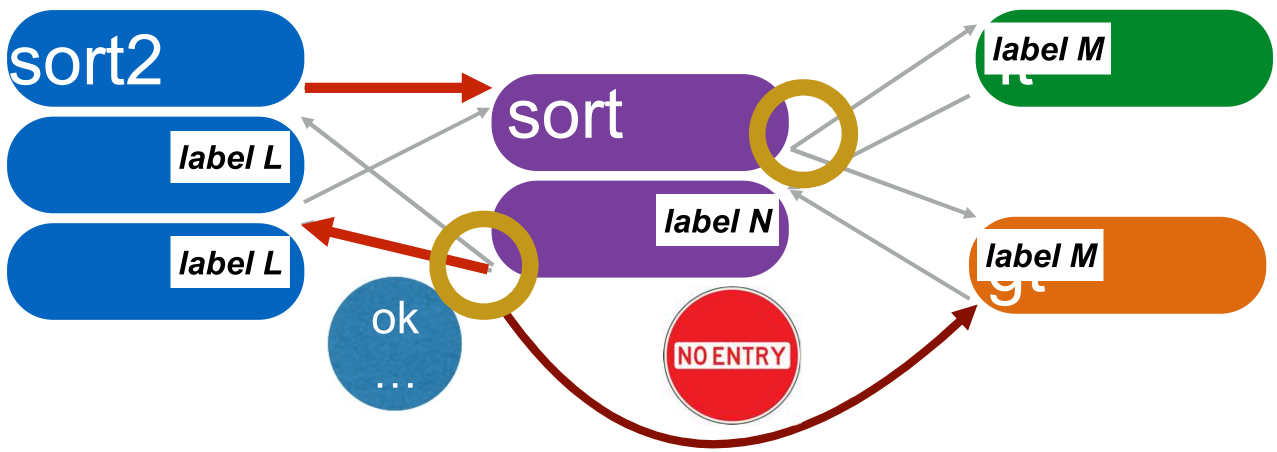
What could go wrong?

Simplest labeling



- Can’t return to functions that aren’t in the graph
- **Can** return to the right function in the wrong order

Detailed labeling



- All potential destinations of **same source** must match
  - Return sites from calls to `sort` must share a label (*L*)
  - Call targets `gt` and `lt` must share a label (*M*)
  - Remaining label unconstrained (*N*)

Prevents more abuse than simple labels,
but still permits call from site A to return to site B

Classic CFI instrumentation

Before CFI

```
FF 53 08                call  [ebx+8]            ; call a function pointer
```

is instrumented using `prefetchnta` destination IDs, to become:

After CFI

```
8B 43 08                mov   eax, [ebx+8]          ; load pointer into register
3E 81 78 04 78 56 34 12 cmp   [eax+4], 12345678h ; compare opcodes at destination
75 13                   jne   error_label           ; if not ID value, then fail
FF D0                   call eax                    ; call function pointer
3E 0F 18 05 DD CC BB AA prefetchnta [AABBCCDDh]  ; label ID, used upon the return
```

Fig. 4. Our CFI implementation of a call through a function pointer.

Bytes (opcodes)	x86 assembly code	Comment
C2 10 00	ret 10h	; return, and pop 16 extra bytes

is instrumented using `prefetchnta` destination IDs, to become:

```
8B 0C 24                mov   ecx, [esp]            ; load address into register
83 C4 14                add   esp, 14h              ; pop 20 bytes off the stack
3E 81 79 04 DD CC BB AA cmp   [ecx+4], AABBCCDDh ; compare opcodes at destination
75 13                   jne   error_label           ; if not ID value, then fail
FF E1                   jmp   ecx                   ; jump to return address
```

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FF 53 08                  call  [ebx+8]            ; call a function pointer
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3E 0F 18 05 DD CC BB AA   prefetchnta [AABBCCDDh]  ; label ID, used upon the return
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```

Efficient?

- **Classic CFI** (2005) imposes **16% overhead** on average, **45%** in the **worst case**
  - Works on arbitrary executables
  - Not modular (no dynamically linked libraries)
- **Modular CFI** (2014) imposes **5% overhead** on average, **12%** in the **worst case**
  - C only
  - Modular, with separate compilation
  - http://www.cse.lehigh.edu/~gtan/projects/upro/

Control-flow Integrity (CFI)

- *Define "expected behavior":*

  Control flow graph (CFG)

- *Detect deviations from expectation efficiently*

  In-line reference monitor (IRM)

- *Avoid compromise of the detector*

  Sufficient randomness, immutability

Can we defeat CFI?

- **Inject code** that has a **legal label**
  - *Won’t work* because we assume **non-executable data**
- **Modify code labels** to allow the desired control flow
  - *Won’t work* because the **code is immutable**
- **Modify stack during a check**, to make it seem to succeed
  - *Won’t work* because **adversary cannot change registers** into which we load relevant data

CFI Assurances

- CFI defeats **control flow-modifying** attacks
  - Remote code injection, ROP/return-to-libc, etc.
- But **not manipulation of control-flow** that is **allowed by the labels**/graph
  - Called **mimicry attacks**
  - The simple, single-label CFG is susceptible to these
- **Nor data leaks or corruptions**
  - Heartbleed would not be prevented
  - Nor the `authenticated` overflow
    - Which is allowed by the graph

```
void func(char *arg1)
{
  int authenticated = 0;
  char buffer[4];
  strcpy(buffer, str);
  if(authenticated) { ...
}
```

Secure?

- MCFI can **eliminate 95.75% of ROP gadgets** on x86-64 versions of SPEC2006 benchmark suite
  - By ruling their use non-compliant with the CFG
- Average Indirect-target Reduction (AIR) **> 99%**
  - Essentially, the percentage of **possible targets of indirect jumps** that CFI rules out