CSE 127: Computer Security

Heap Corruption and CFI

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Slides adopted from Stefan Savage

Now you know about return-to-libc and ROP, what is a reasonable defense strategy?

W^X + ASL not enough?

- Let’s suppose we have shadow/safe stack
  - Are we safe now? A: yes, **B: no**

Attacks via the heap!

Memory management in C/C++

- How do we allocate/deallocate memory?
  - malloc/new
  - free/delete/delete[]
- How do we access memory?
  - through pointers!

Why is this error prone?

- We may:
  - Write/read memory we shouldn't have access to
  - Forget to free memory
  - Free already freed objects
  - Use pointers that point to freed object
- What if the attacker can cause the program to

Heap corruption

- Can bypass security checks (data-only attacks)
  - ➤ .
- Can overwrite function pointers
  - ➤ d
  - ➤

Heap corruption

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  - E.g., isAuthenticated, buffer_size, isAdmin, etc.
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  -
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Heap corruption

- Can bypass security checks (data-only attacks)
  - E.g., isAuthenticated, buffer_size, isAdmin, etc.
- Can overwrite function pointers
  - Direct transfer of control when function is called
  - What's an example? vTables

Heap corruption

- Use after free
  - free(p); p->foo();
  - free(p); q = malloc(n); memcpy(p, buf, k);
- Double free
  - free(p); free(p); q = malloc(n); r = malloc(n);
  - free(p); q = malloc(n); free(p);

vTables

- How do virtual function calls work in C++?
- How is it implemented?
  - E.g., what does bar compile to?
  - *(obj->vtable[0])(obj)

```
class Base {
  public: virtual void foo() {cout << “Hi\n";}
};

class Derived: public Base  {

 public: void foo()  {cout << "Bye\n";}
};

void bar(Base* obj)  { obj->foo(); }

int main(int argc, char* argv[])
{
          Base *b = new Base();
          Derived *d = new Derived();

          bar(b);
          bar(d);
 }
```

vTables

- Each object contains pointer to table
- vtable is array of function pointers
  - one entry per function
- Based on class + func compiler knows which offset to use

```
class Base {
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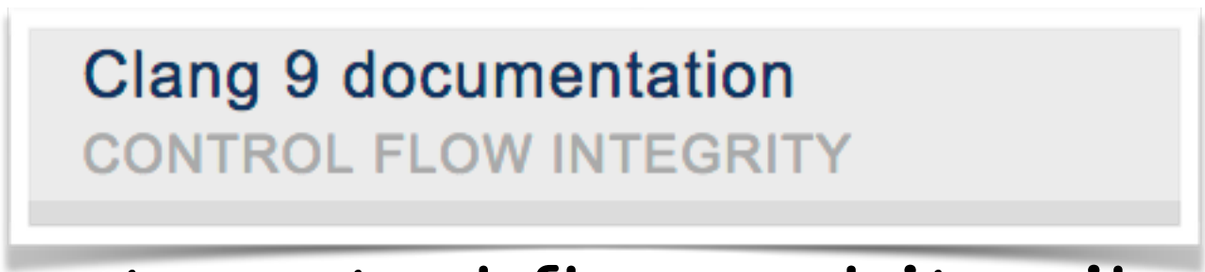
Control Flow Integrity

Clang 9 documentation
CONTROL FLOW INTEGRITY

- **Problem:** we can redirect control flow arbitrarily
- **Idea:** restrict control-flow to legitimate paths
- **Approach:** target

destinations

Control Flow Integrity



- **Problem:** we can redirect control flow arbitrarily
- **Idea:** restrict control-flow to legitimate paths
- **Approach:** [illegible]
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Control Flow Integrity

Clang 9 documentation
CONTROL FLOW INTEGRITY

- **Problem:** we can redirect control flow arbitrarily
- **Idea:** restrict control-flow to legitimate paths
- **Approach:** Match jump, call, return sites to target

destinations

Direct control flow

- Q: do we need to protect direct control flow transfer (i.e., direct jumps/calls)?
  - A: yes, **B: no**
- Q: Why/why not?
  -

Direct control flow

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  - A: yes, **B: no**
- Q: Why/why not?
  - Address is hard-coded in instruction

Indirect control flow transfer

- Jumping to (or calling function at) an address in register or memory
  - What's an example of this?
- Do we need to only worry about where we're jumping to?
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Examples of indirect calls?

- In C: qsort(...fptr...), interrupt handlers
- In C++: virtual functions
- In Wasm: call_indirect

```
void 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;

}
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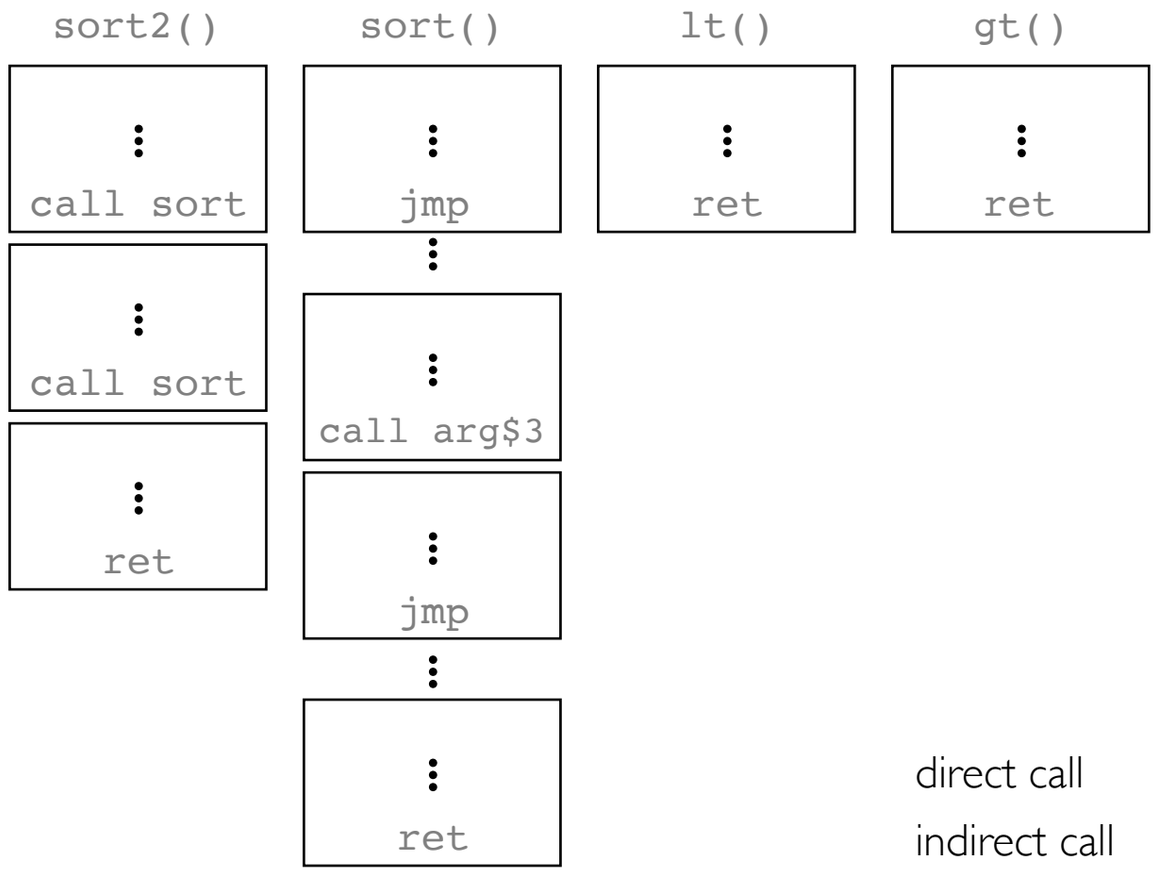

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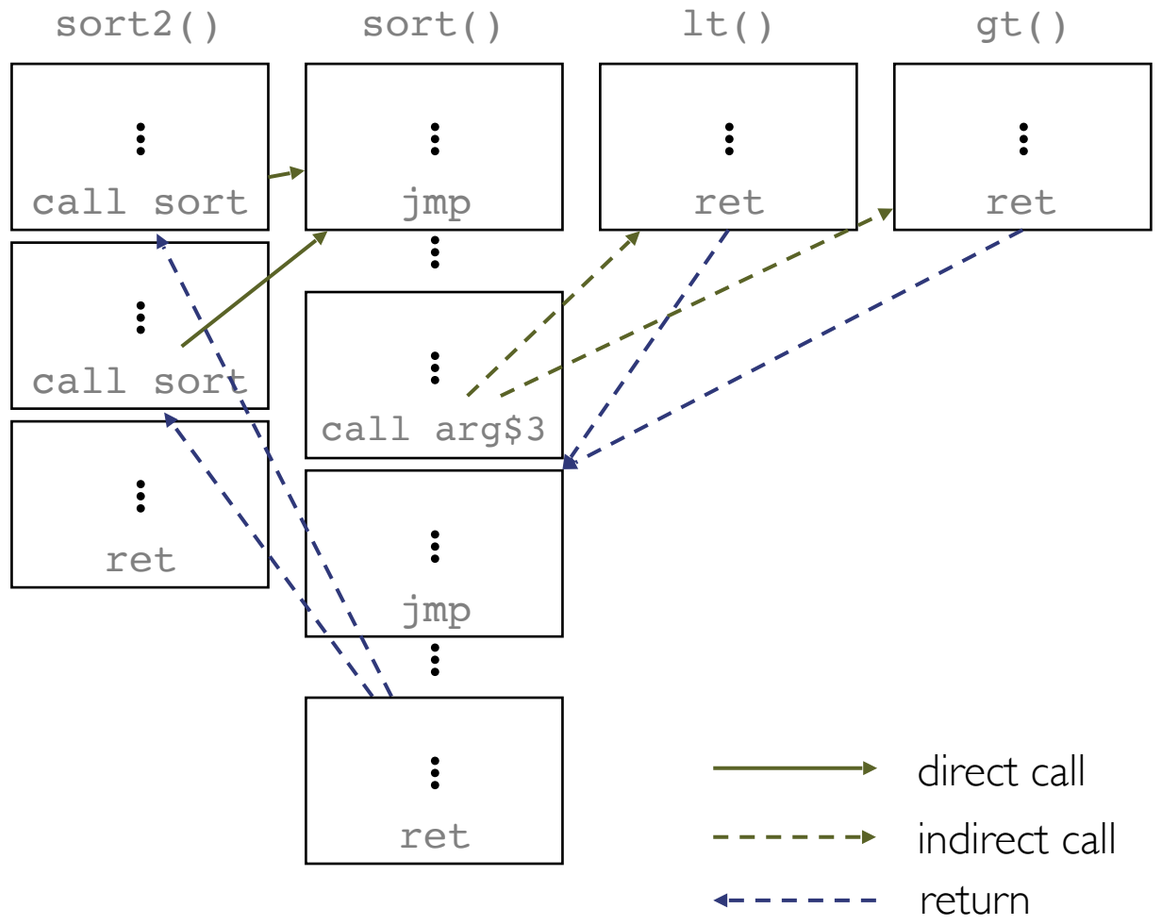

How are we going to match targets?

- Assign labels to all direct jumps and their targets
- After taking an indirect jump:
  - Validate that target label matches jump site
  - Recall stack canaries

Fine grained CFI (Abadi et al.)

- Statically compute control flow graph
- Dynamically ensure program never deviates
  - Assign label to each destination of indirect CF
  - Instrument indirect CT transfers:
    compare label @ dest w/ constant to ensure target is valid

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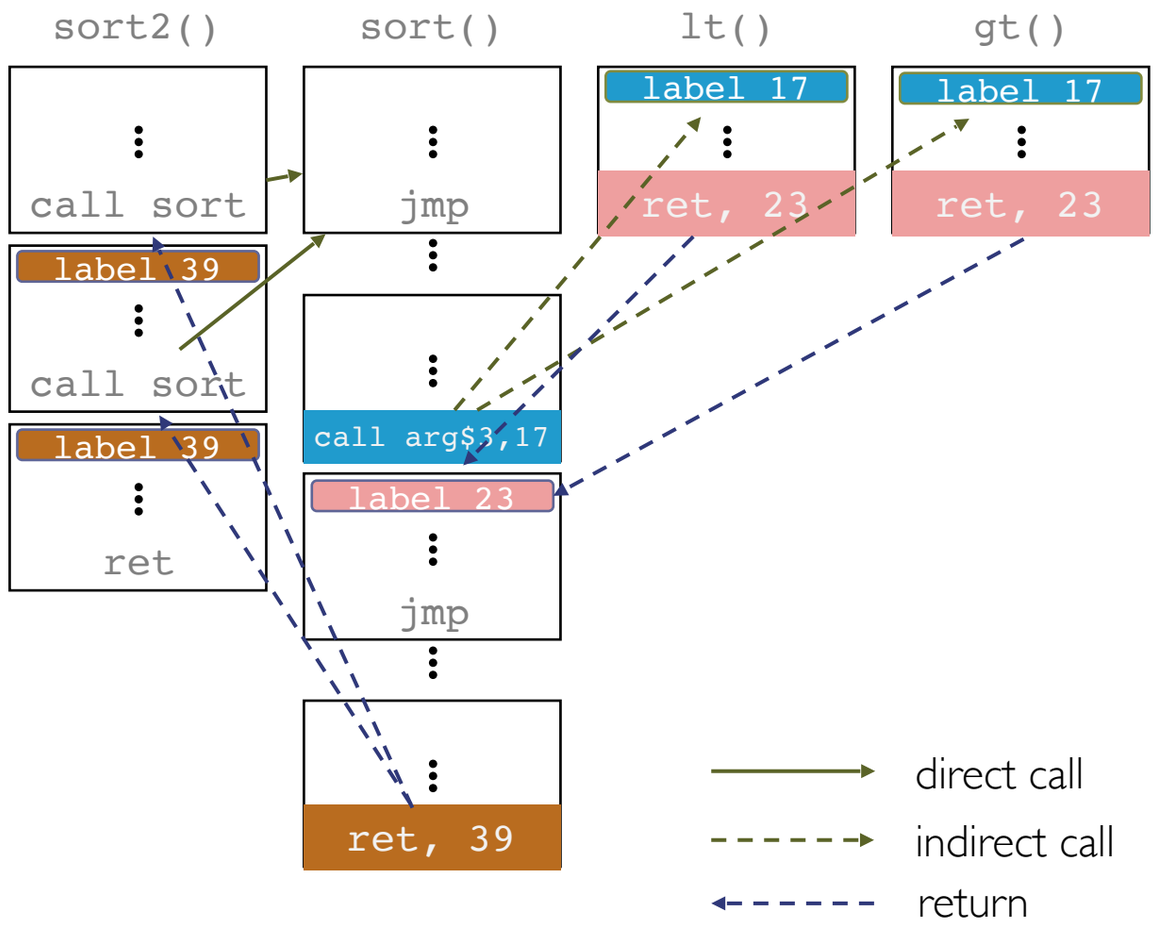

Example of labels

Original code

Source			Destination		
Opcode bytes	Instructions		Opcode bytes	Instructions	
FF E1	jmp ecx	; computed jump	8B 44 24 04	mov eax, [esp+4]	; dst

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Instrumented code

```
B8 77 56 34 12     mov  eax, 12345677h    ; load ID-1          3E 0F 18 05    prefetchnta          ; label
40                 inc  eax               ; add 1 for ID       78 56 34 12       [12345678h]       ;    ID
39 41 04           cmp  [ecx+4], eax      ; compare w/dst      8B 44 24 04    mov  eax, [esp+4]    ; dst
75 13              jne  error_label       ; if != fail         ...
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Abuse an x86 assembly instruction to insert “12345678” tag into the binary

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```
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

Coarse-grained CFI (bin-CFI)

- Label for destination of indirect calls
  - Make sure that every call lands @ function entry
- Label for destination of return and indirect jumps
  - Make sure every indirect jump lands at start of BB

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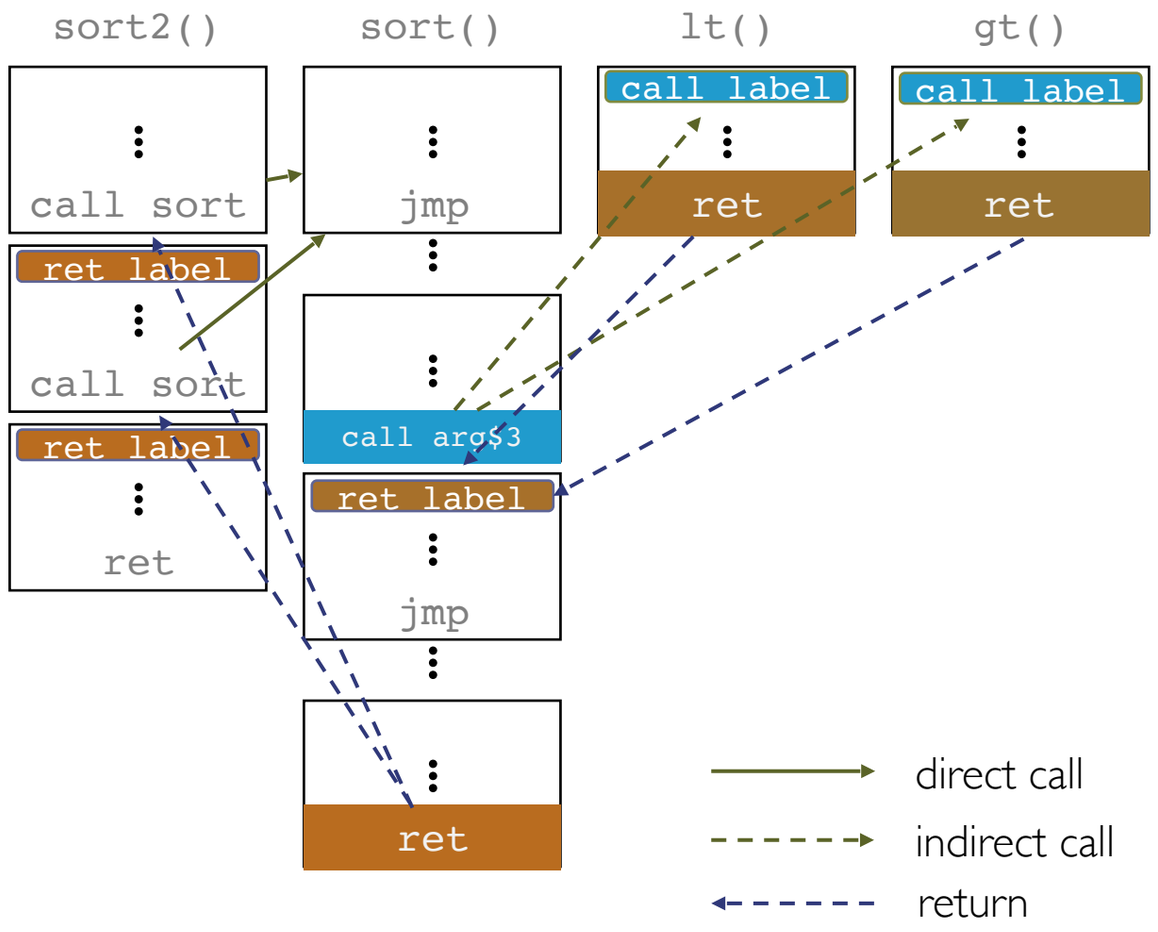

Why not just do fine-grained CFI?

How else can you choose labels?

$$\frac{tf = t_1^* \to t_2^* \qquad C_{\mathsf{table}} = n}{C \vdash \textbf{call\_indirect}\ tf : t_1^*\ \mathsf{i32} \to t_2^*}$$

$$\begin{array}{lcll} s; (\textbf{i32.const}\ j)\ \textbf{call\_indirect}\ tf & \hookrightarrow_i & \textbf{call}\ s_{\mathsf{tab}}(i,j) & \text{if } s_{\mathsf{tab}}(i,j)_{\mathsf{code}} = (\textbf{func}\ tf\ \textbf{local}\ t^*\ e^*) \\ s; (\textbf{i32.const}\ j)\ \textbf{call\_indirect}\ tf & \hookrightarrow_i & \textbf{trap} & \text{otherwise} \end{array}$$

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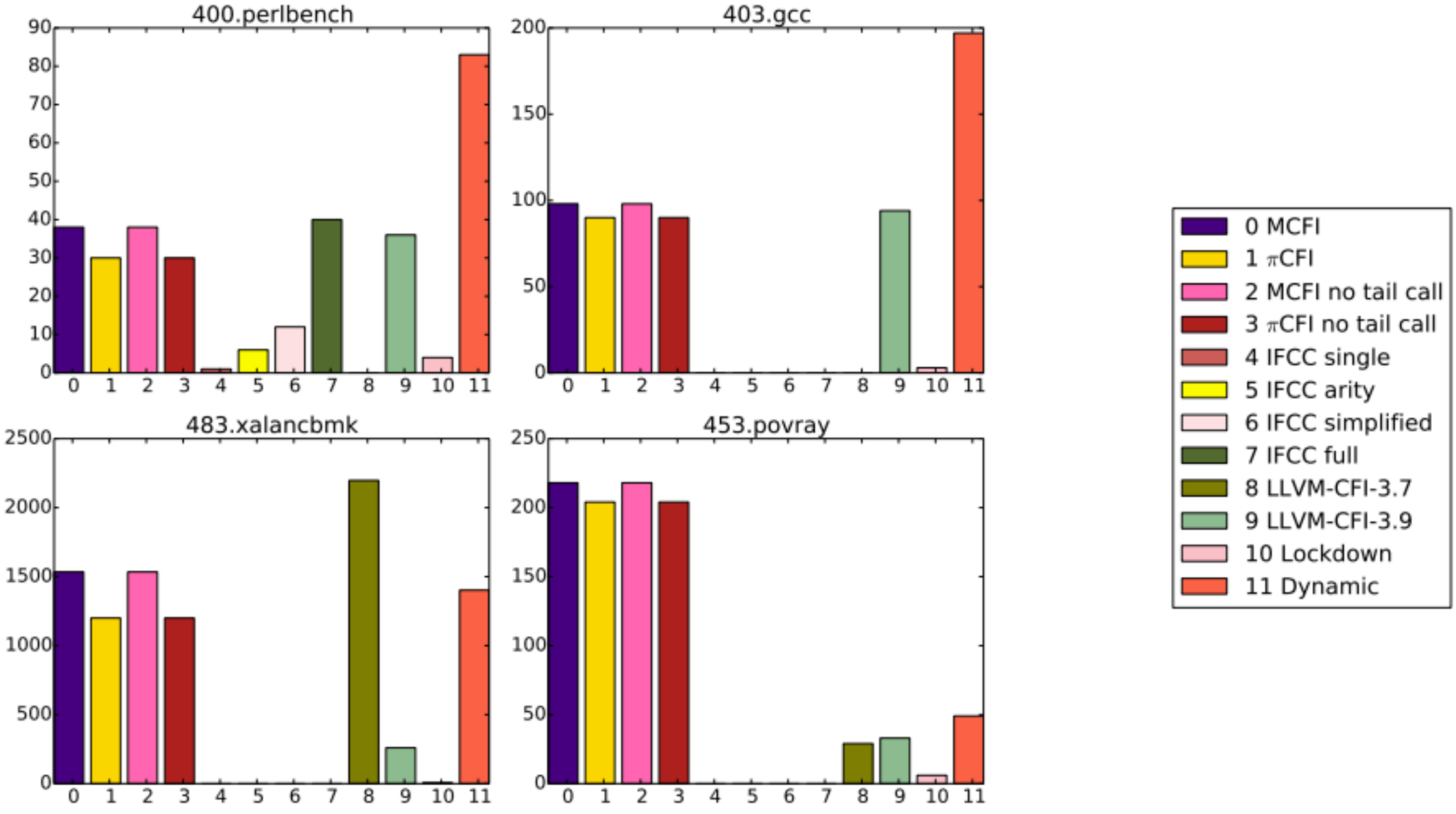

Fig. 4: Total number of forward-edge equivalence classes when running SPEC CPU2006 (higher is better).

Burrow et al.

What's the problem w/ equivalent classes?

What's the problem w/ equivalent classes?

```
int system(const char *command);
```

```
int myFunFunction(const char *command);
```

Limitations

- Precision tradeoff can lead to adverse effects
  - Can create gadgets if you don't bind flow for all indirect control transfers
  - Lot of gadgets on return path w/o shadow stack
    - One way to see this: safely generating labels at run time (this way only return to the function that called)

Limitations

- Overhead
  -
  -
- Scope
  -
  -
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  - Runtime: every indirect branch instruction
  - Size: code before branch + label @ dst
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- Overhead
  - Runtime: every indirect branch instruction
  - Size: code before branch + label @ dst
- Scope
  - Data is not protected!
  - CFI does not protect against data-only attacks
  - Needs reliable W^X/DEP

Control-Flow Integrity: Precision, Security, and Performance

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