CE 874 - Secure Software Systems

Control Flow Integrity

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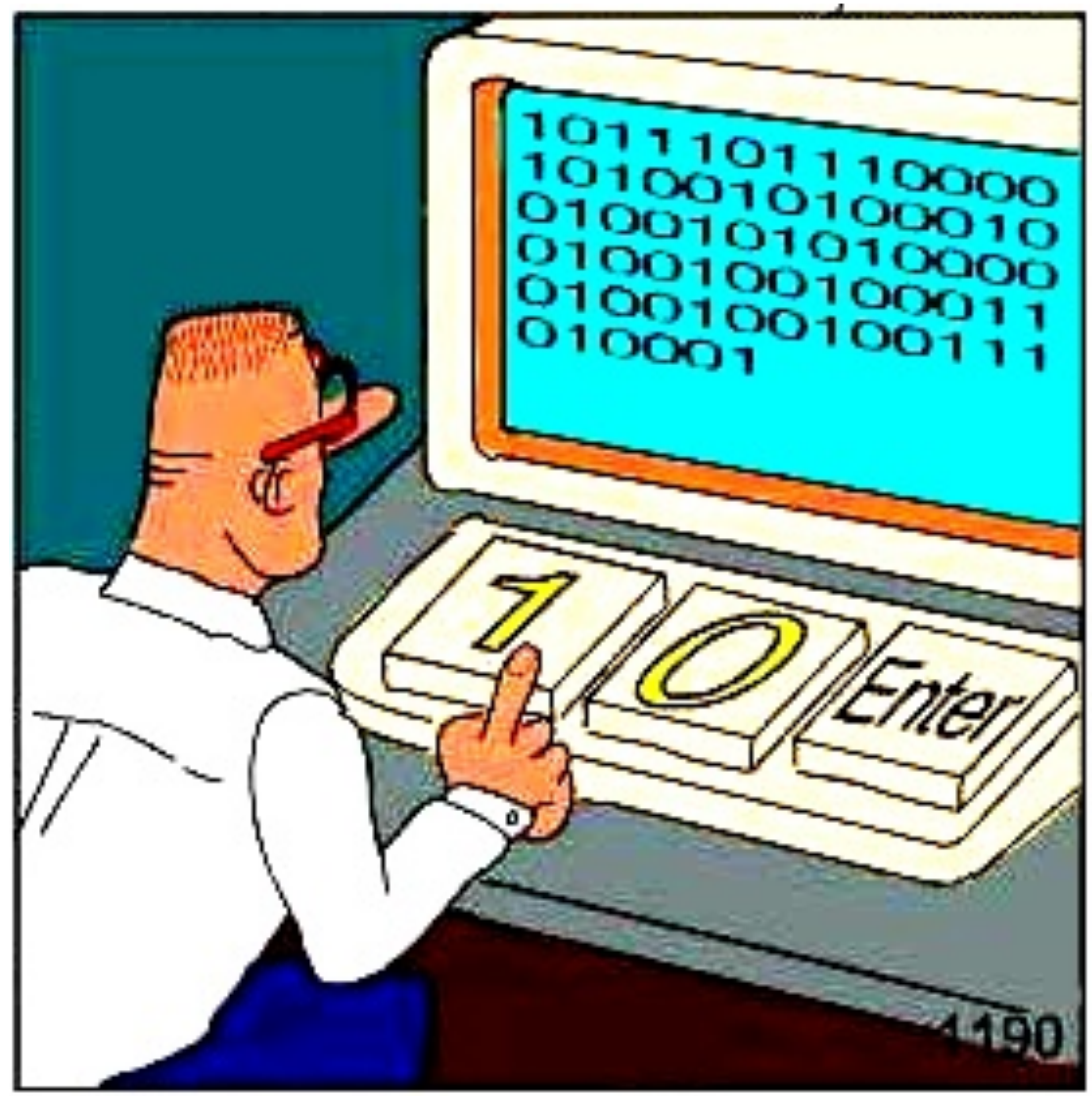
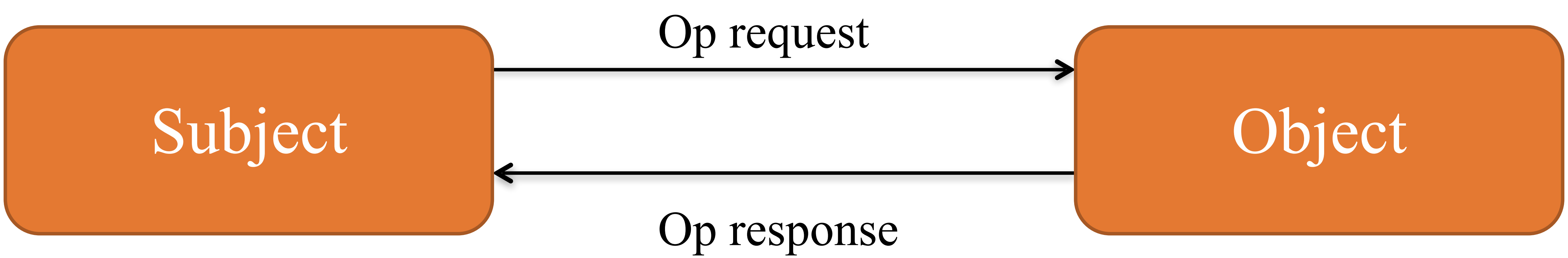
Acknowledgments: Some of the slides are fully or partially obtained from other sources. A reference is noted on the bottom of each slide, when the content is fully obtained from another source. Otherwise a full list of references is provided on the last slide.

Run-Time protection/enforcement

- In many instances we only have access to the binary
- How do we analyze the binary for vulnerabilities?
- How do we protect the binary from exploitation?
- This would be our topic for the next few lectures



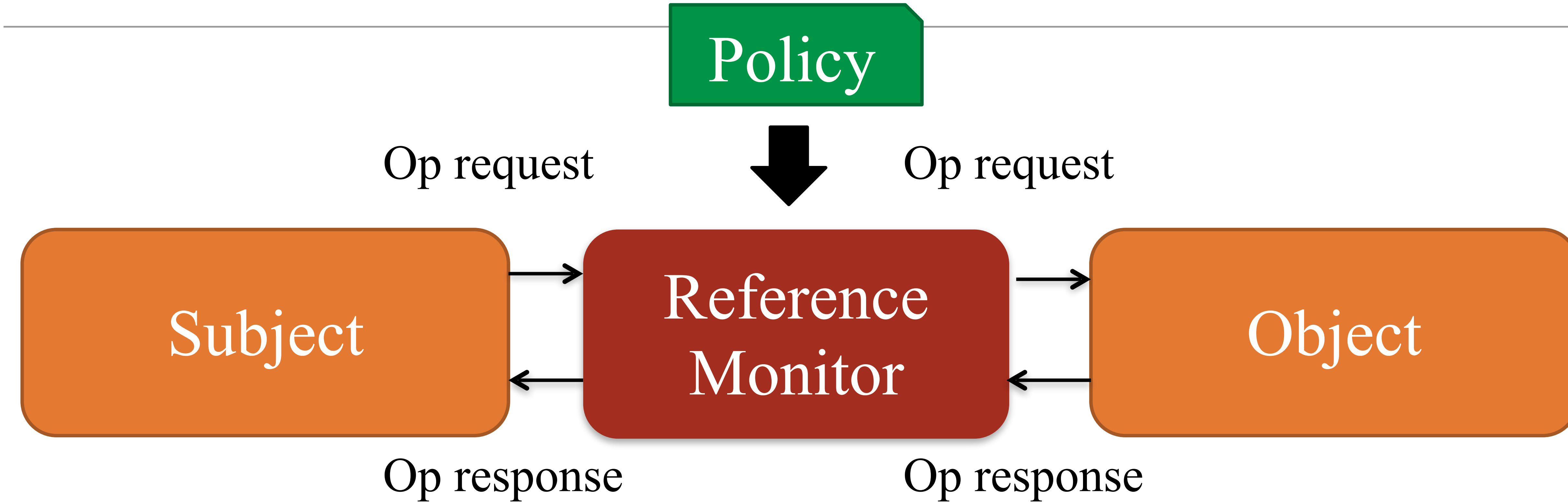
REAL Programmers code in BINARY.



People
Processes
Computer Operations

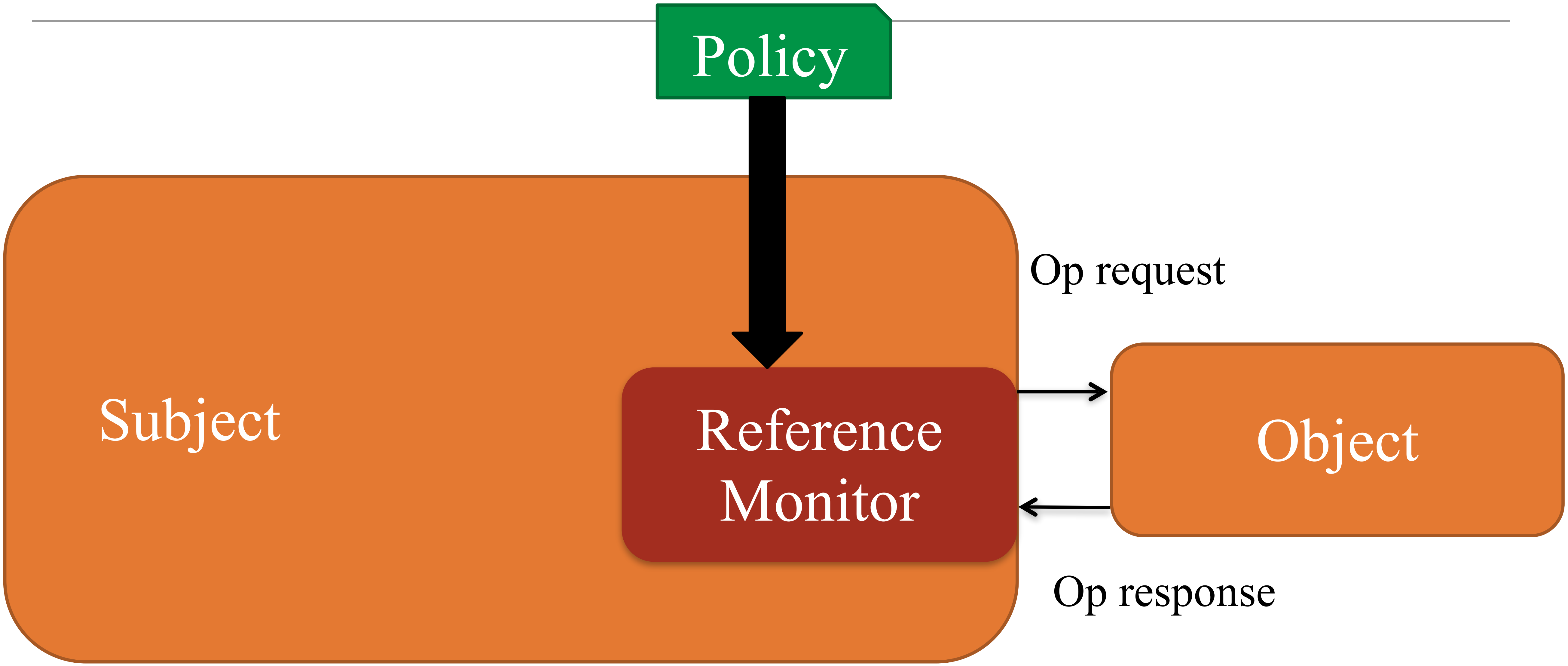
Files
Sockets
Computer Operations

Reference Monitor: Principles



- **Complete Mediation:** The reference monitor must always be invoked
- **Tamper-proof:** The reference monitor cannot be changed by unauthorized subjects or objects
- **Verifiable:** The reference monitor is small enough to thoroughly understand, test, and ultimately, verify.

Inlined Referenced Monitor



Today's Example:
Inlining a control flow policy into a program

Control-Flow Integrity: Principles, Implementations, and Applications

Martin Abadi, Mihai Budiu, U´lfar Erlingsson, Jay Ligatti, CCS 2005

Control Flow Integrity

- protects against powerful adversary
  - with full control over entire data memory
- widely-applicable
  - language-neutral; requires binary only
- provably-correct & trustworthy
  - formal semantics; small verifier
- efficient
  - hmm… 0-45% in experiments; average 16%

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CFI Adversary Model

Can

- Overwrite any data memory at any time
  - stack, heap, data segs
- Overwrite registers in current context

Can Not

- Execute Data
  - NX takes care of that
- Modify Code
  - text seg usually read-only
- Write to %ip
  - true in x86
- Overwrite registers in other contexts
  - kernel will restore regs

CFI Overview

- Invariant: Execution must follow a path in a control flow graph (CFG) $\underbrace{\text{created ahead of run time}}_{\text{“static”}}$.
- 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

Control Flow Graphs

Basic Block

- **Defn 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

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

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

6. jmp 3

3 static
basic blocks

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

1 dynamic
basic block

Basic Block

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

- D…
  no outside instruction can execute between two instructions in the sequence

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

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

6. jmp 3

3 static basic blocks

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

1 dynamic basic block

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.

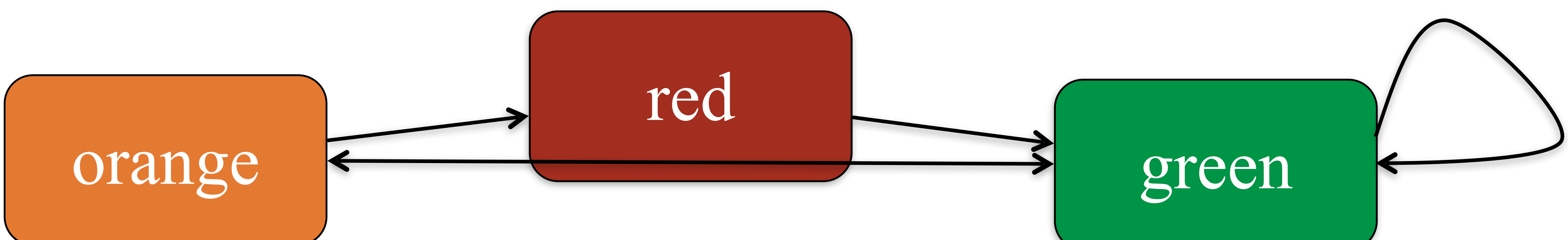
Call Graph

- 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)
{
green();
...
}
```

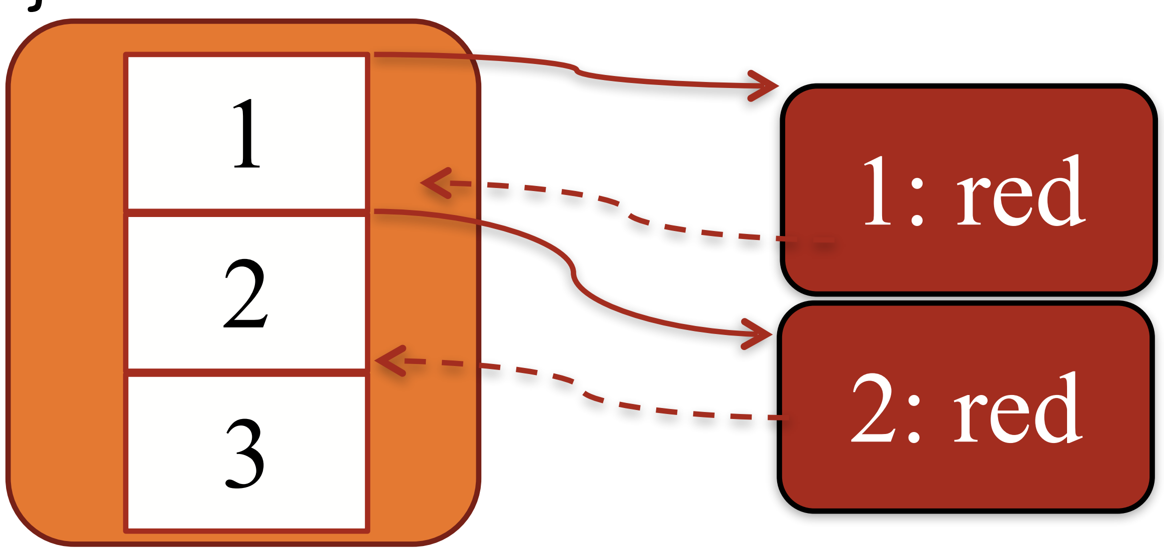
```
void green()
{
  green();
  orange();
}
```



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 <u>*context sensitive*</u> super-graph for orange lines 1 and 2.

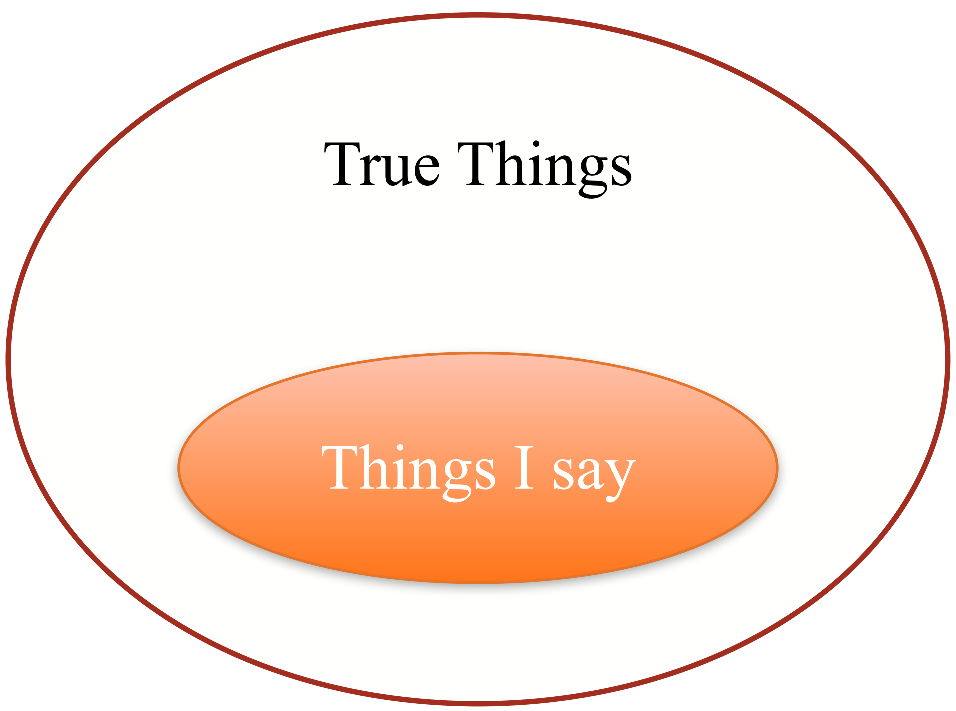
Precision: Sensitive or Insensitive

- The more precise the analysis, the more accurate it reflects the “real” program behavior.
    - More precise = more time to compute
    - More precise = more space
    - Limited by soundness/completeness tradeoff

- Common Terminology in any Static Analysis:
    - Context sensitive vs. context insensitive
    - Flow sensitive vs. flow insensitive
    - Path sensitive vs. path insensitive

Soundness

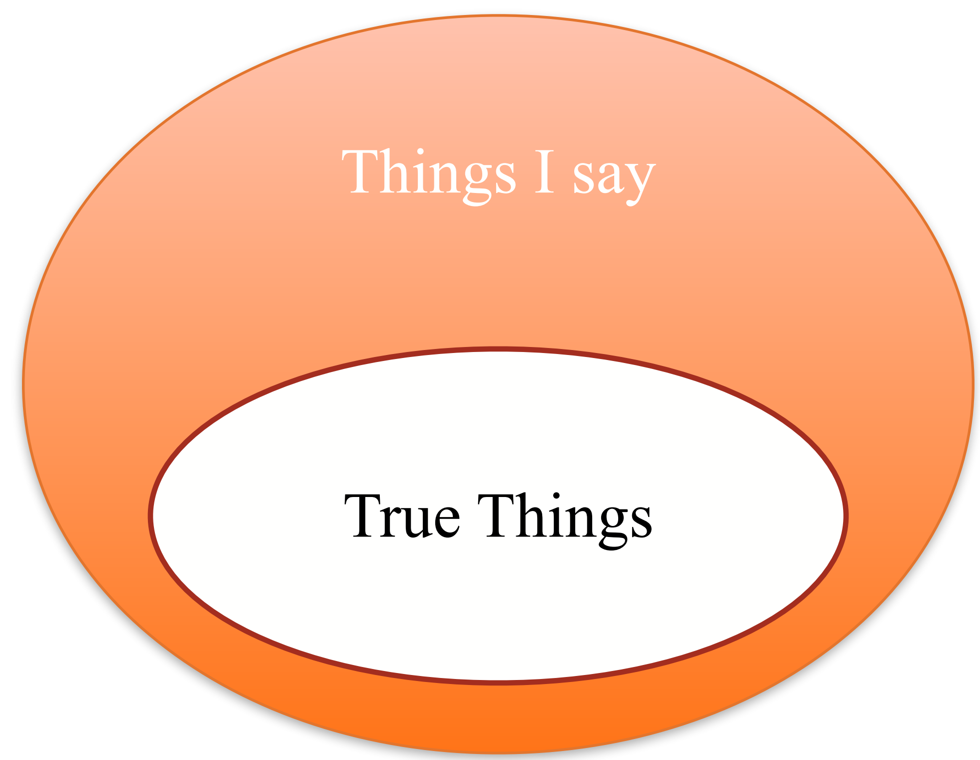
If analysis says X is true, then X is true.



Trivially Sound: Say nothing

Completeness

If X is true, then analysis says X is true.



Trivially complete: Say everything

Soundness | Completeness

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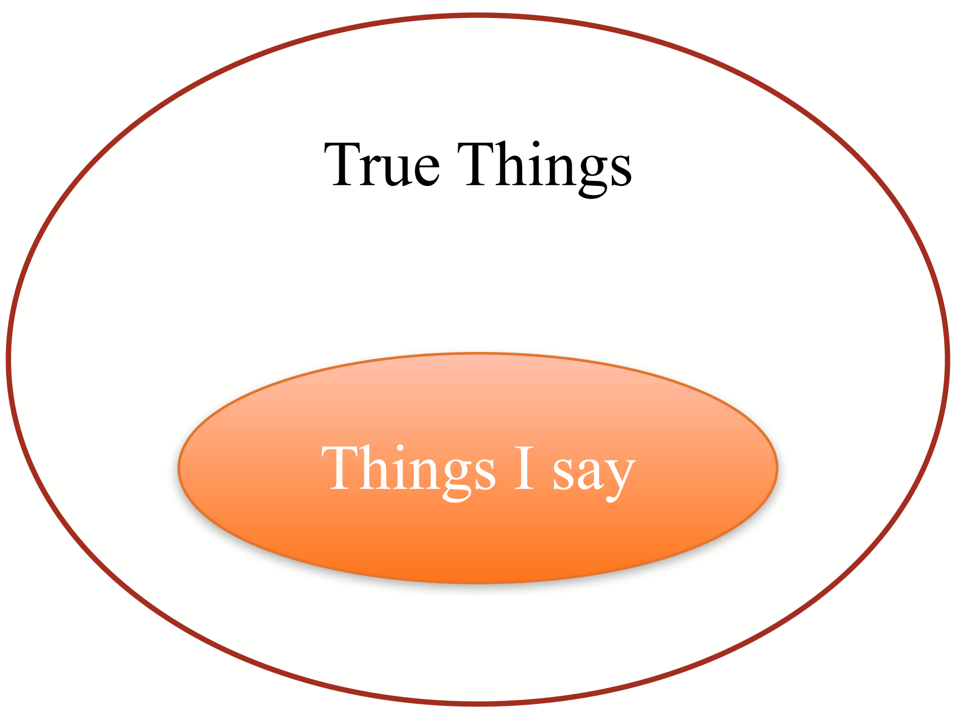

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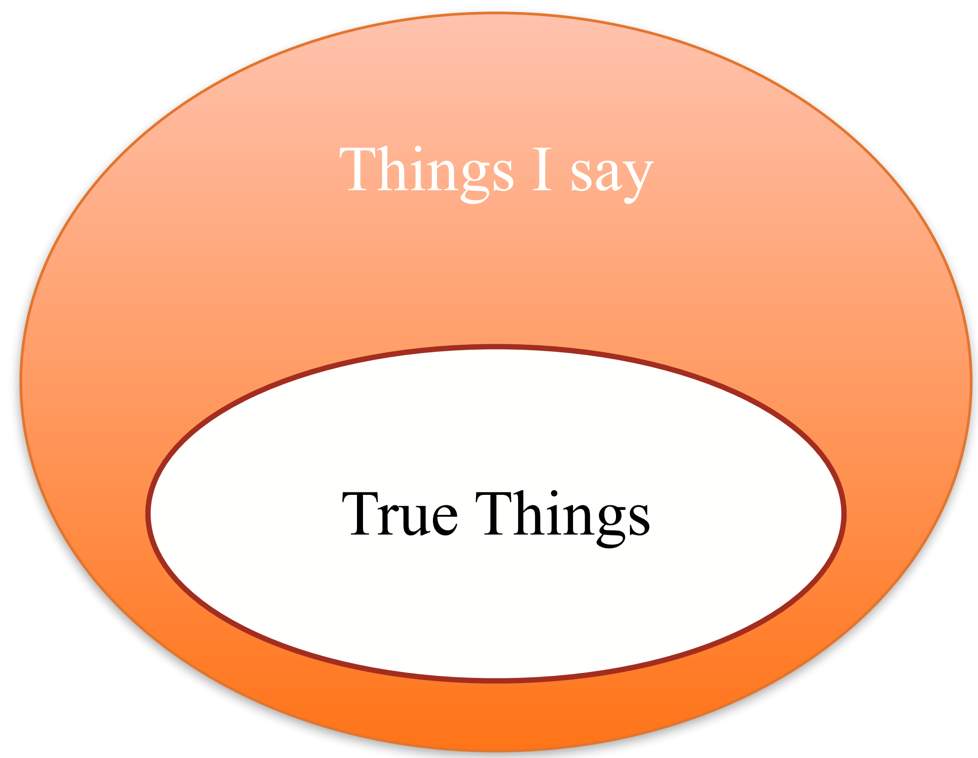


Trivially complete: Say everything

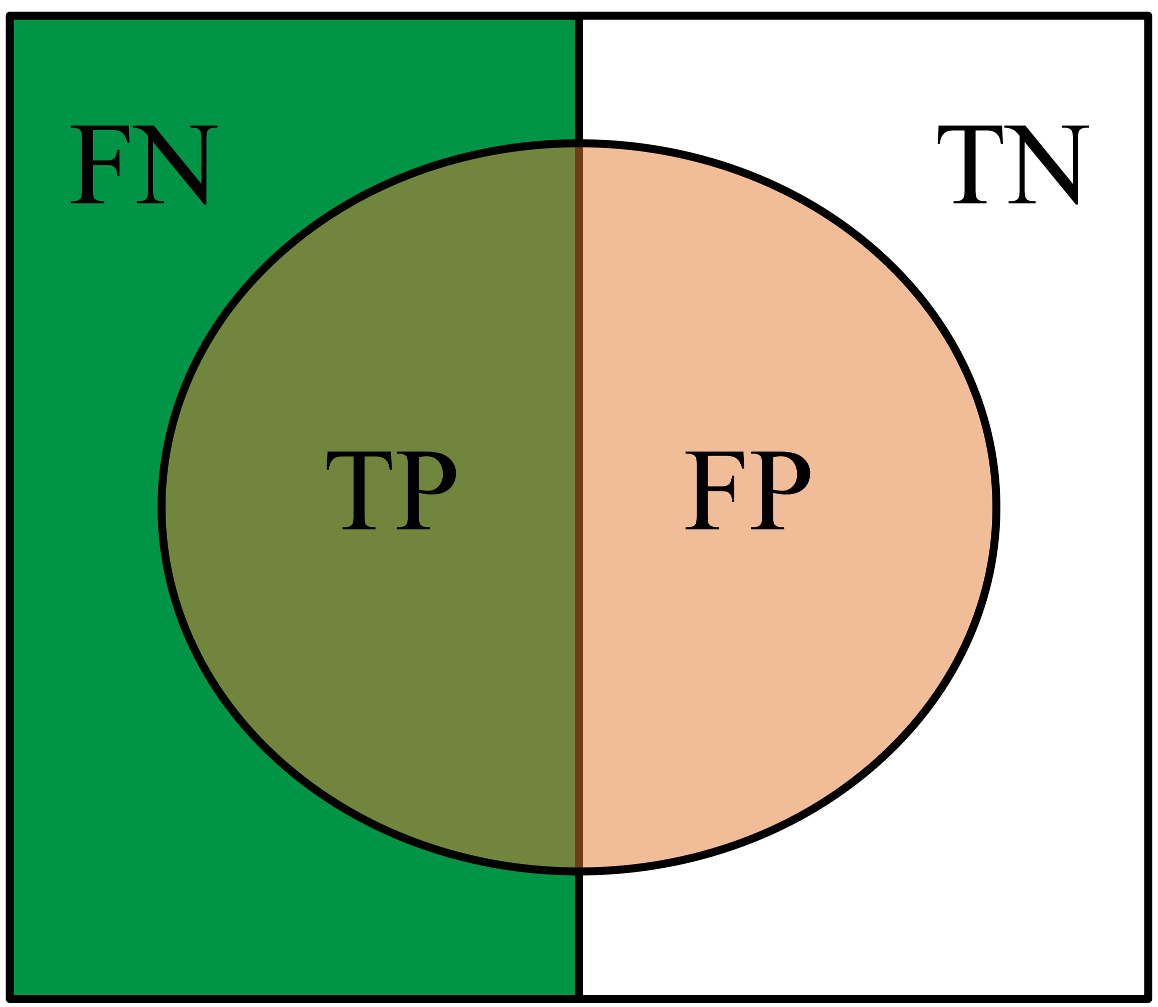
Sound and Complete: Say exactly the set of true things!

Soundness, Completeness, Precision, Recall, False Negative, False Positive, All that Jazz…

Imagine we are building a *classifier*.

Ground truth: things on the left is "in".

Our classifier: things inside circle is "in".



Sound means FP is empty

Complete means FN is empty

Precision = TP/(TP+FP)

Recall = TP/(FN+TP)

False Positive Rate = FP/(TP+FP)

False Negative Rate = FN/(FN+TN)

Accuracy = (TP+TN)/(Σ everything)

Context Sensitive

Whether different calling contexts are distinguished

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

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

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

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
(color denotes matching call/ret)

Context sensitive can tell one call returns 4, the other 5

```
a = id(4);

b = id(5);
```

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

Context-Insensitive
(note merging)

Context insensitive will say both calls return {4,5}

Flow Sensitive

- A flow sensitive analysis considers the order (flow) of statements
- Examples:
  - Type checking is flow insensitive since a variable has a single type regardless of the order of statements
  - Detecting uninitialized variables requires flow sensitivity

```
x = 4;
....
x = 5;
```

Flow sensitive can distinguish values of x, flow insensitive cannot

Flow Sensitive Example

```
1. x = 4;
....
n. x = 5;
```

Flow sensitive:
x is the constant 4 at line 1, x is the constant 5 at line n

Flow insensitive:
x is not a constant

Path Sensitive

- A path sensitive analysis maintains branch conditions along each execution path
  - Requires extreme care to make scalable
  - Subsumes flow sensitivity

Path Sensitive Example

```
1. if(x >= 0)
2.    y = x;
3. else
4.    y = -x;
```

path sensitive:
y >= 0 at line 2,
y > 0 at line 4

path insensitive:
y is not a constant

Precision

Even path sensitive analysis approximates behavior due to:

- loops/recursion
- unrealizable paths

```
1. if(aⁿ + bⁿ = cⁿ && n>2 && a>0 && b>0 && c>0)
2.     x = 7;
3. else
4.     x = 8;
```

Unrealizable path.
x will always be 8

Control Flow Integrity (Analysis)

CFI Overview

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

- Method:
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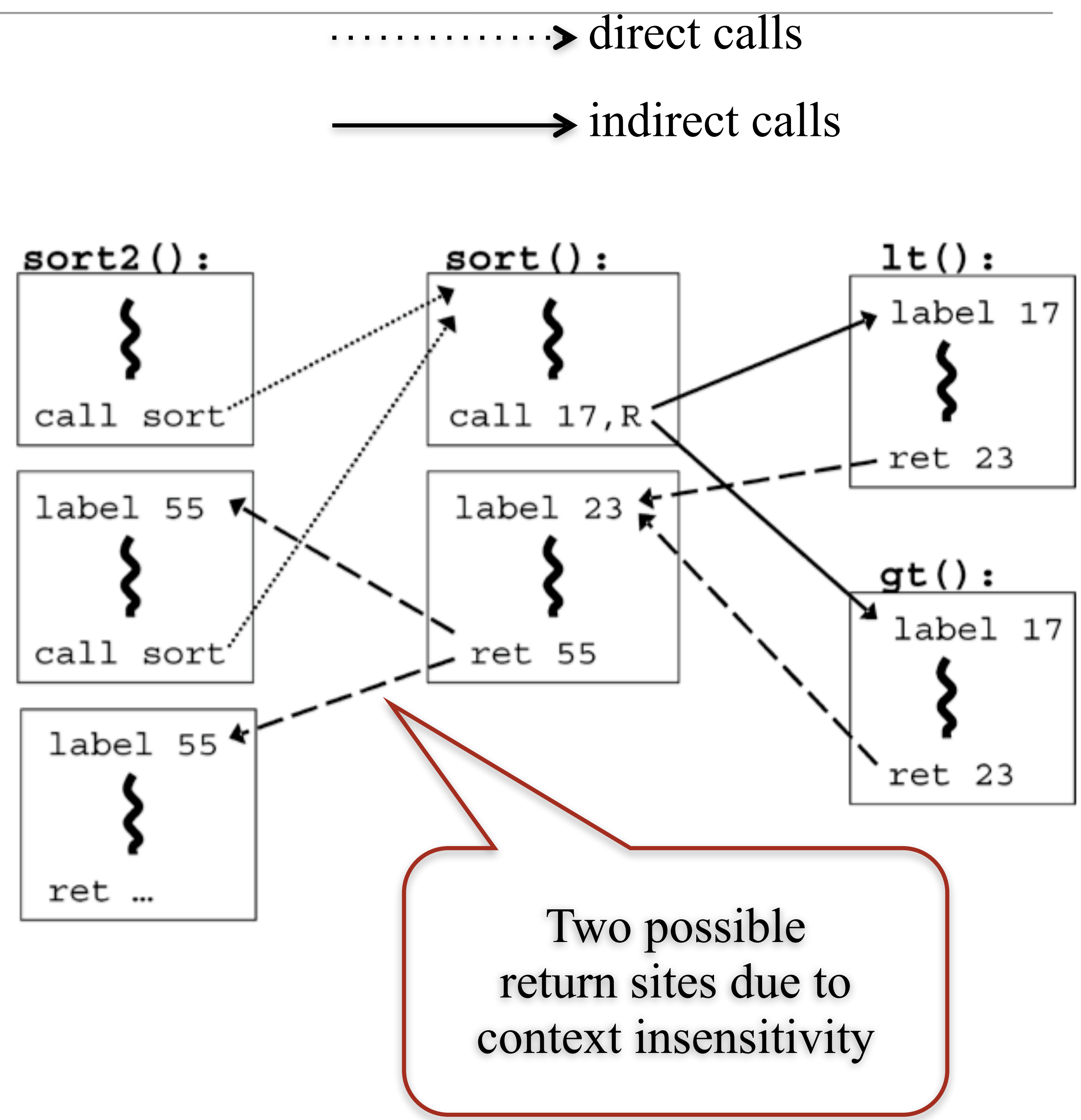
  - instrument (rewrite) binary, e.g., at install time
    - add IDs and ID checks; maintain ID uniqueness
  - verify CFI instrumentation at load time
    - direct jump targets, presence of IDs and ID checks, ID uniqueness
  - perform ID checks at run time
    - indirect jumps have matching IDs

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)
{
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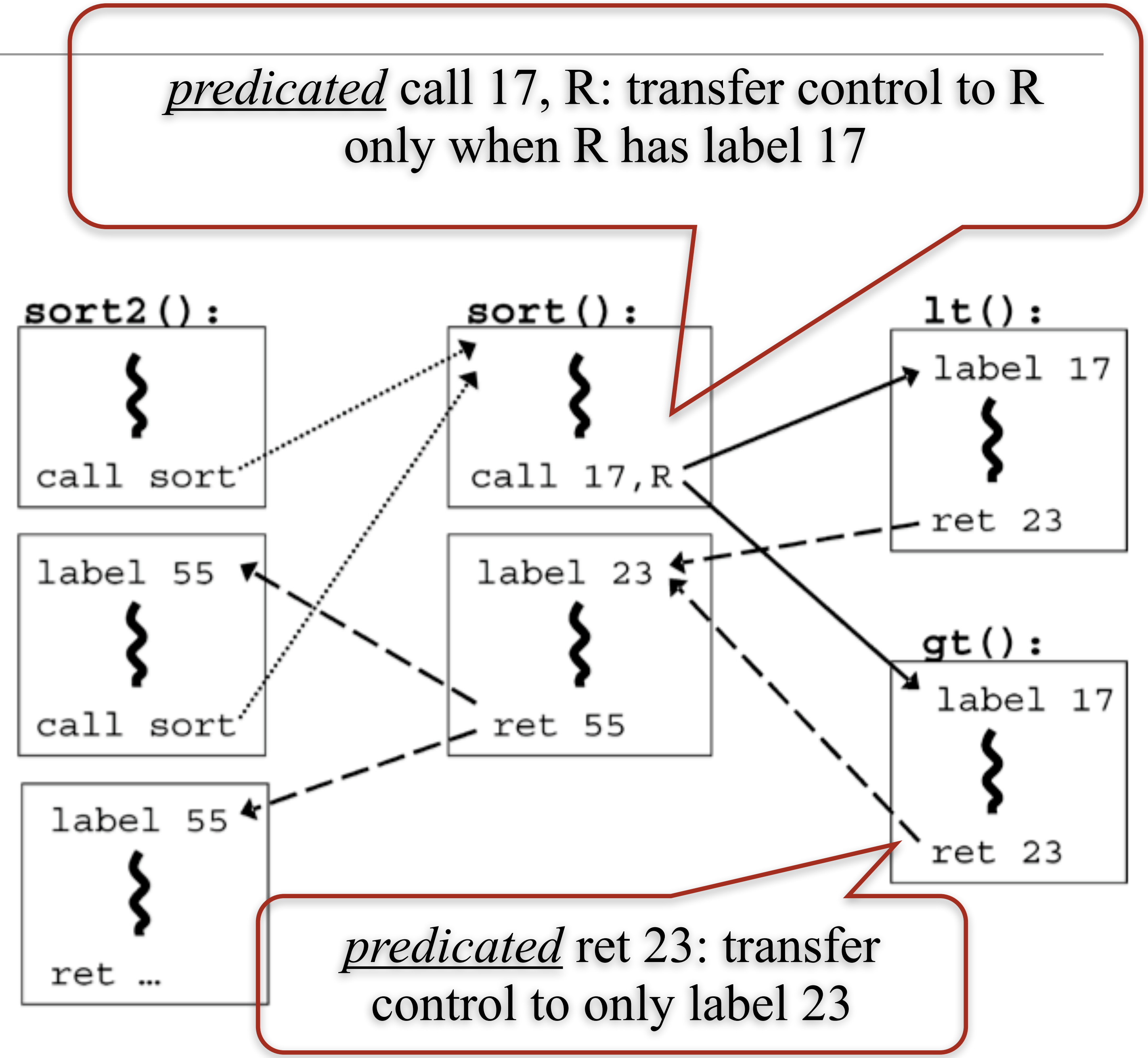

- Insert a unique number at each destination
- Two destinations are equivalent if CFG contains edges to each from the same source

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?

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easy to implement correctly => trustworthy

What about indirect jumps and ret?

ID Checks

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

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

```
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

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```
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
```

ID Checks

Check dest label

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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
```

Performance

- Size: increase 8% avg
- Time: increase 0-45%; 16% avg

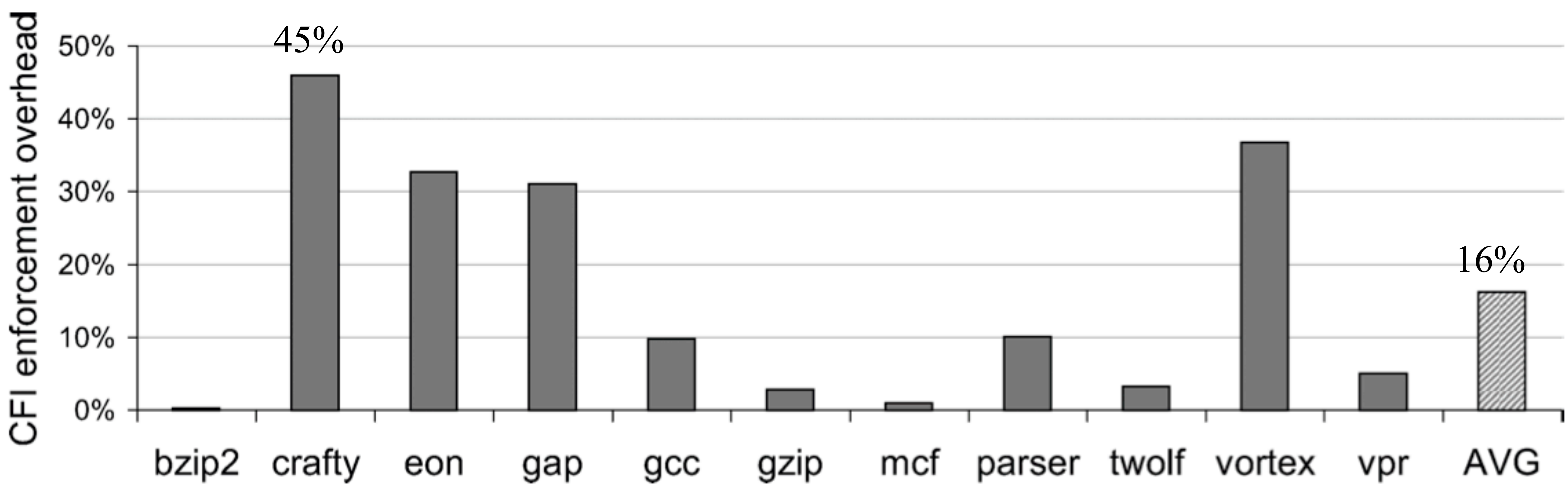

Fig. 6. Execution overhead of inlined CFI enforcement on SPEC2000 benchmarks.

Security Guarantees

- Effective against attacks based on illegitimate control-flow transfer
  - buffer overflow, ret2libc, pointer subterfuge, etc.

Any check becomes non-circumventable.

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Any check becomes non-circumventable.

- Allow data-only attacks since they respect CFG!
  - incorrect usage (e.g. printf can still dump mem)
  - substitution of data (e.g. replace file names)

Software Fault Isolation

- SFI ensures that a module only accesses memory within its region by adding checks
  - e.g., a plugin can accesses only its own memory

```
if(module_lower < x < module_upper)
    z = load[x];
```

SFI Check

- CFI ensures inserted memory checks are executed

Inline Reference Monitors

- IRMs inline a security policy into binary to ensure security enforcement

- Any IRM can be supported by CFI + Software Memory Access Control
  - CFI: IRM code cannot be circumvented

    +

  - SMAC: IRM state cannot be tampered

Accuracy vs. Security

- The accuracy of the CFG will reflect the level of enforcement of the security mechanism.

```
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 );
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}
```
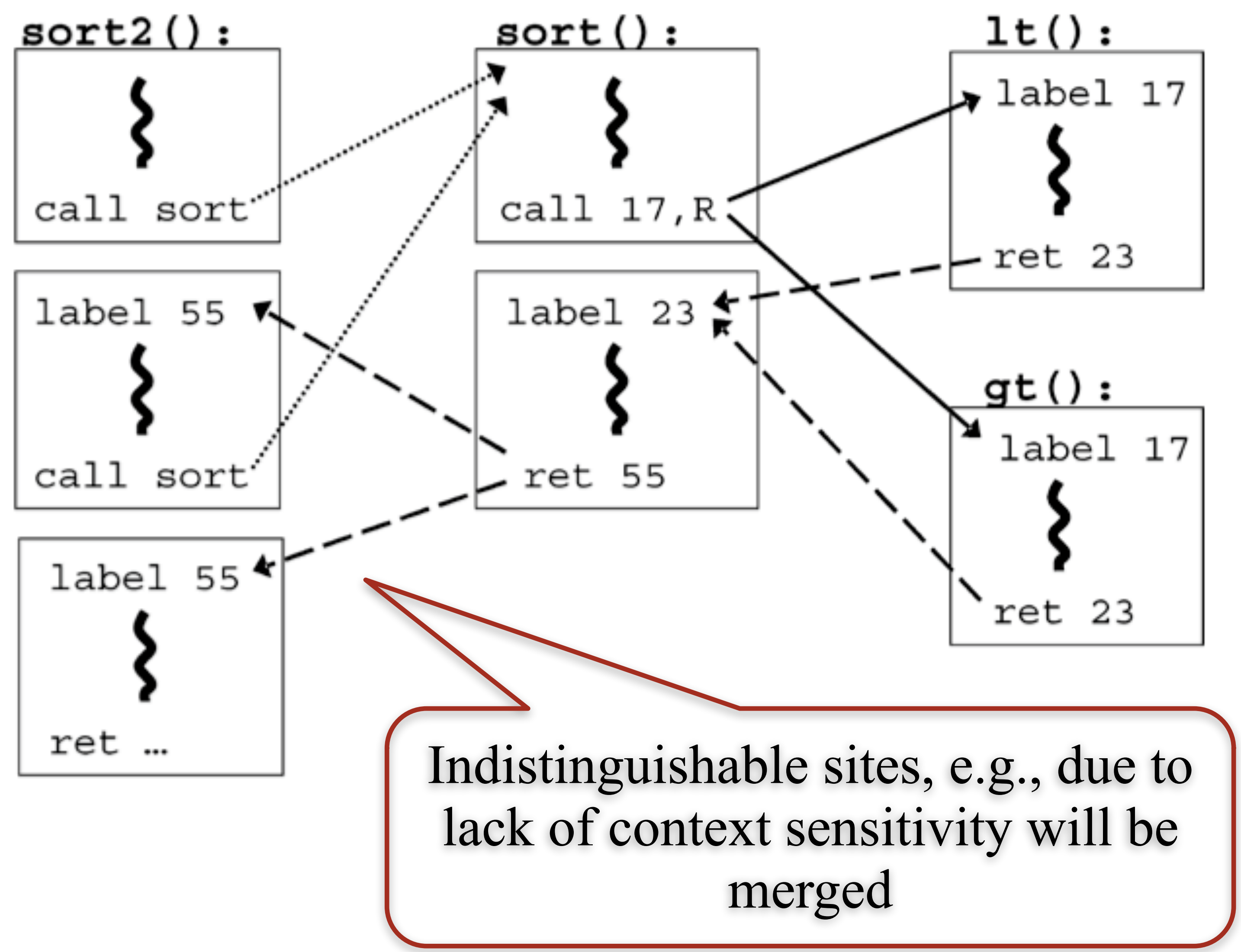



Context Sensitivity Problems

- Suppose A and B both call C.
- CFI uses same return label in A and B.

- How to prevent C from returning to B when it was called from A?
- Shadow Call Stack
  - a protected memory region for call stack
  - each call/ret instrumented to update shadow
  - CFI ensures instrumented checks will be run

CFI Summary

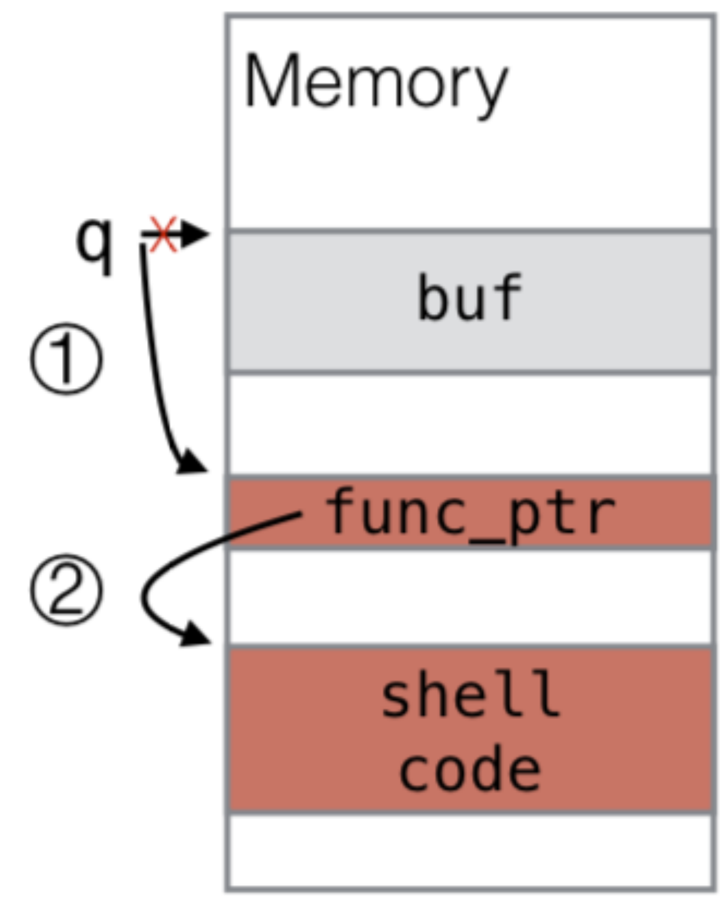
- Control Flow Integrity ensures that control flow follows a path in CFG
  - Accuracy of CFG determines level of enforcement
  - Can build other security policies on top of CFI

Code Pointer Integrity

Volodymyr Kuznetsov, László Szekeres, Mathias Payer, George Candea, R. Sekar, Dawn Song, OSDI 2014

Control-Flow Hijack Attack

```
① int *q = buf + input;
② *q = input2;
   …
③ (*func_ptr)();
```



① Attacker corrupts a data pointer
② Attacker uses it to overwrite a code pointer
③ Control-flow is transferred to shell code

Memory safety prevents control-flow hijacks

python Java C# Swift ...

- ... but memory safe programs still rely on C/C++ ...
- Sample Python program (Dropbox SDK example):

Python program	3 KLOC of Python
Python runtime	500 KLOC of C
libc	2500 KLOC of C

 [Kuznetsov’14]

Memory safety can be retrofitted to C/C++

C/C++	Overhead
SoftBound+CETS	116%
CCured (language modifications)	56%
Watchdog (hardware modifications)	29%
AddressSanitizer (approximate)	73%

State of the art: Control-Flow Integrity

Static property:
limit the set of functions that can be called at each call site

Coarse-grained CFI can be bypassed [1-4]

and

Finest-grained CFI has 10-21% overhead [5-6]

[1] Göktaş et al., IEEE S&P 2014
[2] Göktaş et al., USENIX Security 2014
[3] Davi et al., USENIX Security 2014
[4] Carlini et al., USENIX Security 2014
[5] Akritidis et al., IEEE S&P 2008
[6] Abadi et al., CCS 2005

Programmers have to choose

Safety
Security

vs

Flexibility
Performance

Code-Pointer Integrity, provides both

Control-flow hijack protection	**and**	**Unmodified C/C++**
Practical protection		**0.5 - 1.9% overhead**
Guaranteed protection		**8.4 - 10.5% overhead**

Key insight: memory safety for code pointers only.

Tested on:

FreeBSD hardened

python

SQLite

lame

OpenSSL

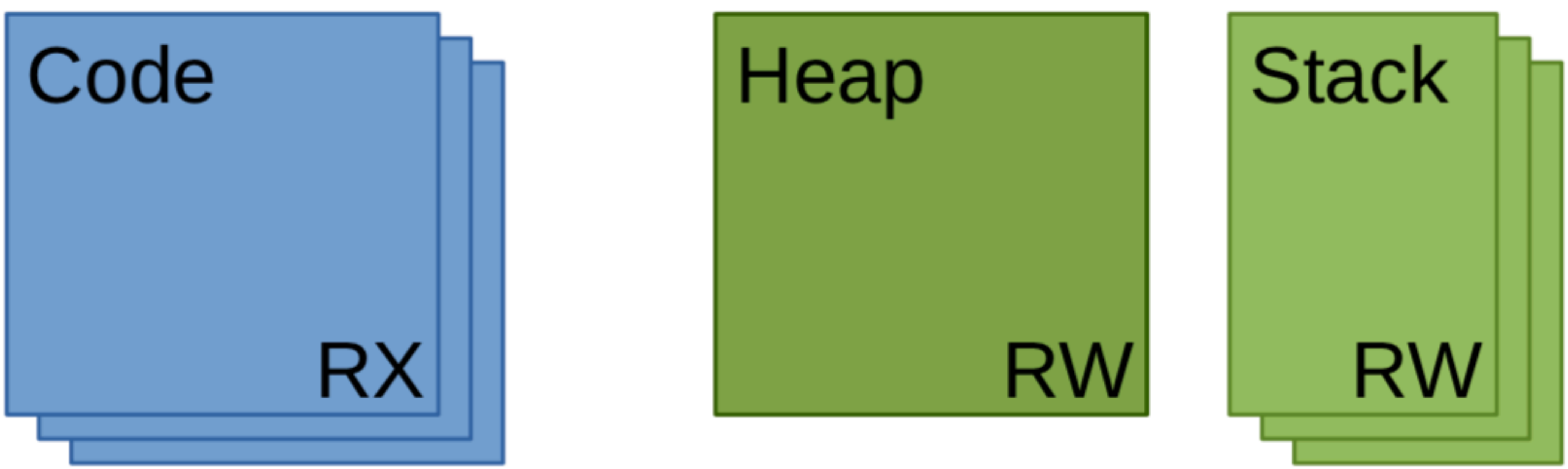
PostgreSQL

GraphicsMagick

Apache

Threat Model

- Attacker can read/write data, read code
- Attacker cannot
  - Modify program code
  - Influence program loading



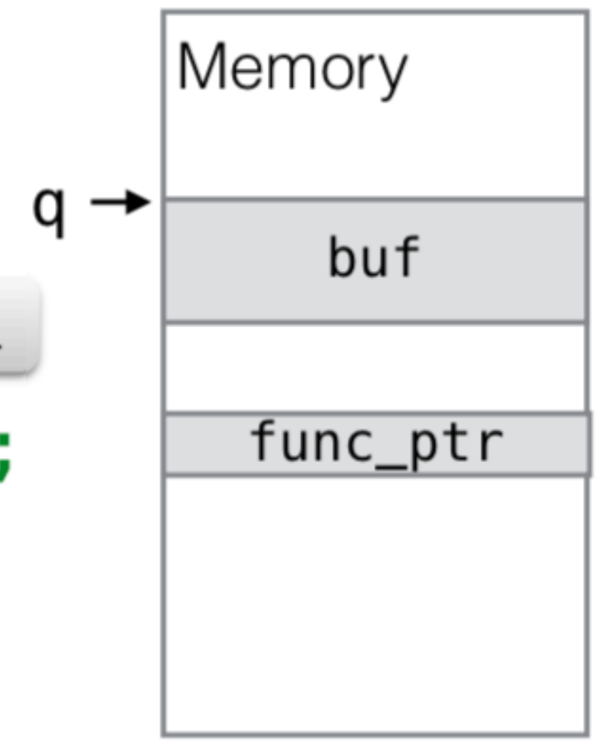
Memory Safety: program instrumentation

```
char *buf = malloc(10);
buf_lower = p; buf_upper = p+10;
…
char *q = buf + input;
q_lower = buf_lower; q_upper = buf_upper;
if (q < q_lower || q >= q_upper-size)
  abort();
*q = input2;
…
(*func_ptr)();
```

1. Assign metadata

2. Propagate metadata

3. Check metadata



116% average performance overhead (Nagarakatte et al., PLDI'09 and ISMM'10)

All-or-nothing protection

Memory Safety

116% average performance overhead

Can memory safety be enforced for code pointers only ?

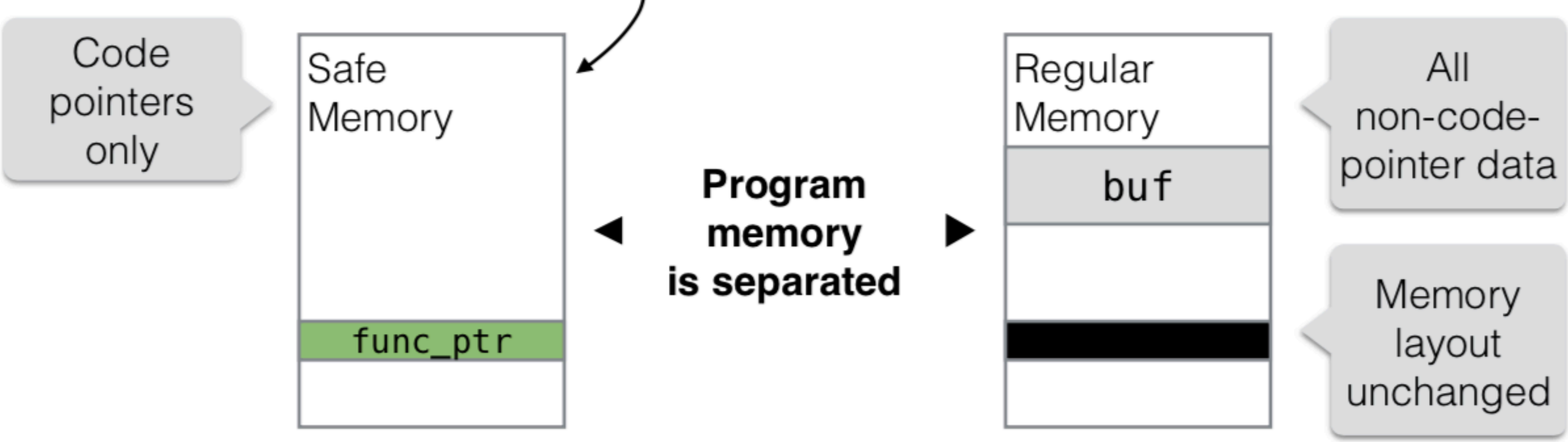
Control-flow hijack protection
1.9% or 8.4% average performance overhead

Practical Protection (CPS): Heap

```
int *q = buf + input;
*q = input2;
…
(*func_ptr)();
```

Instructions that access code pointers are identified using type-based static analysis

Separation is enforced using hardware-enforced instruction-level isolation

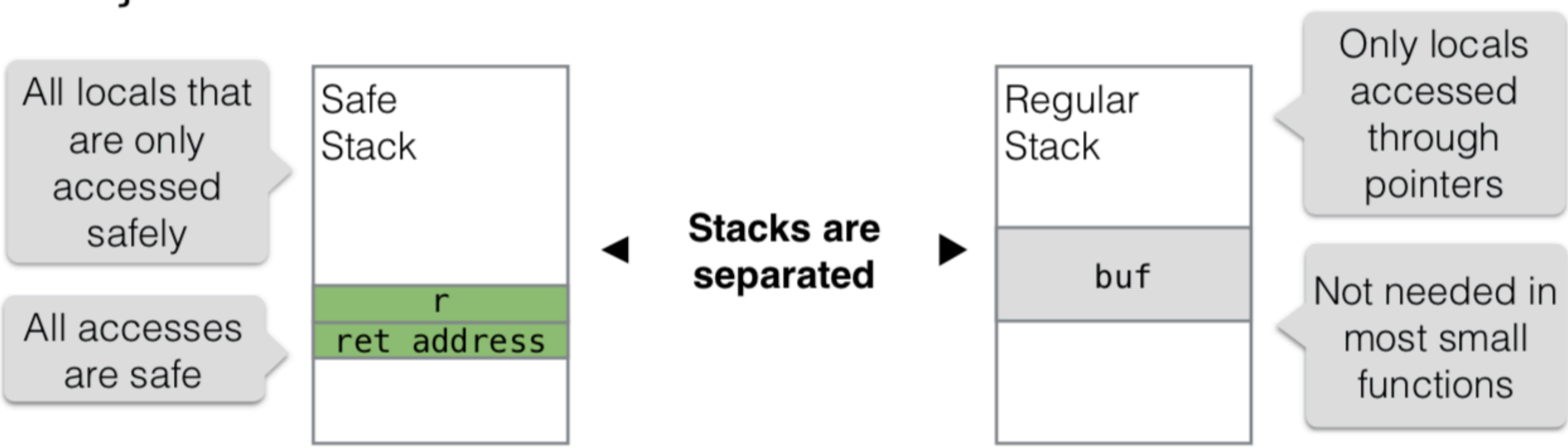


2.5% memory accesses (on SPEC2006 CPU)

97.5% memory accesses (on SPEC2006 CPU)

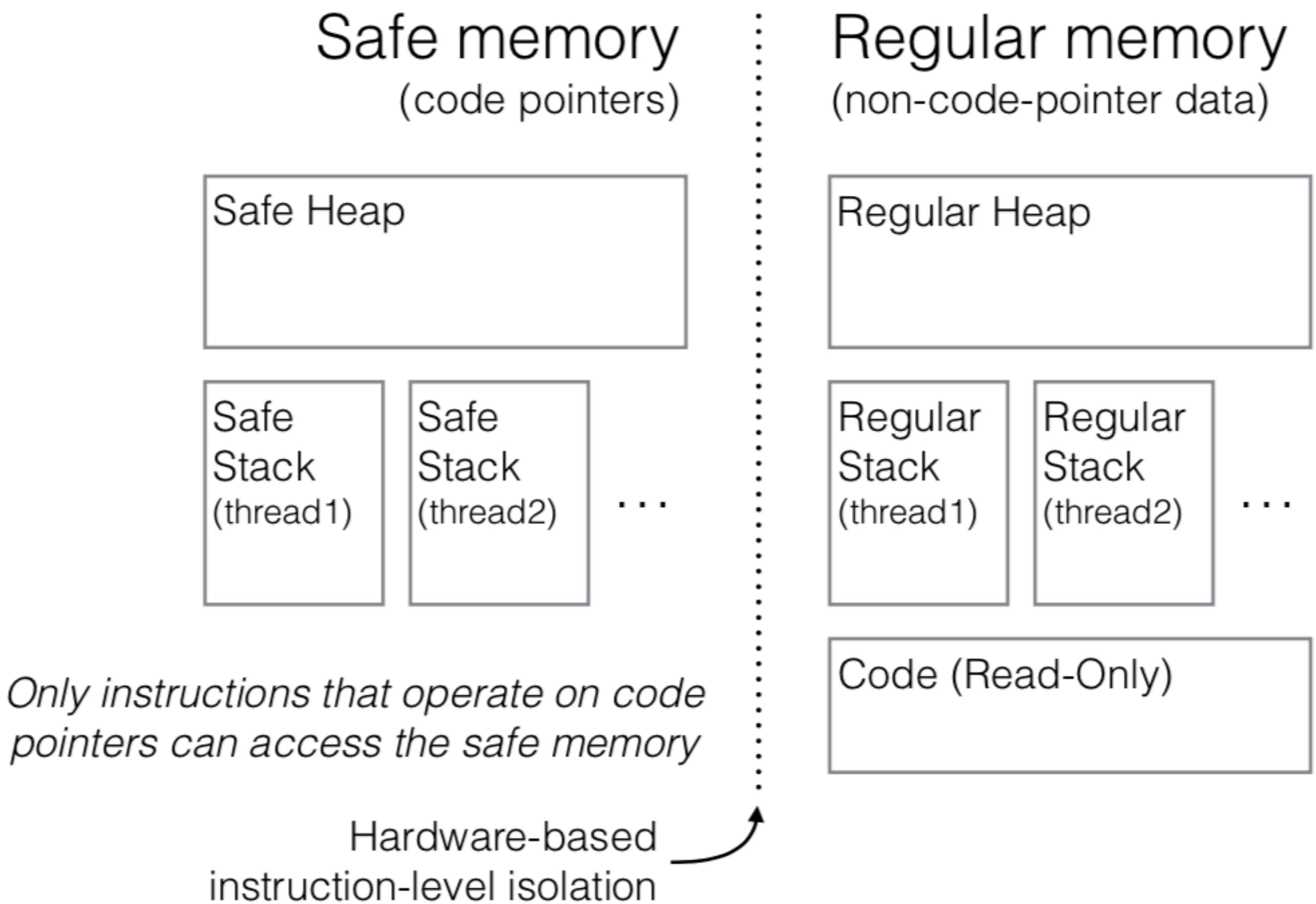
Practical Protection (CPS): Stack

```
int foo() {
  char buf[16];
  int r;
  r = scanf("%s", buf);
  return r;
}
```



Safe stack adds <0.1% performance overhead!

Practical Protection (CPS): Memory Layout



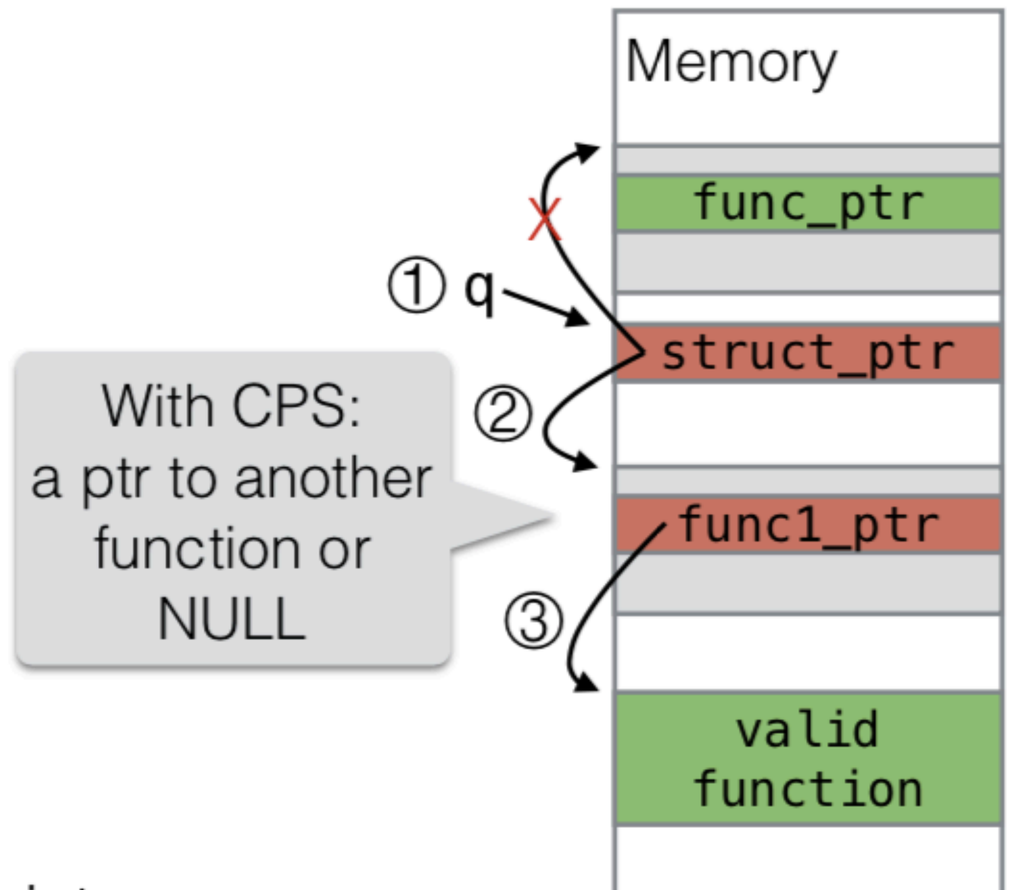
The CPS Promise

Under CPS, an attacker
cannot forge a code pointer

Under CPS, an attacker cannot forge a code pointer

Contrived example of an attack on a CPS-protected program

```
① int *q = p + input;
② *q = input2;
  …
③ func_ptr = struct_ptr->f;
④ (*func_ptr)();
```

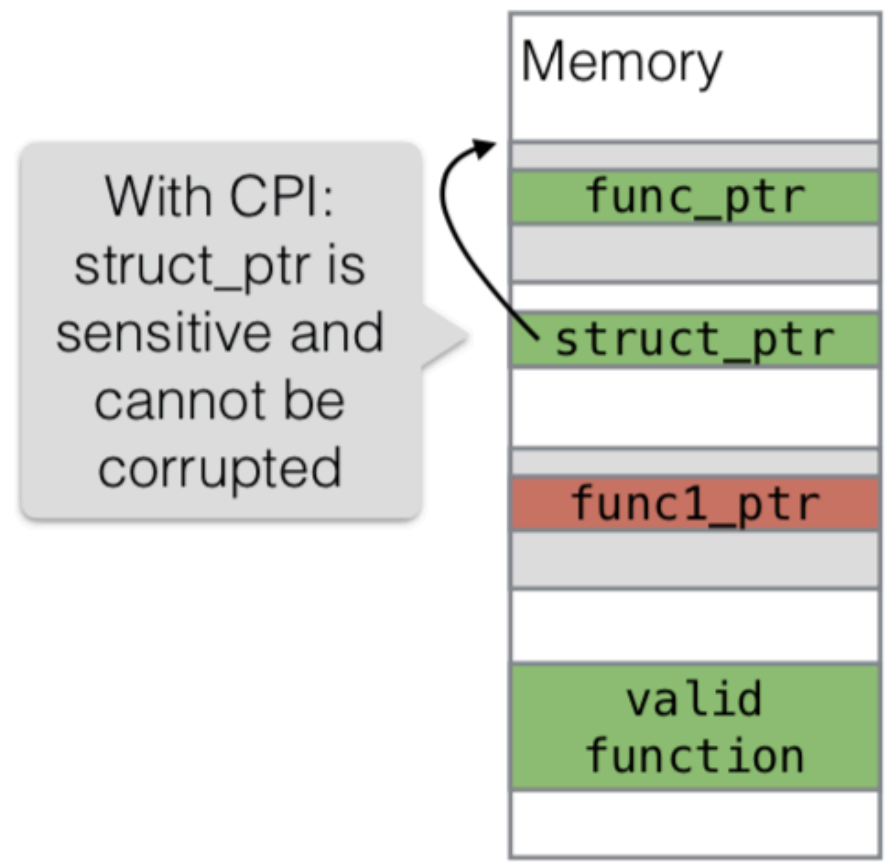


① Attacker corrupts a data pointer
② Attacker uses it to corrupt a struct pointer
③ Program loads a function pointer from wrong location in the safe memory
④ Control-flow is transferred to different function whose address was previously stored in the safe memory

Under CPS, an attacker cannot forge a code pointer

Contrived example of an attack on a CPS-protected program

```
int *q = p + input;
*q = input2;
…
func_ptr = struct_ptr->f;
(*func_ptr)();
```



Precise solution: protect all *sensitive*[1] pointers

[1]*Sensitive* pointers = code pointers and **pointers used to access sensitive pointers**

Code-Pointer Separation

- Identify Code-Pointer accesses using static type-based analysis
- Separate using instruction-level isolation (e.g., segmentation)

- CPS security guarantees
  - An attacker cannot forge new code pointers
  - Code-Pointer is either immediate or assigned from code pointer
  - An attacker can only replace existing functions through indirection: e.g., foo->bar->func() vs. foo->bar->func2()

Code-Pointer Integrity (CPI)

- Sensitive Pointers = code pointers and

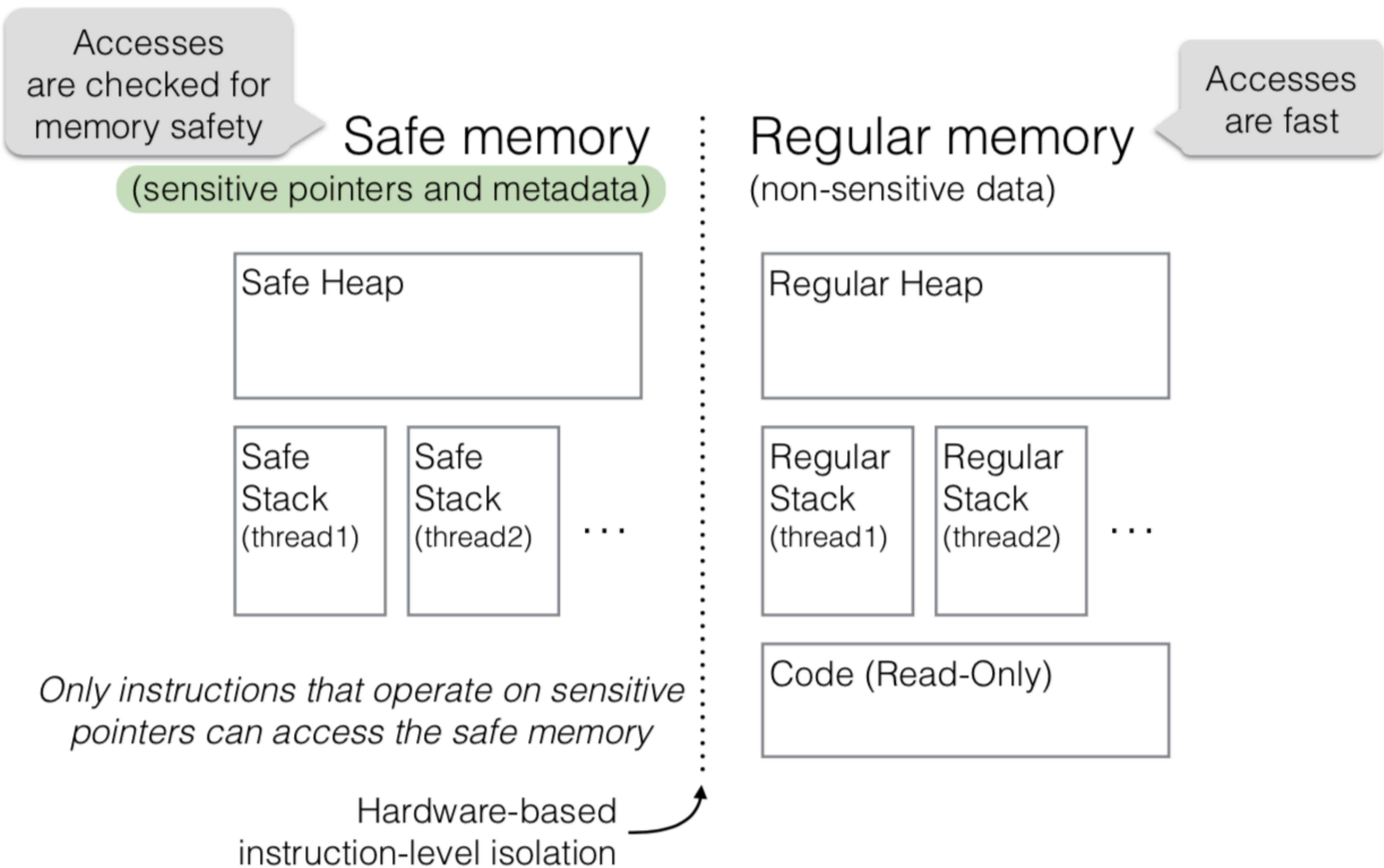
  pointers used to access sensitive pointers

- CPI identifies all sensitive pointers using an over-approximate type-based static analysis:

  is_sensitive(v) = is_sensitive_type(type of v)

- Over-approximation only affects performance
  - On SPEC2006 <= 6.5% accesses are sensitive

Guaranteed Protection (CPI): Memory Layout



Guaranteed Protection (CPI)

- Guaranteed memory safety for all sensitive pointers
  - Sensitive Pointers = code pointers and **pointers used to access sensitive pointers**

- **==>** Guaranteed protection against control-flow hijack attacks enabled by memory bugs

Code-Pointer Integrity vs. Separation

- Separate sensitive pointers from regular data
  - Type-based static analysis
  - Sensitive pointers = code pointers + **pointers to sensitive pointers**
- Accessing sensitive pointers is **safe**
  - Separation + runtime (bounds) checks
- Accessing regular data is **fast**
  - Instruction-level safe region isolation

Security Guarantees

- Code-Pointer Integrity: formally guaranteed protection
  - 8.4% to 10.5% overhead (~6.5% of memory accesses)
- Code-Pointer Separation: strong protection in practice
  - 0.5% to 1.9% overhead (~2.5% of memory accesses)
- Safe Stack: full ROP protection
  - Negligible overhead

Protects Against	Technique	Security Guarantees	Average Overhead
Memory corruption vulnerabilities	Memory Safety	Precise	116%
Control-flow hijack vulnerabilities	**CPI** (Guaranteed protection)	Precise	8.4-10.5%
	CPS (Practical protection)	Strong	0.5-1.9%
	Finest-grained CFI	Medium (attacks may exist) Göktaş el., IEEE S&P 2014	10-21%
	Coarse-grained CFI	Weak (known attacks) Göktaş el., IEEE S&P 2014 and USENIX Security 2014, Davi et al, USENIX Security 2014 Carlini et al., USENIX Security 2014	4.2-16%
	ASLR DEP Stack cookies	Weakest (bypassable + widespread attacks)	~0%

Implementation

- LLVM-based prototype
  - Front end (clang): collect type information
  - Back-end (llvm): CPI/CPS/SafeStack instrumentation pass
  - Runtime support: safe heap and stack management
  - Supported ISA's: x64 and x86 (partial)
  - Supported systems: Mac OSX, FreeBSD, Linux

Current status

- Great support for CPI on Mac OSX and FreeBSD on x64
- Upstreaming in progress
  - Safe Stack coming to LLVM soon
  - Fork it on GitHub now: https://github.com/cpi-llvm
- Code-review of CPS/CPI in process
  - Play with the prototype: http://levee.epfl.ch/levee-early-preview-0.2.tgz
  - Will release more packages soon
- Some changes to super complex build systems needed
  - Adapt Makefiles for FreeBSD

Conclusion

- CPI/CPS offers strong control-flow hijack protection
    - Key insight: memory safety for code pointers only
- Working prototype
    - Supports unmodified C/C++, low overhead in practice
    - Upstreaming patches in progress, SafeStack available soon!
    - Homepage: http://levee.epfl.ch
    - GitHub: https://github.com/cpi-llvm

Acknowledgments/References

- [Brumley’15] Introduction to Computer Security (18487/15487), David Brumley and Vyas Sekar, CMU, Fall 2015.
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- [Payer’14] Code-Pointer Integrity, Mathias Payer, Slides in (Chaos Communication Congress) CCC 2014.