DataShield: Configurable Data Confidentiality and Integrity

Scott A. Carr, Mathias Payer

Purdue University

AsiaCCS 2017

Motivation

Heartbleed

- Missing bounds check in OpenSSL
- Leak private key
- Not prevented by deployed defenses
  - DEP, Stack Canaries, CFI

We need new tools to protect *sensitive data*

Introduction

Data Confidentiality and Integrity

- Some data are more sensitive
  - Worth paying overhead
  - Ex: stack canaries, DEP, CFI[1], CPI[2]
- Let the programmer choose
- Partial protection => Lower overhead
- Compiler inserts dynamic checks to protect sensitive data

1. Control-Flow Integrity. Abadi et al. CCS 2005
2. Code Pointer Integrity. Kuznetsov et al. OSDI 2014.

Our Assumptions

- Only low overhead is acceptable
  - 5-10% may be undetectable by the user [1]
- Have program source code
- Original program is buggy but benign
- Attackers exploit bugs to read/write unintended data

1. Everything You Want to Know About Pointer-Based Checking. Nagarakatte et al. SNAPL 2015.

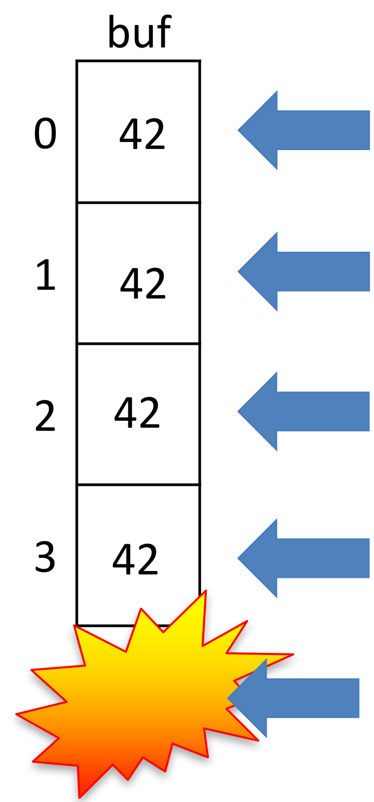
What is Memory Safety?

Reads/writes through pointers R/W the object to which the pointer was most recently assigned

- Confidentiality ⇔ reads
- Integrity ⇔ writes

Spatial Memory Safety

```
i = 0;
while (i <= 4) {
   buf[i++] = 42;
}
```



Why not Complete Memory Safety?

- Protecting all data is too costly
  - ~100% overhead [1,2]
- Overhead is a function of # of dynamic checks

1. SoftBound: Highly Compatible and Complete Memory Safety for C. Nagarakatte et al. PLDI 2009
2. CETS: Compiler-Enforced Temporal Safety for C. Nagarakatte et al. ISMM 2010.

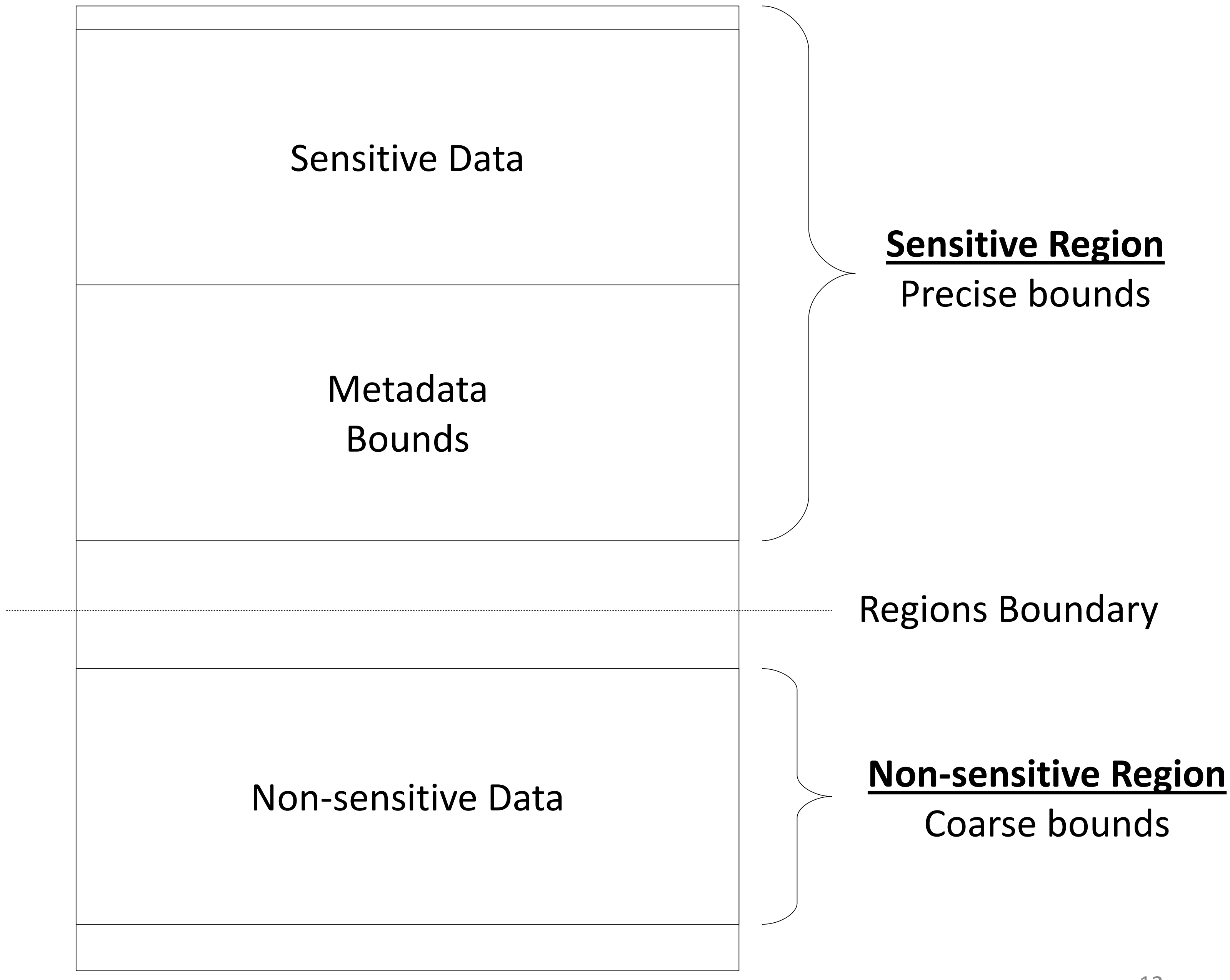
DCI Contributions

- New policy for protecting selected data
- Lower overhead than full memory safety
- Coarse bounds check implementations
- Security evaluation
  - Detects attacks in mbedTLS

Design

DCI Policy

- *Sensitive pointers* can only access the intended sensitive object
- *Non-sensitive pointers* can access any non-sensitive data
- Explicit data-flow between sensitive and non-sensitive objects is forbidden


Sensitive Data
Metadata
Bounds
Sensitive Region
Precise bounds
Regions Boundary
Non-sensitive Data
Non-sensitive Region
Coarse bounds

Annotations

- Type based
- Marks type and members
- Cannot be cast away
- Mixed sensitivity `structs` not allowed

```
__attribute__((annotate("sensitive")))
```

Type Sensitivity

- All nested types have same sensitivity
- Pointers to sensitive types are sensitive
- Nesting a primitive type *P* does not make **every** *P* sensitive

```
struct S {
  int x;
  struct T *t;
};

struct T {
  float z;
  struct U *u;
}

struct U {
  …
};
```

Implementation

Annotation Example (1)

```
struct foo {
    char* name;
    int x,y,z;
};
```

```
__attribute__((annotate("sensitive"))) struct foo ignore;
```

Sensitive Allocation Example

```
struct foo* ptr = malloc(sizeof(struct foo));
```

Sensitive Allocation Example

```
~~struct foo* ptr = malloc(sizeof(struct foo));~~
struct foo* ptr = sensitive_malloc(sizeof(struct foo));
```

```
table[&ptr].base = ptr;
table[&ptr].end = ptr + sizeof(struct foo);
```

Sensitive Access Example

```
bounds = table[&ptr]
assert(bounds.base <= &(ptr->x));
assert(&(ptr->x) + sizeof(ptr.x) < bounds.end);


ptr->x = 5;
```

Non-sensitive Example

```
int* arr = malloc(sizeof(int)*100);

int* idx = arr+8;

*idx = 42;
```

Non-sensitive Example

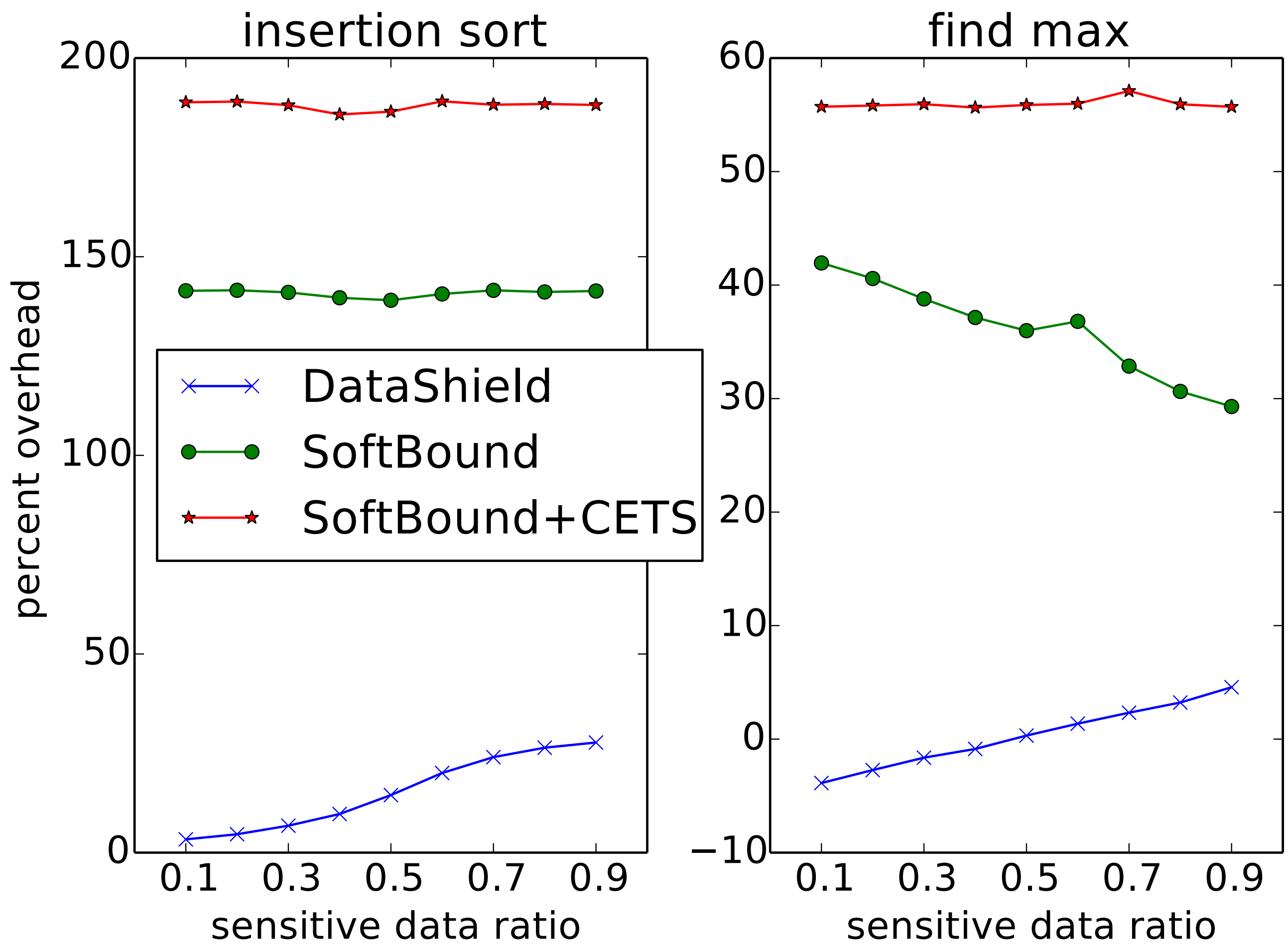
```
int* arr = malloc(sizeof(int)*100);
int* arr = non_sensitive_malloc(sizeof(int)*100);

int* idx = arr+8;

*idx = 42;

int* idx_masked = idx & mask;
*idx_masked = 42;
```

Implementation Overview

1. Compile time analysis
    - Module-level analysis
    - Inter-procedural type & context sensitive analysis
2. Runtime
    - Separate sensitive/non-sensitive variables
    - Heap, Stack, Global

Evaluation

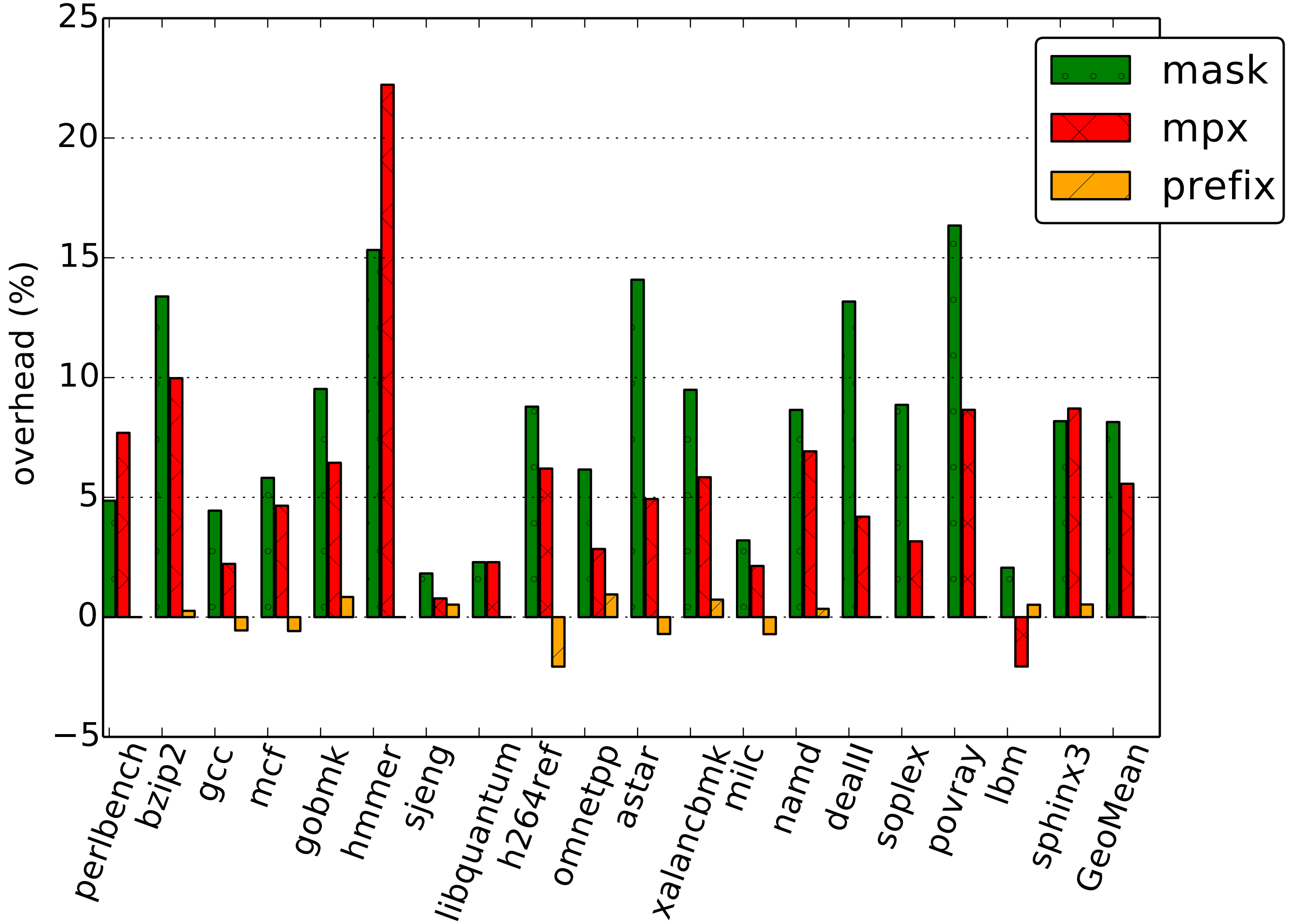
Evaluation - Sensitivity Ratio



Evaluation – SPEC CPU2006

- No annotations added
- Sensitive regions bounds still enforced
- Measured overhead of code that does not access sensitive data

Evaluation – Coarse Bounds Checks



Security Evaluation

- CVE-2015-5291 from mbedTLS
- Malicious session ticket causes *buffer overflow*
- Proof of concept exploit publically available
- Compiled pre-patch version of mbedTLS
- Ran exploit
- Detected by DCI

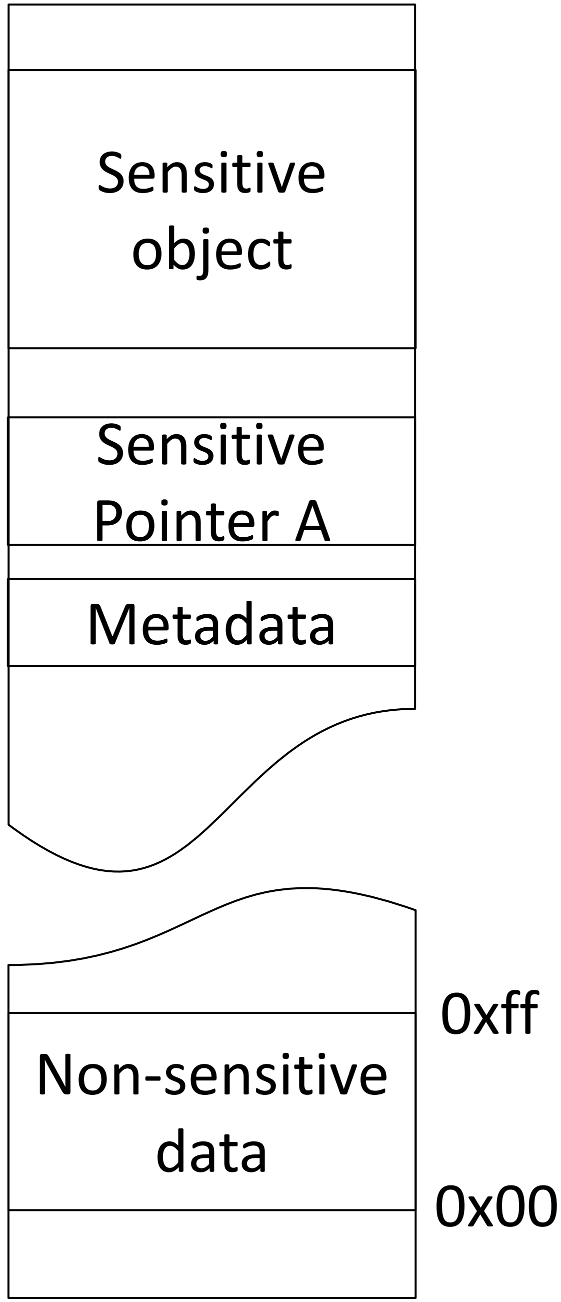
Extra Slides

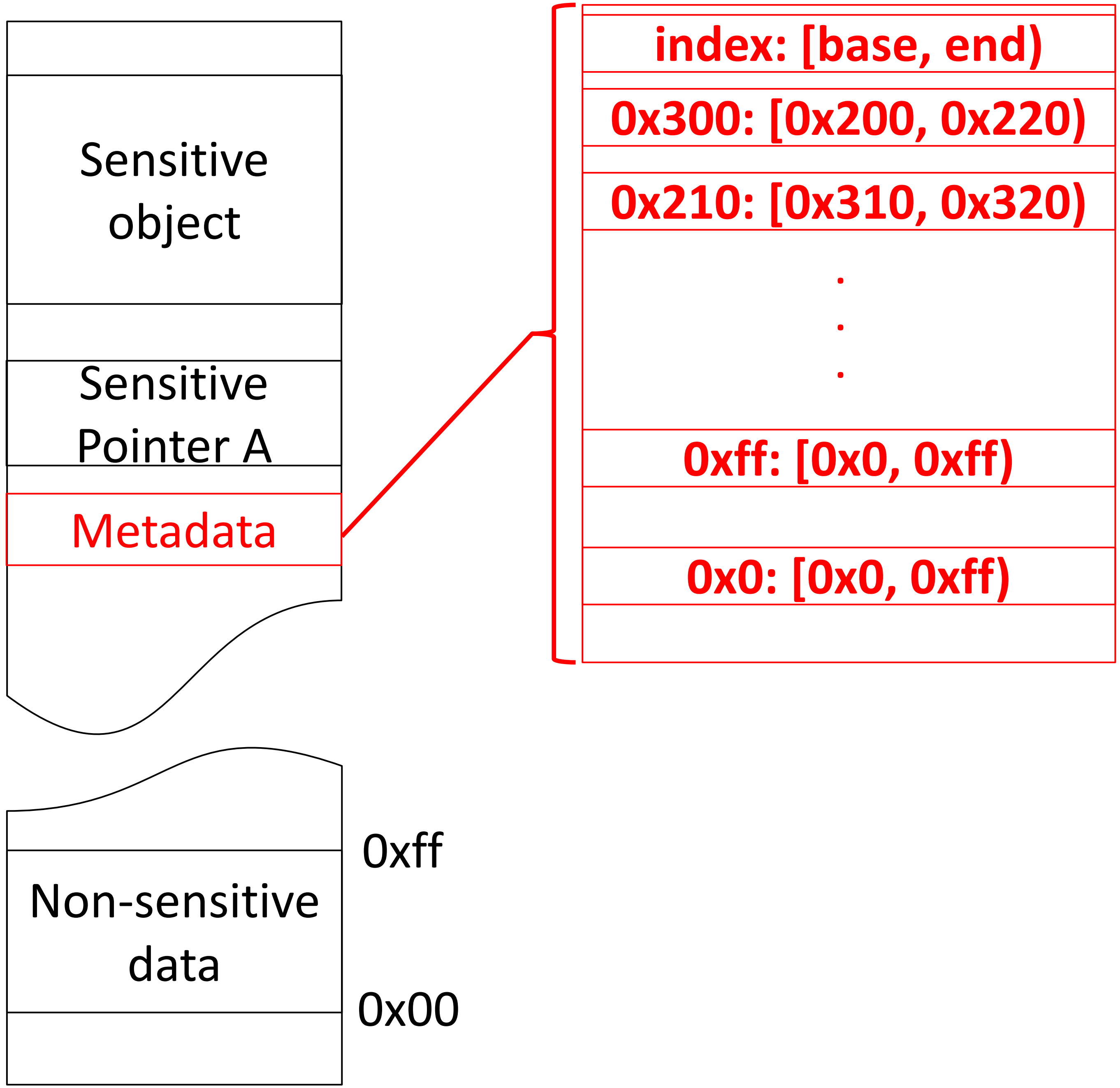
DCI Summary

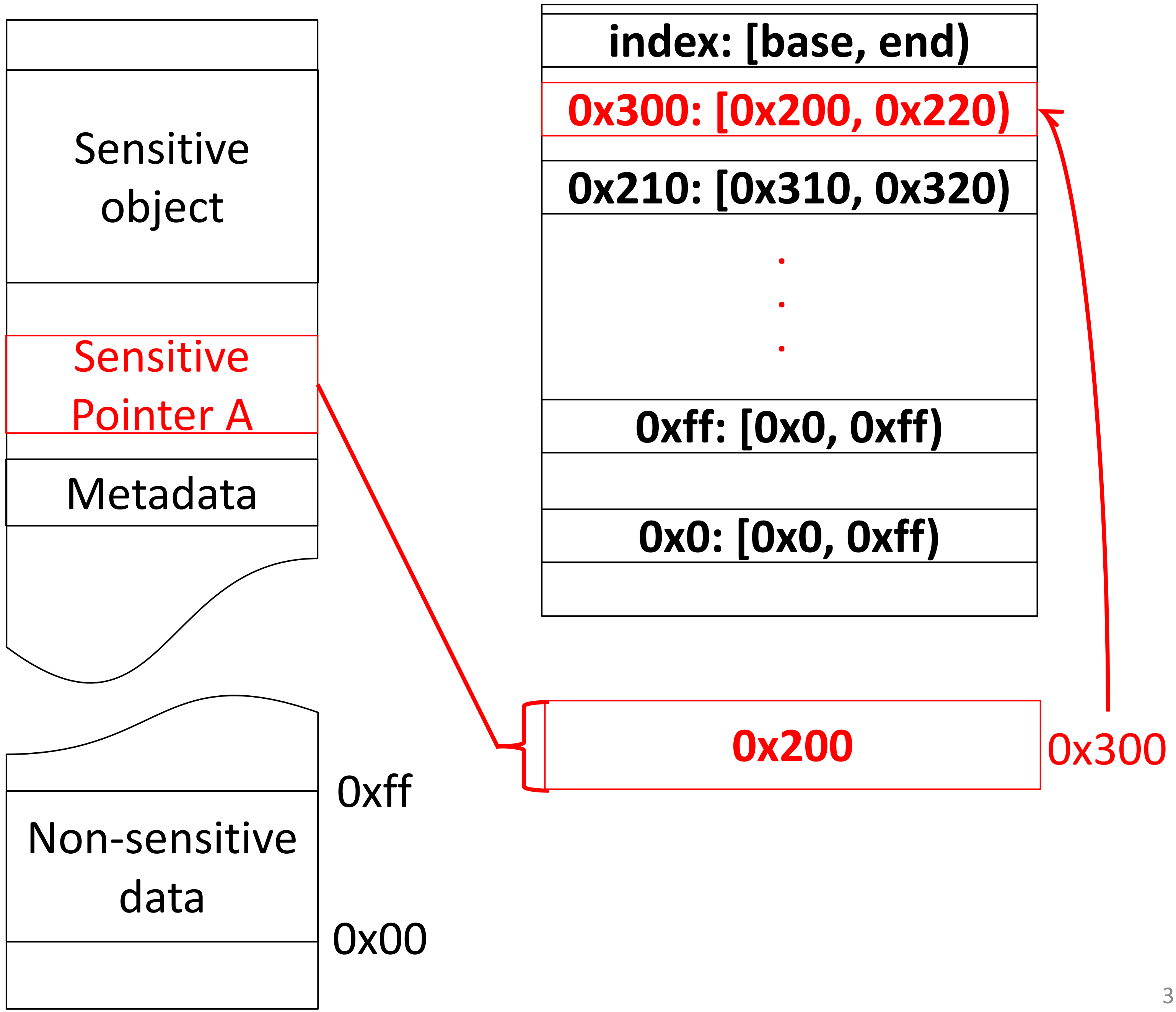
- *Strong* protection for *sensitive data*
- *Weaker* (but lower overhead) protection for *non-sensitive*
- Lower overhead vs. complete memory safety
- Detects vulnerabilities in production software

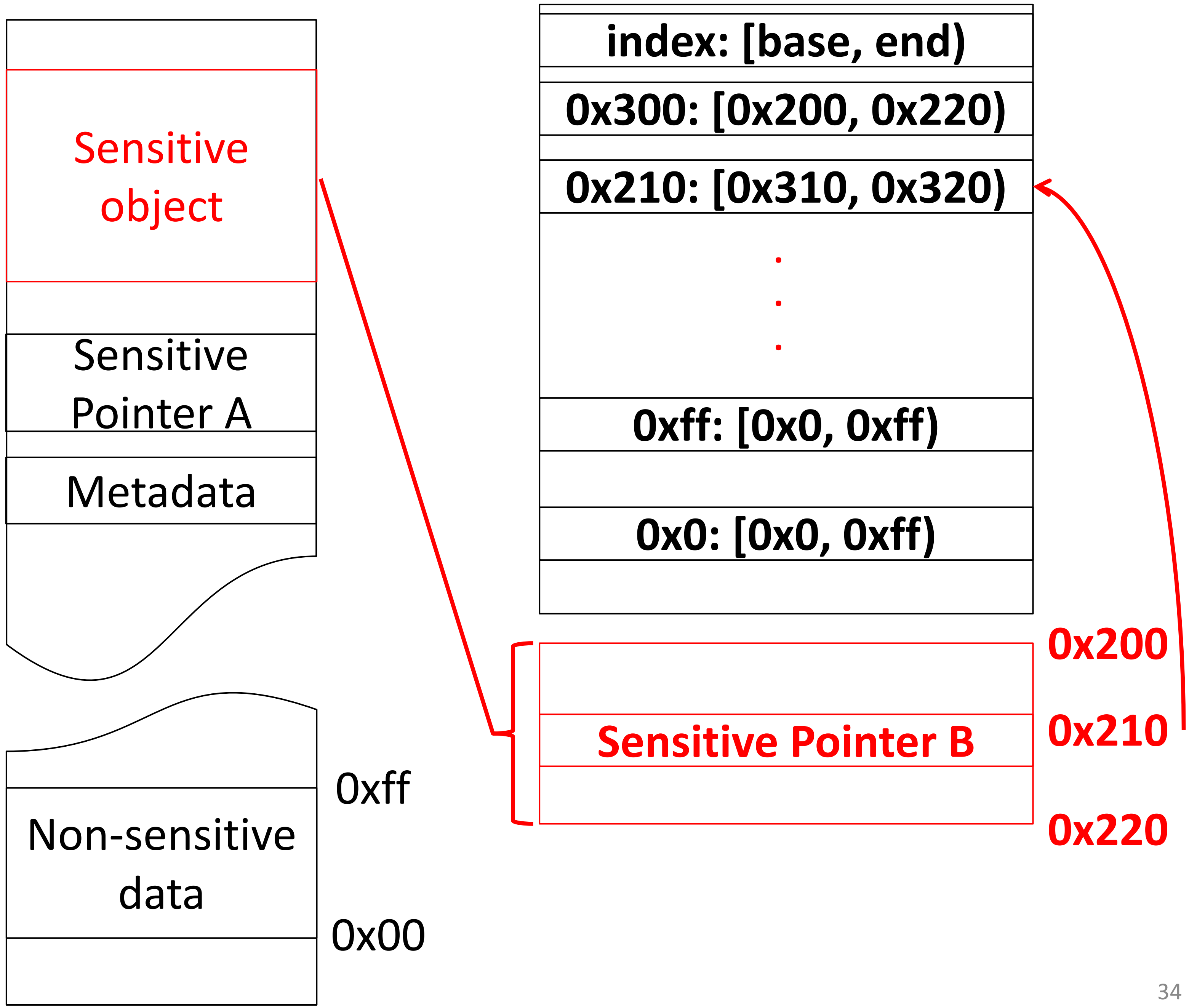
https://github.com/HexHive/datashield

Extra Slides


Sensitive object
Sensitive Pointer A
Metadata
0xff
Non-sensitive data
0x00


Sensitive object
Sensitive Pointer A
Metadata
Non-sensitive data
0xff
0x00
index: [base, end)
0x300: [0x200, 0x220)
0x210: [0x310, 0x320)
.
.
.
0xff: [0x0, 0xff)
0x0: [0x0, 0xff)


Sensitive object
Sensitive Pointer A
Metadata
Non-sensitive data
0xff
0x00
index: [base, end)
0x300: [0x200, 0x220)
0x210: [0x310, 0x320)
0xff: [0x0, 0xff)
0x0: [0x0, 0xff)
0x200
0x300


Sensitive object
Sensitive Pointer A
Metadata
Non-sensitive data
0xff
0x00
index: [base, end)
0x300: [0x200, 0x220)
0x210: [0x310, 0x320)
0xff: [0x0, 0xff)
0x0: [0x0, 0xff)
Sensitive Pointer B
0x200
0x210
0x220

Standard Library Support

- Option 1: per-application lib
  - Rewrite specialized versions of each library function on-demand
  - Same analysis/rewriting as application
  - Con: Requires unique lib per application
  - Pro: Internal checks
- Option 2: drop in replacement lib
  - Make all library allocated data non-sensitive
  - Use wrappers and copies for sensitive
  - Con: No internal checks
  - Pro: Allows single, compatible lib

Evaluation - astar

- C++: 4,285 LoC
- Relaxed policy: separation mode
  - Primitive arithmetic does not propagate sensitivity
  - Reduces overhead 96% -> 9.12%
  - Reduce sensitive bounds checks by 10^6 times

Evaluation - mbedTLS

- C: 30,000 LoC
- Instrument sample server and client
- Annotate `ssl_context`
- 35.7% overhead

- Challenge: sensitive data passed to callee through function pointer

Limitations

- Variadic arguments as sensitive
- Temporal metadata not implemented
- Region-based temporal protection if one sensitive type
  - Similar to Cling [1]

1. Cling: A Memory Allocation to Mitigate Dangling Pointers. P. Akritidis. USENIX Security 2010