HeapTherapy+: Efficient Handling of (Almost) All Heap Vulnerabilities Using Targeted Calling-Context Encoding

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NEC Laboratories America
Relentless passion for innovation

Trend of Memory Vulnerability Exploitation

- Memory vulnerability exploitation
  - Stack-based
  - Heap-based
- Many effective protection for call stacks
  - Stack canaries
  - Reordering local variables
  - Safe SEH (Structured Exception Handling)
- Heap vulnerability exploitation becomes the trend
  - **Heartbleed**: heap buffer overread
  - **WannaCry**: heap buffer overwrite
  - Popular **ROP (return oriented programming) attack** [1]:
    Heap overflow => overwrite a function pointer => **stack pivoting**

[1] McAfee, “Emerging ‘Stack Pivoting’ Exploits Bypass Common Security”, 2013

"Because the success of stack-based exploits has been reduced by the numerous security measures, heap-based attacks are now common" **[Ratanaworabhan 2009]**

[Ratanaworabhan 2009] Ratanaworabhan, et al.."NOZZLE: A Defense Against Heap-spraying Code Injection Attacks." *USENIX Security*. 2009.

Types of Heap Vulnerabilities

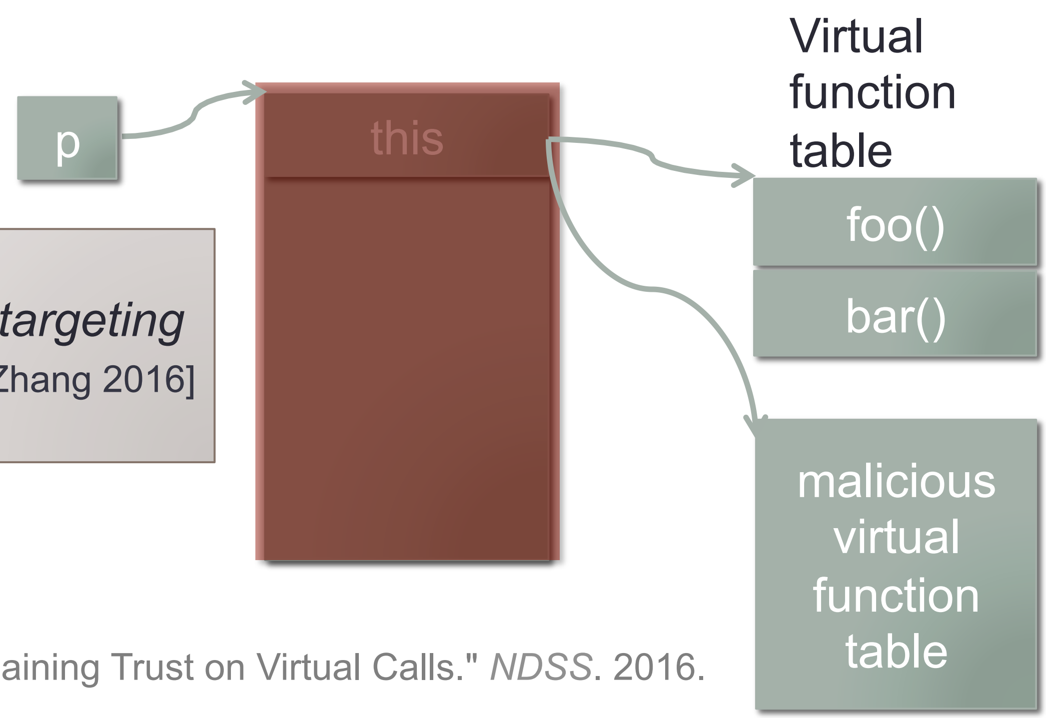
- Uninitialized read
  - Information leakage; …

```
str = (char*) malloc(128);
… // str is not initialized
cout << str;
```

Types of Heap Vulnerabilities

- Uninitialized read
  - Information leakage; …
- Use-after-free
  - Control-flow hijacking; …

```
(1) D *p = new D();
…
(2) delete p;
(3) …// buffer re-allocated and used
(4) p->foo(); // use-after-free
```



> *"More than 50% of known attacks targeting Windows 7 exploit use-after-free"* [Zhang 2016]

[Zhang 2016] Zhang, Chao, et al. "VTrust: Regaining Trust on Virtual Calls." *NDSS*. 2016.

Types of Heap Vulnerabilities

- Uninitialized read
  - Information leakage; …
- Use-after-free
  - Control-flow hijacking; …
- Buffer overflow
  - Over-write
    - Manipulating data; control-flow hijacking; …
  - Over-read
    - Information leakage; …

Existing Measures

- Checking every buffer access is great…but expensive
  - SoftBound (handle overflow and use-after-free): 67%
  - AddressSanitizer (handle overflow and use-after-free): 73%
  - MemorySanitizer (handle uninitialized read): 2.5x
- SFI (software fault isolation), CFI (control-flow integrity), XFI, CPI (code pointer integrity), …
  - Challenges when working with existing shared libs (legacy code)
  - Some (like XFI) are still very expensive
- Our previous work
  - Cruiser [PLDI'11], Kruiser [NDSS'12]: only handle overwrite
  - HeapTherapy [DSN'15]: only handle overwrite and overread

A Patching Perspective

- Patching is an indispensable step throughout the life of a software system; however,
  - 153 days on average for delivering a patch [1]
  - Only 65% of vulnerabilities have patches available [2]
  - Fresh patches break systems frequently

- ***Our goals***
  - Handle heap **overflow, uninitialized read, and use-after-free**
  - Generate patches instantly with **zero** manual diagnosis efforts
  - Install patches without altering code, i.e., **code-less patching**
  - A **very small** overhead

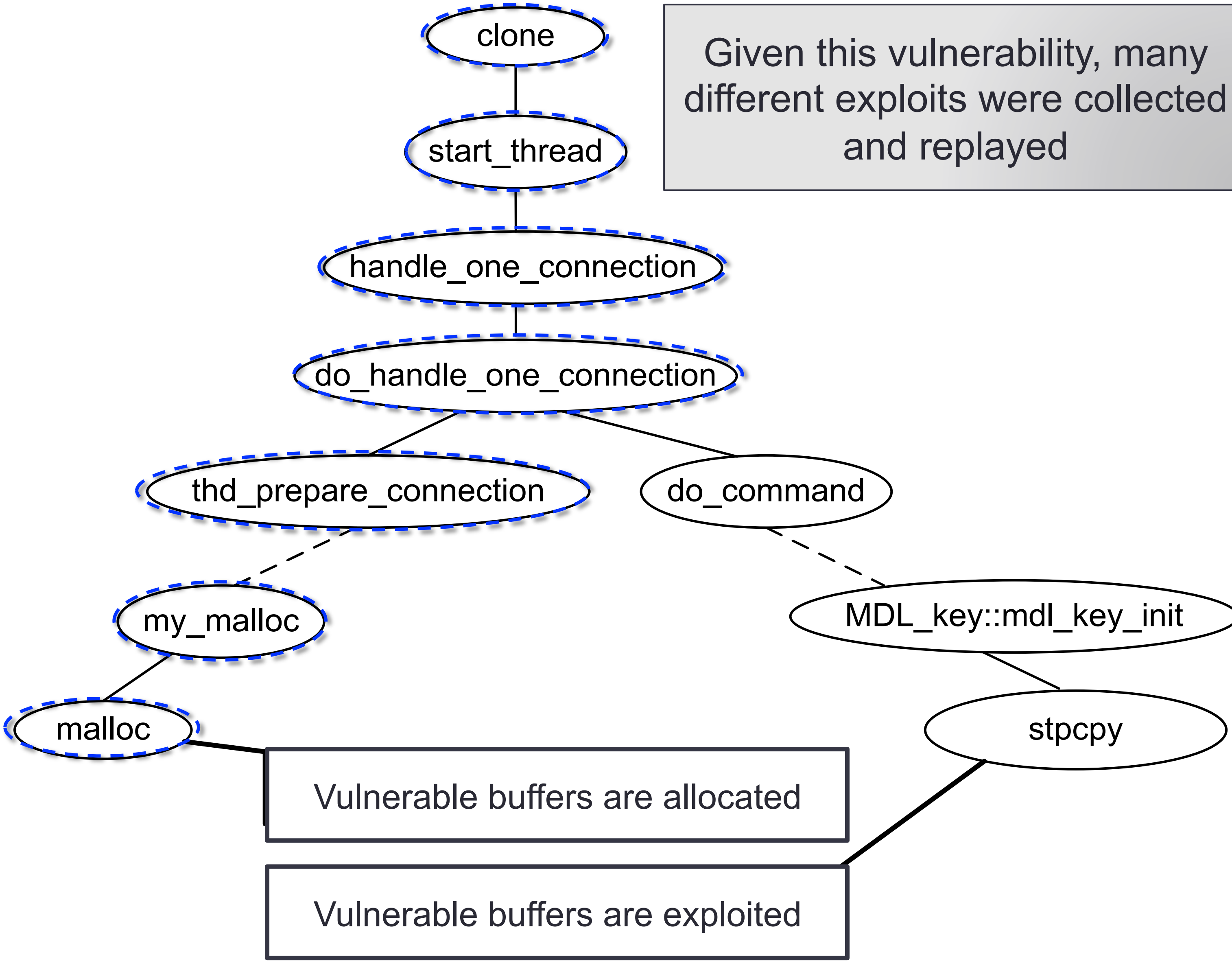
[1] S. Frei, "The Known Unknowns," 2013.
[2] S. frei, "" "End-point security failures, insight gained from secunia psi scans," 2011.

Hypotheses

Given a heap buffer overflow bug, the vulnerable buffers share the same calling context when they are *allocated*

More generally, for a use-after-free or uninitialized-read vulnerability, the vulnerable buffers share the same calling context when they are allocated

Verifying Hypotheses



Given this vulnerability, many different exploits were collected and replayed

Main Approach

Using **allocation-time calling context** to characterize vulnerable buffers

1. When replaying the attack, record the allocation-time calling context of each buffer. When the offending operation (e.g., overflow) is detected, output the allocation-time calling context of the vulnerable buffer

2. During runtime, if a buffer being allocated has that allocation-time calling context, enhance it

Challenges

- How to retrieve and compare calling contexts efficiently?
  - Retrieving calling context via stack walking is too **expensive**
  - ASLR makes the collected RAs **useless**
- How to bridge offline attack analysis and online defense generation?
- How to achieve code-less patching?
- How to handle the diverse vulnerabilities in a uniform way?

- **Targeted Calling Context Encoding**
- **Offline Attack Analysis and Patch Generation**
- **Online Defense Generation**

Calling Context Encoding

- Using an integer (or very few integers) to encode the calling context
  - The integer is updated at each function *call* and *return*; using simple arithmetic operations
- <3% slowdown; concise representation
- Wide applications: testing coverage, anomaly detection, compilation optimization, logging, …

	PCC [Bond 2007]	PCCE [Sumner 2010]	DeltaPath [Zeng 2014]
Support Object-Oriented	✔	✗	✔
Decoding	✗	✔	✔
Scalability	✗	✗	✔

Example: PCC

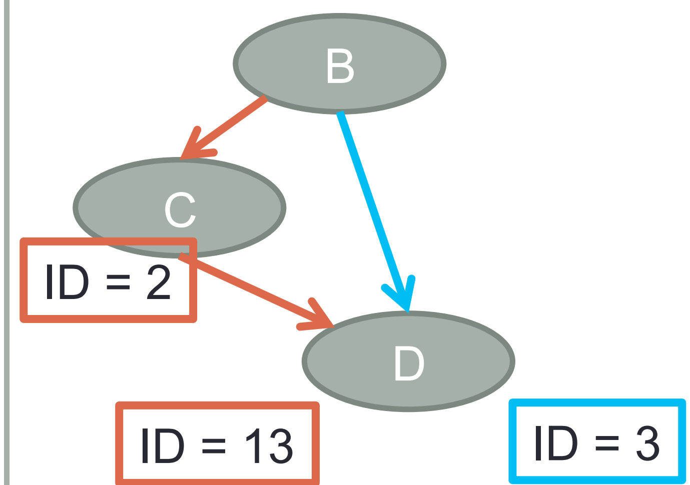
- Goal: each unique ID represents a unique calling context

```
ID = 0

B() {          // t = ID
 C();          // ID = t * 3 + 2
 D();          // ID = t * 3 + 3
}

C() {          // t = ID
D();           // ID = t * 3 + 7
}

D() {
 Sensitive API! // calling context?
}
```



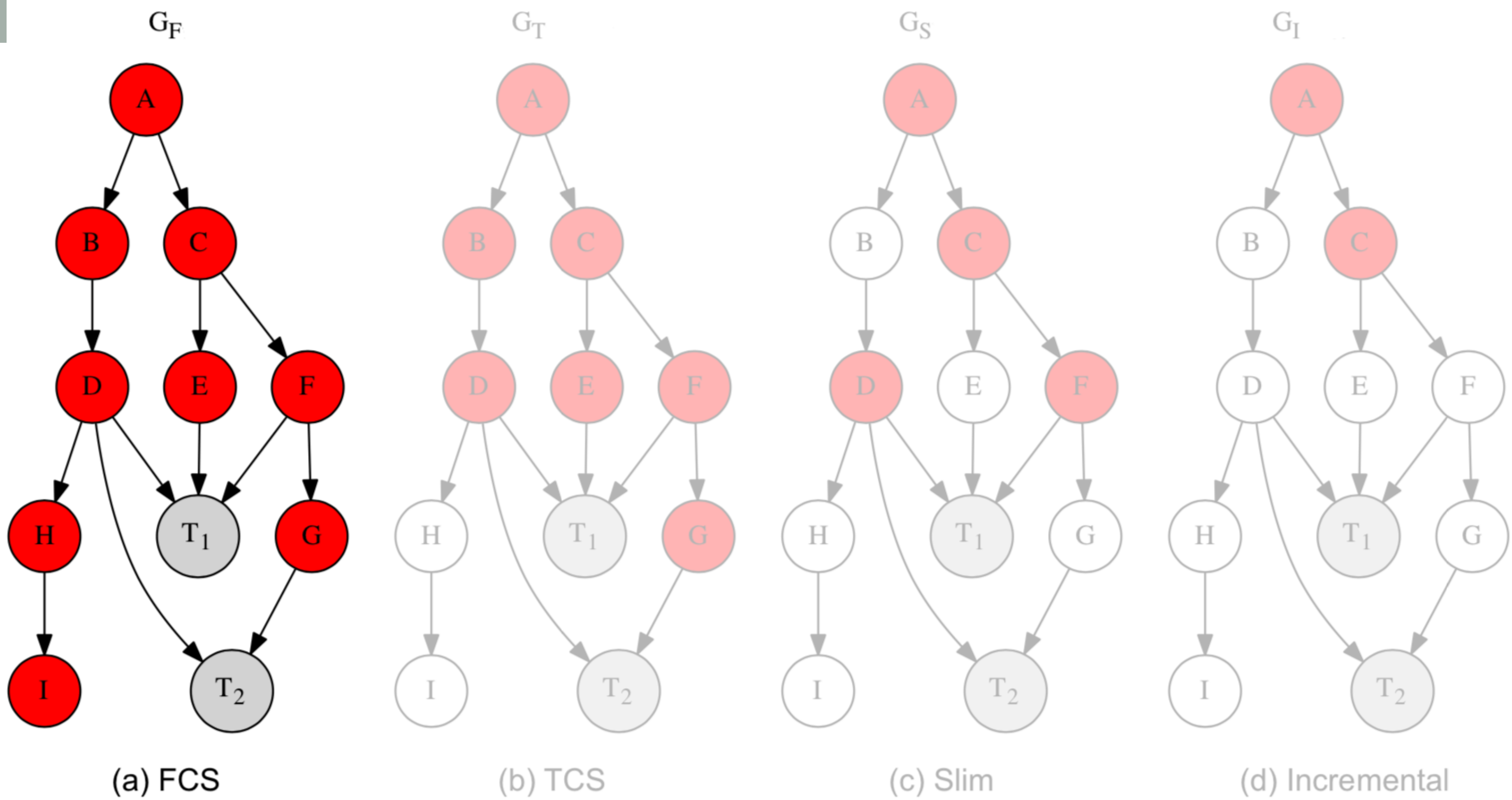
Answer: Read the variable “ID” to get the calling context ID

Targeted Calling Context Encoding

- A set of ideas that can minimize the encoding overhead

- **Key insight**: When the *target functions*, whose calling contexts are of interest, are known, many call sites do no need to be instrumented
  - E.g., some functions never appear in the calling contexts that lead to the target functions

- Target functions in our work:
  - malloc, calloc, realloc, memalign, aligned_alloc



(a) FCS (full-call-site instrumentation): original PCC encoding

(b) TCS (targeted-call-site): **H** and **I** cannot reach the targets **T1** and **T2**

(c) Slim: **B**, **E** and **G** each has only one out-going edge that reaches the targets

(d) Incremental: **F-T_1** and **F-G-T_2** can be distinguished through the target

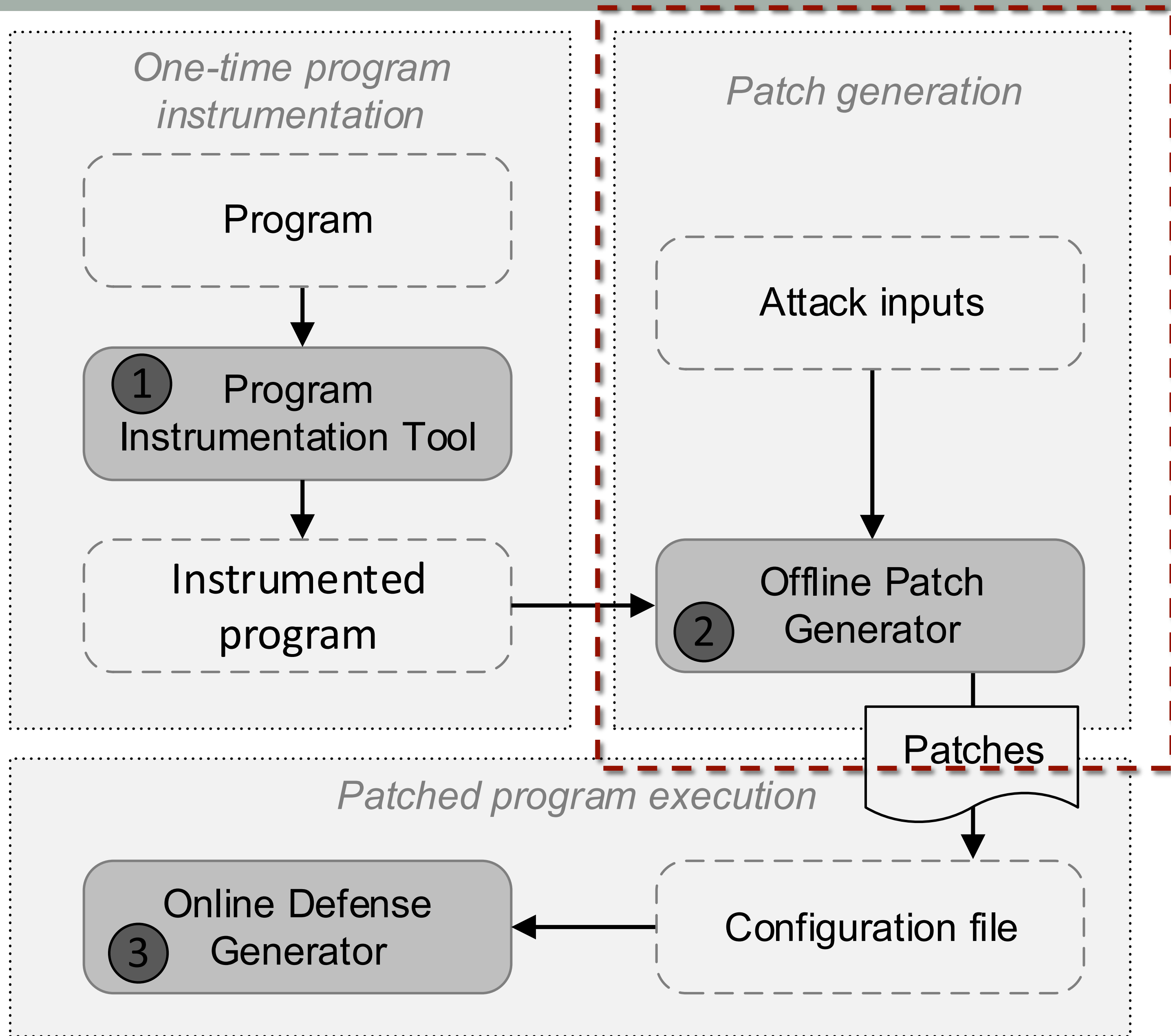
Encoding overhead

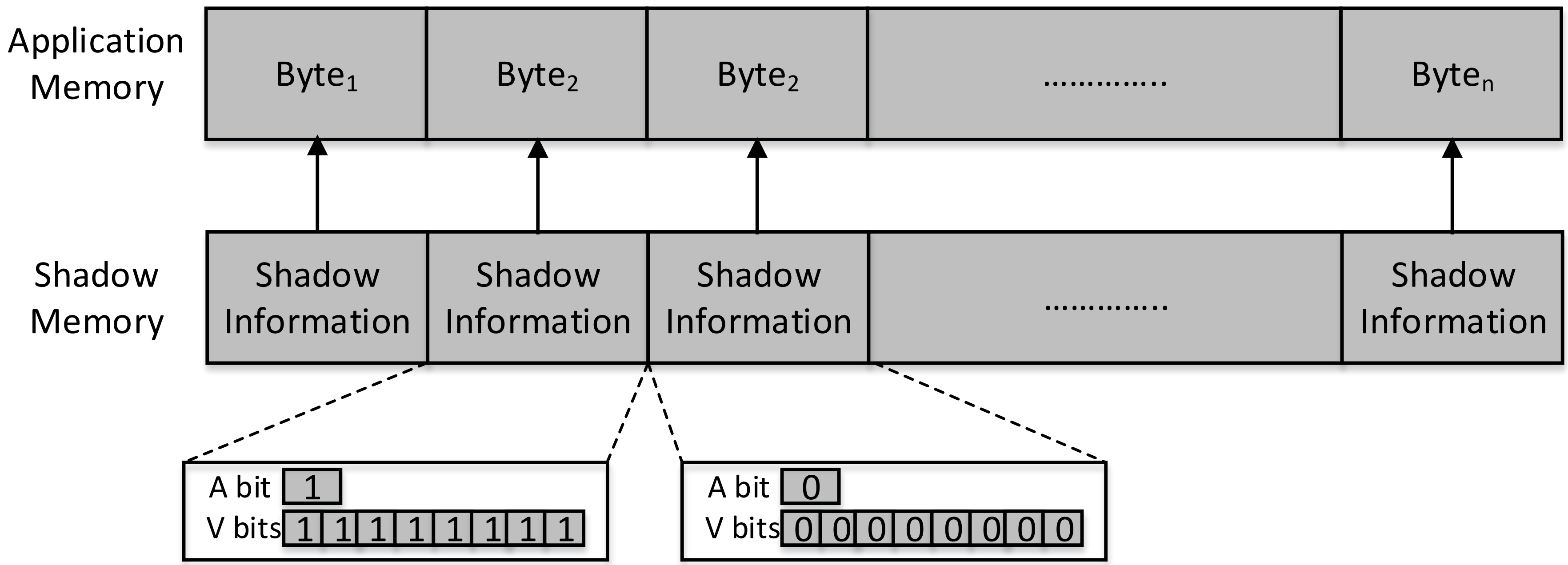
- Implementation: added an LLVM pass for instrumentation
- Evaluation: SPEC CPU2006 Integer

- Size overhead
  - PCC: 12%
  - Targeted Calling context Encoding: 4.4%
  - 2.7x of improvement

- Speed overhead
  - PCC: 2.4%
  - Targeted Calling Context Encoding: 0.4%
  - **6x of speed up**

- **Targeted Calling Context Encoding**
- **Offline Attack Analysis and Patch Generation**
- **Online Defense Generation**


One-time program instrumentation
Program
1 Program Instrumentation Tool
Instrumented program
Patch generation
Attack inputs
Offline Patch Generator 2
Patches
Patched program execution
Online Defense Generator 3
Configuration file



- Accessibility-bit (A-bit): whether the byte can be accessed
  - If a buffer has been free-ed, all its A-bits are 0
  - Each buffer is surrounded by two red zones (16B each), whose A-bits are 0
- Validity-bit (V-bit): whether the bit is initialized
  - When a fresh buffer is malloc-ed, all it V-bits are 0
- Each buffer's alloc-API and CCID are recorded

(1) Detect overflow: an overflow will touch the inaccessible red zone
(2) Detect use-after-free: a free-ed buffer is set as inaccessible and then added to a queue to delay the space reuse
(3) Detect uninitialized read: more complex, but mainly relies on V-bits

Patches as a configuration file

- Each patch is simply a tuple

  <alloc-API, CCID, vul-type>

- Code-less patching: to “install” a patch, just add one line in the config file

Configuration file

```
<API,        CCID,         Vulnerability>
-------------------------------------------
<memalign, 1854955292,  OVERFLOW>
<calloc,     8643565443,  USE-AFTER-FREE>
<malloc,     2598251483,  UNINITIALIZED-READ>
… ...
```

- **Targeted Calling Context Encoding**
- **Offline Attack Analysis and Patch Generation**
- **Online Defense Generation**

Patches read into a hash table

Configuration file

<API,	*CCID,*	*Vulnerability>*
<memalign,	1854955292,	OVERFLOW>
<calloc,	8643565443,	USE-AFTER-FREE>
<malloc,	2598251483,	UNINITIALIZED-READ>
… ...		

Read by *Online Defense Generator*

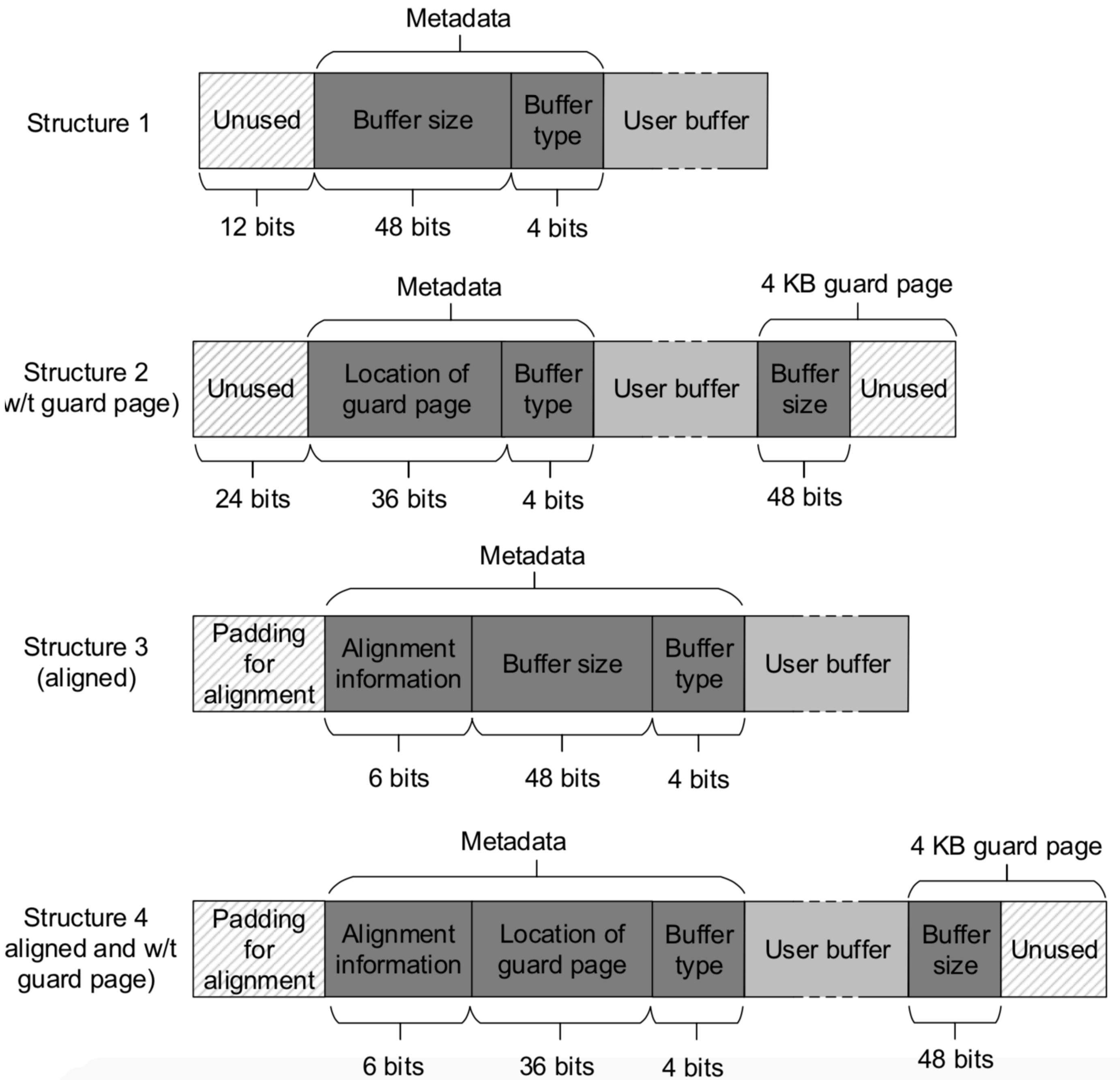
A shared lib

Hash table

Key	*Value*
<MEMALIGN, 1854955292>	$(001)_2$
<CALLOC, 8643565443>	$(010)_2$
<MALLOC, 2598251483>	$(100)_2$
…..	… …

Vulnerability Handling

- Handle overflow
  - Append a guard page to each vulnerable buffer
- Handle use-after-free
  - Delay the deallocation of the free-ed vulnerable buffers
- Handle uninitialized read
  - Initialize the newly allocated vulnerable buffer with zeros


Metadata
Structure 1
Unused
Buffer size
Buffer type
User buffer
12 bits
48 bits
4 bits
Metadata
4 KB guard page
Structure 2 (w/t guard page)
Unused
Location of guard page
Buffer type
User buffer
Buffer size
Unused
24 bits
36 bits
4 bits
48 bits
Metadata
Structure 3 (aligned)
Padding for alignment
Alignment information
Buffer size
Buffer type
User buffer
6 bits
48 bits
4 bits
Metadata
4 KB guard page
Structure 4 aligned and w/t guard page)
Padding for alignment
Alignment information
Location of guard page
Buffer type
User buffer
Buffer size
Unused
6 bits
36 bits
4 bits
48 bits

Evaluation

- Effectiveness

Program	Vulnerability	Reference
Heartbleed	UR & Overflow	CVE-2014-0160
bc-1.06	Overflow	Bugbench [57]
GhostXPS 9.21	UR	CVE-2017-9740
optipng-0.6.4	UaF	CVE-2015-7801
tiff-4.0.8	Overflow	CVE-2017-9935
wavpack-5.1.0	UaF	CVE-2018-7253
libming-0.4.8	Overflow	CVE-2018-7877
SAMATE Dataset	Variety	23 heap bugs [58]

- Efficiency
  - SPEC CPU2006: 4.3% (zero patch), 4.7% (one patch), 5.2% (five)
    - 1.9% due to malloc/free hooking, 2% due to buffer metadata maintaining
    - The 3.9% can be eliminated if our system is integrated into the allocator
  - MySQL (w/t Heartbleed): mysql-stress-test.pl; no observable overhead
  - Nginx (w/t Heartbleed): AB; throughput overhead 4.2%

Contribution and Limitations

- The first work that can patch all the following heap vulnerabilities without manual analysis effort
  - **Overflow, use after free, uninitialized read**
- Prominent features:
  - Code-less patching
  - Very small overhead (several percentages)
  - You can still use your favorite heap allocator
- A showcase how heavyweight offline analysis can be seamlessly combined with lightweight online defenses
- **Targeted calling context encoding: 6x speed up**
- Limitations
  - Cannot handle some vulnerabilities: e.g., an overflow within a struct
  - Overflow leads to DoS: padding may be considered, as used in HeapTherapy
  - Re-compilation needed: binary instrumentation is possible

THANKS!

Q&A

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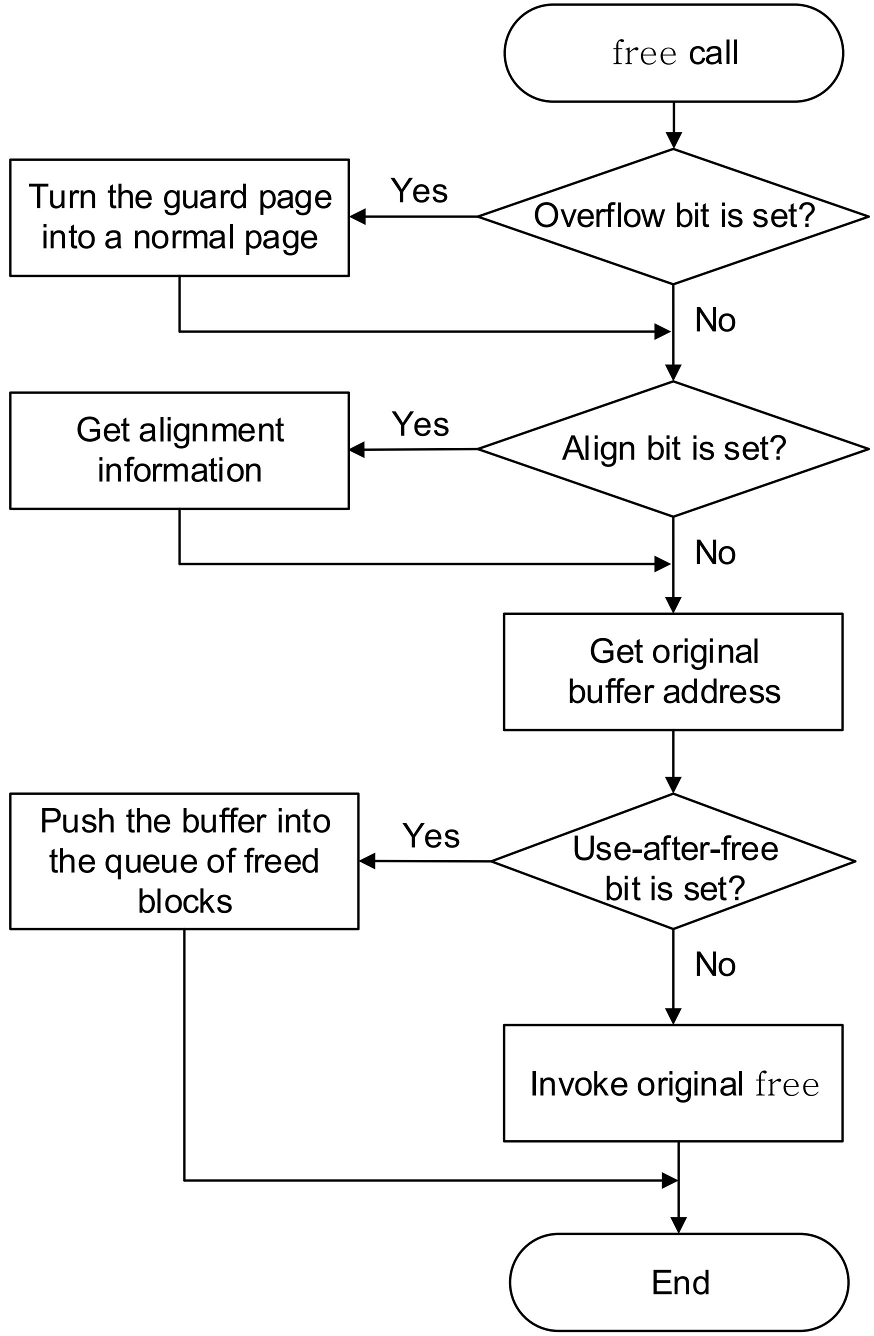
free call
Overflow bit is set?
Yes
Turn the guard page into a normal page
No
Align bit is set?
Yes
Get alignment information
No
Get original buffer address
Use-after-free bit is set?
Yes
Push the buffer into the queue of freed blocks
No
Invoke original free
End