Stack Bounds Protection with Low Fat Pointers

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Overview

Heap Bounds Protection with Low Fat Pointers, CC 2016

New method for detecting bounds overflow errors without explicit metadata

**Pros:** Fast (~13% w.o.), near zero memory overheads, highly compatible

**Cons:** Only protects heap allocation (malloc) only!

Stack

Heap Bounds Protection with Low Fat Pointers, NDSS 2017

Extend bounds overflow protection to **stack objects**

Requires a whole new bag of tricks

**Pros:** Fast (~17% w.o.), near zero memory overheads, highly compatible
Motivation

Buffer overflows (spatial memory errors) are classic security problem – from 1970s to present

Continue to be an active threat: Heartbleed, Ghost, Cloudbleed (Feb 2017), etc.

Common defenses have weaknesses:

- ASLR^Cache: Practical Cache Attacks on the MMU (NDSS’17)

Stronger defenses are rarely used

- Overheads
- Compatibility
Countermeasures

Perennial problem, many countermeasures have been proposed.

**Indirect methods:**

- ASLR and DEP
- Control Flow Integrity (CFI), Code Pointer Integrity, etc.
- Data Flow Integrity (DFI)
- Shadow Stacks, etc.

**Direct methods:**

- Many existing systems: AddressSanitizer, SoftBound, SafeC, CCured, BaggyBounds, PAriCheck, low-fat-pointers, etc. etc.
- Most systems track *bounds metadata*  

```c
if (p < base(0) || p >= base(0)+size(0))
    error();
*p = v;
```
Bounds Checking Approaches

“Fat pointers” combine pointers and meta data

```c
struct fat_ptr {
    void *ptr;
    void *base;
    size_t size;
};
```

`size(p) = p.size`
`base(p) = p.base`

Shadow space stores metadata in separate memory

```c
size(p) = SHADOW[p].size
base(p) = SHADOW[p].base
```
Low Fat Pointers

**Low fat pointers** are like fat pointers *without the fat*:

```c
union low_fat_ptr {
    void *ptr;
    uintptr_t size:10;
};
```

```c
size(p) = p.un.size
base(p) = (p / size(p)) * size(p)
```

Compact encoding with no space overheads.
Flexible Low Fat Pointers

A simple encoding does not work well in practice

- Only 48 bits are used → high bits must be zero!
- 10 bits not big enough \(2^{10}=1024\) max object size…

Better approach: *Heap Bounds Protection with Low Fat Pointers* (CC’16)

- Virtual address space subdivided into several large regions (eg. 32GB each)
- Each region is used to allocate objects of a specific size (16B, 32B, 48B, etc.).
Bounds Checking with Low Fat Pointers

Object size is linked to regions, and used for bounds checking:

$$\text{size}(p) = \text{SIZES}[p / 32\text{GB}]$$
$$\text{base}(p) = (p / \text{size}(p)) \times \text{size}(p)$$

if ($p < \text{base}(p)$ || $p \geq \text{base}(p)+\text{size}(p)$)
error();
*p = v;

This works fine for heap allocation, but not for stack allocation!
Stack Challenges

Problem #1: how to round up object size to allocation size?

Problem #2: what should the alignment be?

Problem #3: where to place the object?

Problem #4: how to not waste memory?

Solutions:

Lookup tables
Virtual memory tricks
Allocation Size Over Approximation

Given: `char object[N]; /* Stack allocation */`

Problem: which region does `object` belong to???

Must decide in a few instructions.

Solution:

Use a lookup table (`SIZES`) indexed by `lzcnt(N)`

```
char object[50];

lzcnt(50) = 58
```

```
55 56 57 58 59 60 61 62 63 64
512 256 128  64  32  16  16  16  16  16
```

```
lzcnt %rax, %rax
sub SIZES(%rax,8), %rsp
```
Allocation Size Alignment

**Problem:** We have to align the object.

\[
\text{base}(p) = (p / \text{size}(p)) \times \text{size}(p)
\]

**Solution:** just use the \texttt{attribute(aligned(N))}: 

\[
\text{char object[64] attribute(aligned(64));}
\]

For \textit{variable length} objects we also use lookup tables.

\[
\begin{array}{cccccccc}
55 & 56 & 57 & 58 & 59 & 60 & 61 & 62 & 63 & 64 \\
-512 & -256 & -128 & -64 & -32 & -16 & -16 & -16 & -16 & -16 \\
\end{array}
\]

\texttt{lzcnt %rax, %rax and MASKS(,%rax,8), %rsp}
Stack Object Mirroring

**Problem:** stack objects are allocated from the stack!

**Solution:** Split the stack into N stacks, one for each size region:

Related work: shadow stacks
Stack Object Mirroring (cont.)

Stack Object Mirroring also implemented using tables:

Each object allocated in correction region.

Backwards compatible with deallocation, `longjmp`, C++ exceptions, asm code, etc.

**CON**: Uses more memory

1 stack replaced with N stacks.

Fragmentation.

\[
\Delta_{58} = \&\text{region } #4 - \&\text{stack}
\]

\[
lzcnt \ %\text{rax}, \ %\text{rax} \\
\text{add } \text{OFFSETS}(,\%\text{rax},8), \ %\text{rsp}
\]
Memory Aliasing

**Problem:** Increasing stack memory is unsatisfactory.

**Solution:** make all stacks *share the same physical memory*:

Program uses a single stack
(same as before)

Uses *shared memory objects*

```
shm_open
```
Evaluation Basic (timings)

- Baseline: -O2
- Lowfat: 63% overhead (base unoptimized)
- Lowfat alias: 58% overhead with memory aliasing
- Address Sanitizer: 92% overhead
Evaluation (memory)

- 7% overhead
- 3% overhead with memory aliasing
Evaluation Timings Optimized (integrity/writes only [WO])

- **Lowfat**: 17% overhead
- **Address Sanitizer (ASAN)**: 45% overhead
Summary and Conclusion

Low fat stack allocation effectively replaces:

```
sub %rax, %rsp
and $-16, %rsp
mov %rsp, %rbx
```

with

```
lzcnt %rax, %rax
sub SIZES(%rax,8), %rsp
and MASKS(%rax,8), %rsp
mov %rsp, %rbx
add OFFSETS(%rax,8), %rbx
```

Extends protection to **stack objects (& heap)**
- Consequently also protects stack metadata

Desirable properties of low fat pointers preserved:
- Fast (~17% w.o.)
- Low space overheads (~3-15%)
- No metadata - **highly compatible**!