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

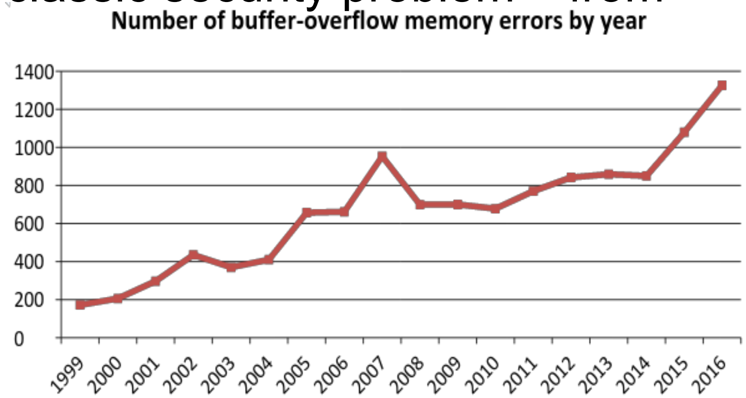
Pros: Fast (~17% w.o.), near zero memory overheads, highly compatible

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*

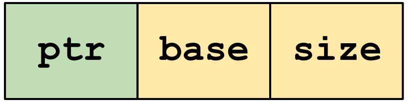
```
if (p < base(O) || p >= base(O)+size(O))
    error();
*p = v;
```

Bounds Checking Approaches

"**Fat pointers**" combine pointers and meta data

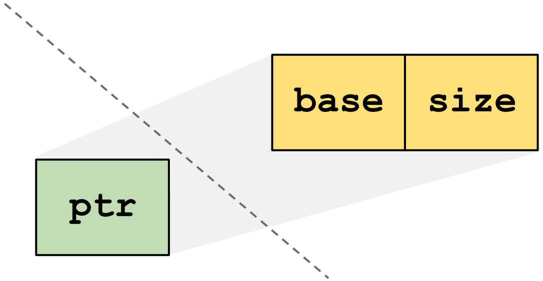
```
struct fat_ptr {
  void *ptr;
  void *base;
  size_t size; };
```

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



Shadow space stores metadata in separate memory

```
size(p) = SHADOW[p].size
base(p) = SHADOW[p].base
```

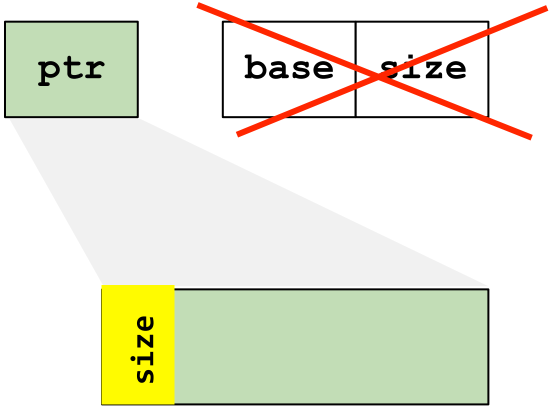


Low Fat Pointers

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

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

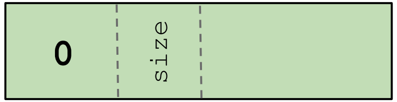
```
size(p) = p.un.size
base(p) = (p / size(p)) * size(p)
```



Compact encoding with no space overheads.

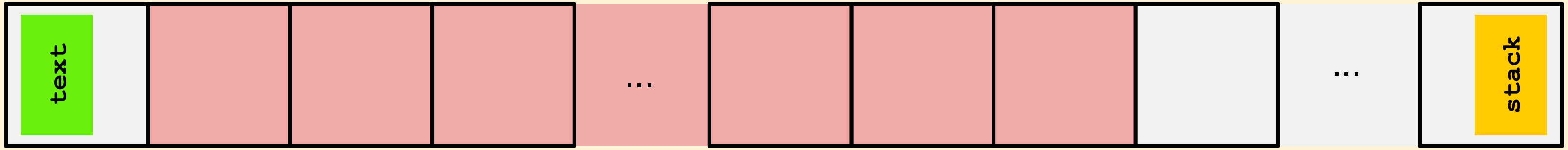
Flexible Low Fat Pointers

A simple encoding does not work well in practice



- Only 48bits are used → high bits must be zero!
- 10bits 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.).

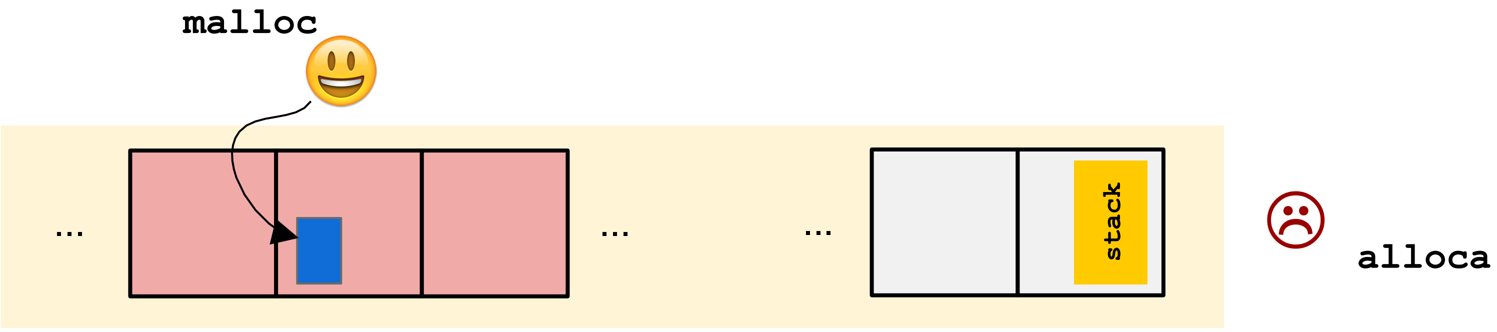
Bounds Checking with Low Fat Pointers

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

```
size(p) = SIZES[p / 32GB]
base(p) = (p / size(p)) * size(p)
```

```
if (p < base(p) || p >= base(p)+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

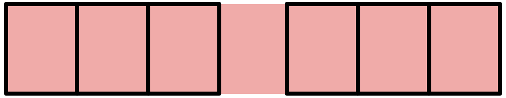
Allocation Size Over Approximation

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
```

SIZES

...	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.

```
base(p) = (p / size(p)) * size(p)
```

Solution: just use the `attribute(aligned(N))`:

```
char object[64] attribute(aligned(64));
```

```
and $-64, %rsp
```

For ***variable length*** *objects* we also use lookup tables.

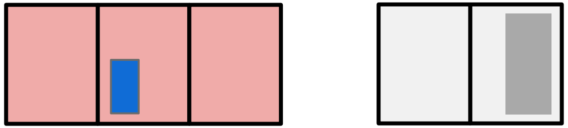
	55	56	57	58	59	60	61	62	63	64
...	-512	-256	-128	-64	-32	-16	-16	-16	-16	-16

MASKS

```
lzcnt %rax, %rax
and MASKS(,%rax,8), %rsp
```

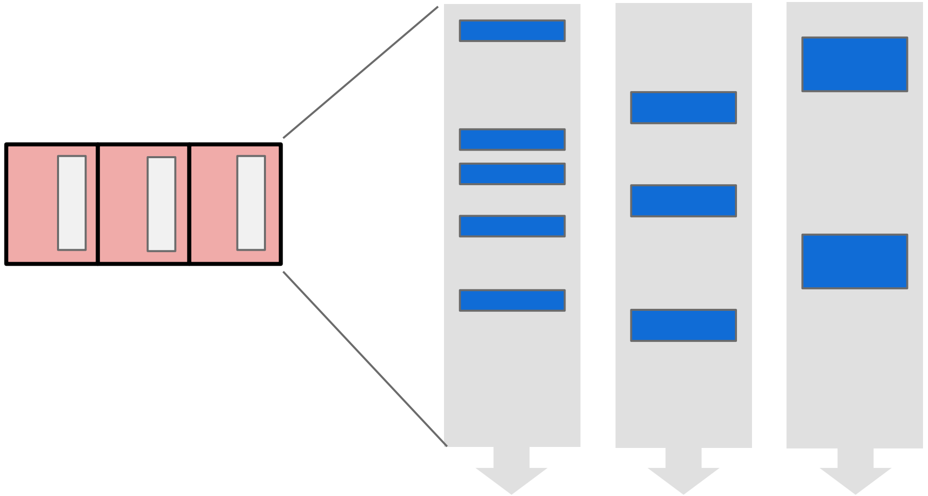
Stack Object Mirroring

Problem: stack objects are allocated from the stack!



☹ **`alloca`**

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



😃 **`alloca`**

Related work: *shadow stacks*

Stack Object Mirroring (cont.)

Stack Object Mirroring also implemented using tables:

	55	56	57	58	59	60	61	62	63	64
...	Δ_{55}	Δ_{56}	Δ_{57}	Δ_{58}	Δ_{59}	Δ_{60}	Δ_{61}	Δ_{62}	Δ_{63}	Δ_{64}

OFFSETS

Δ_{58}= **&region #4 - &stack**

```
lzcnt %rax, %rax
add OFFSETS(,%rax,8), %rsp
```

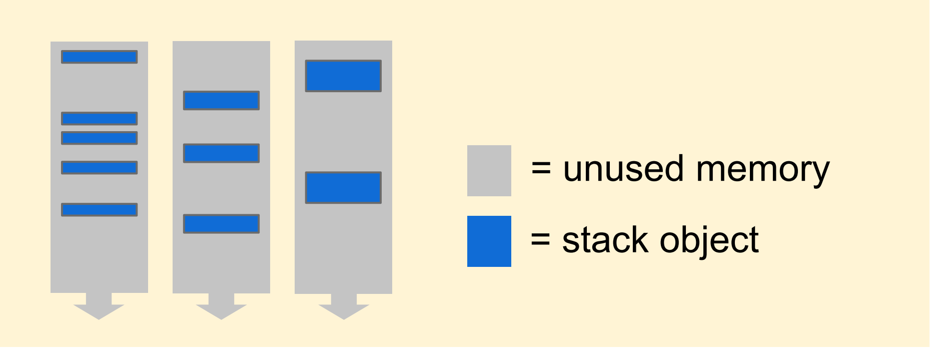
Each object allocated in correction region.

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

CON: Uses more memory

1 stack replaced with N stacks.

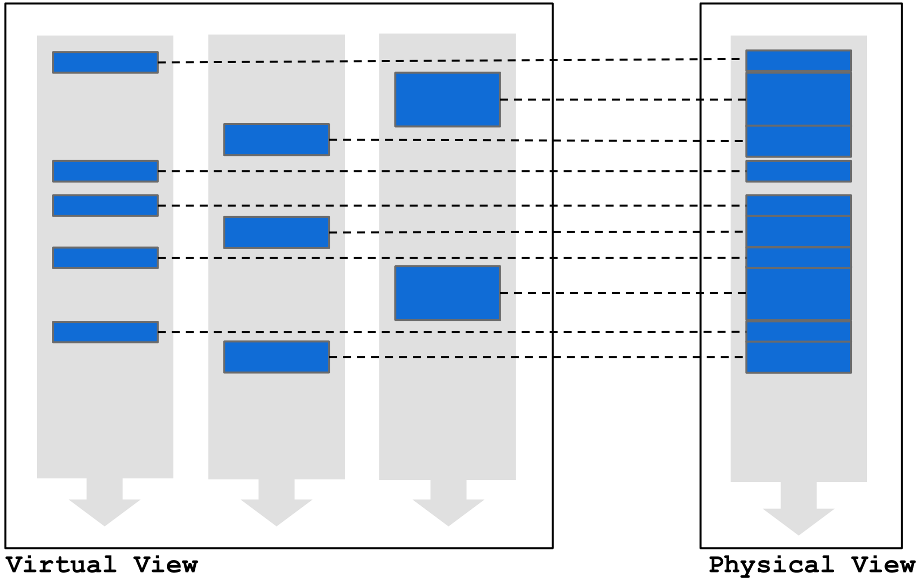
Fragmentation.



Memory Aliasing

Problem: Increasing stack memory is unsatisfactory.

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



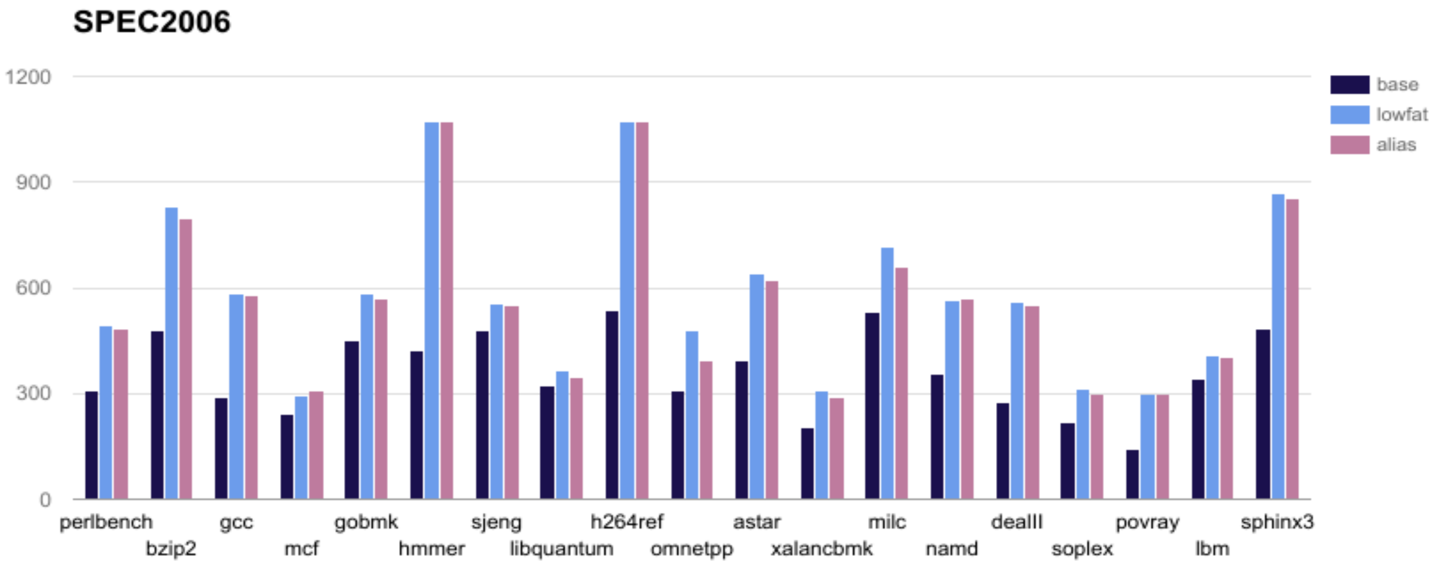
Program uses a single stack

(same as before)

Uses *shared memory objects*

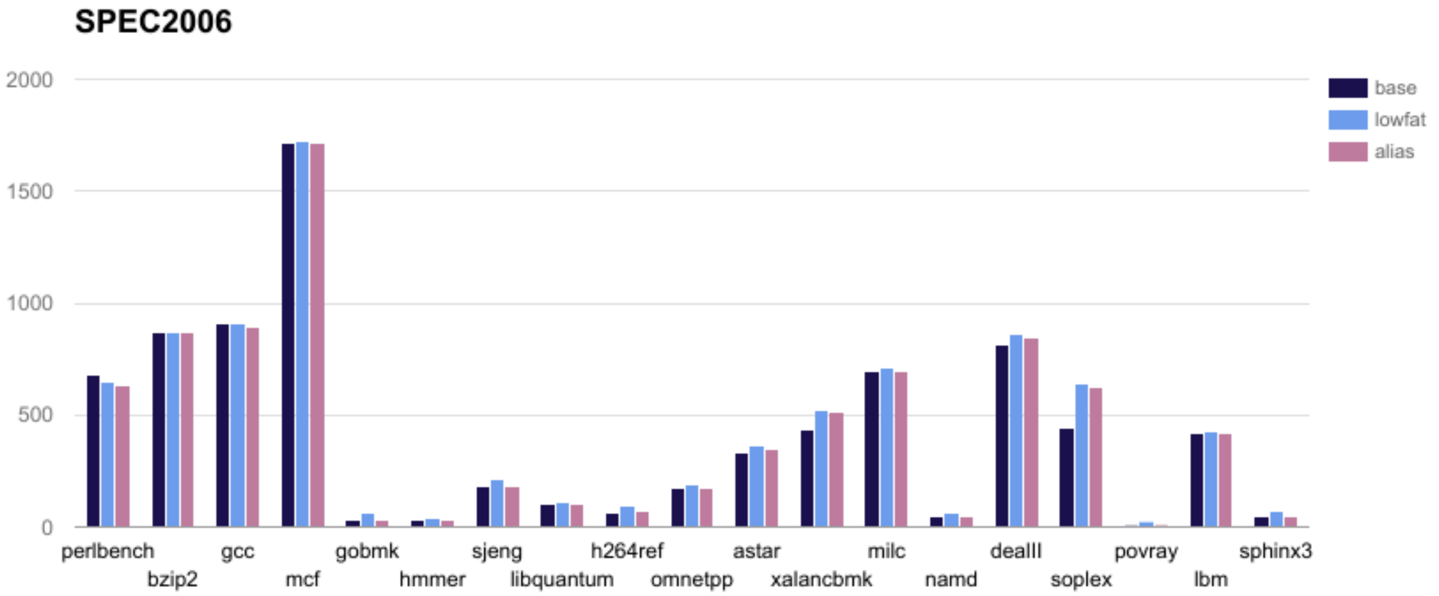
`shm_open`

Evaluation Basic (timings)



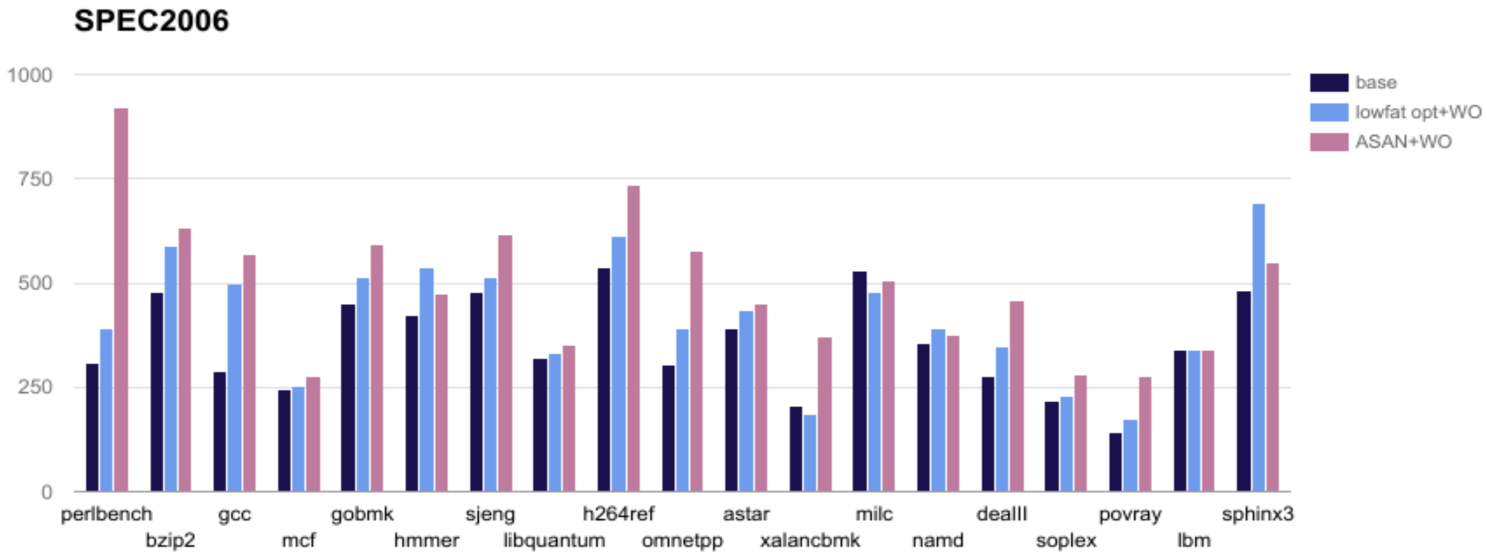
- Baseline: -O2
- Lowfat: 63% overhead (base unoptimized)
- Lowfat alias: 58% overhead with memory aliasing
- Address Sanitizer: 92% overhead

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**!