

so far

many vulnerabilities we looked at due to poor bounds checking
one exception: use-after-free and related

can we just fix this?

adding bounds checking

```
char buffer[42];  
memcpy(buffer, attacker_controlled, len);
```

couldn't compiler add check for len

modern Linux: it does

added bounds checking

```
char buffer[42];  
memcpy(buffer, attacker_controlled, len);
```

```
subq    $72, %rsp  
leaq    4(%rsp), %rdi  
movslq  len, %rdx  
movq    attacker_controlled, %rsi  
movl    $42, %ecx  
call    __memcpy_chk
```

length 42 passed to __memcpy_chk

`_FORTIFY_SOURCE`

Linux C standard library + GCC features

adds automatic checking to a bunch of string/array functions

also printf (disable %n unless format string is a constant)

often enabled by default

GCC options:

- D_FORTIFY_SOURCE=1 — enable (backwards-compatible only)
- D_FORTIFY_SOURCE=2 — enable (constant sizes only)
- D_FORTIFY_SOURCE=3 — enable (computed sizes, sometimes)
- U_FORTIFY_SOURCE — disable

bounds checking will happen...

will add checks (gcc 9.3 -**O2**, FORTIFY_SOURCE=1/2)

```
void example1() {  
    char dest1[1024]; memcpy(dest1, ...); ...  
}  
char dest2[1024];  
void example2() {  
    memcpy(dest2, ...); ...  
}  
void example3() {  
    char *p = &dest2[4]; memcpy(p, ...); ...  
}
```

bounds checking will happen...

will add checks (gcc 14.2 or clang 20 -**O**s, FORTIFY_SOURCE=3)

```
char dest2[1024];  
void example4() {  
    char *p = &dest2[mystery()]; memcpy(p, ...); ...  
}
```

no checking with FORTIFY_SOURCE=2

extra overhead: computing $\min(50, 1024 - \text{mystery}())$

bounds checking will happen...

will add check (gcc 14.2 or clang 20 -O_s, FORTIFY_SOURCE=3)

```
char dest2[1024];  
void example5() {  
    char dest3[128];  
    char *p = dest2;  
    if (mystery()) p = dest3;  
    memcpy(p, ...); ...  
}
```

checks for maximum possible with FORTIFY_SOURCE=2

bounds checking won't happen...

```
char dest2[1024];
struct Foo {
    char buffer1[128];
    int *pointer;
    ...
};
void example6(struct Foo *f, int size) {
    memcpy(f->buffer1, dest2, size);
}
```

bounds checking won't quite happen...

```
char dest2[1024];
struct Foo {
    char buffer1[128];
    int *pointer;
    ...
};
struct Foo f;
void example6(int size) {
    memcpy(f.buffer1, dest2, size);
}
```

checks that size is less than sizeof(struct Foo) (not 128)

implementation

GCC/clang expose 'object size' and 'dynamic object size' function

relies on compiler analysis to know size from see declaration or
malloc/etc. assignment

limited

non-checking library functions

some C library functions make bounds checking hard:

```
strcpy(dest, source);  
strcat(dest, source);  
sprintf(dest, format, ...);
```

bounds-checking versions (*added to library later*):

```
/* might not add \0 (!) */  
strncpy(dest, source, size);  
strncat(dest, source, size);  
snprintf(dest, size, format, ...);
```

poor bounds-checking APIs

```
char dest[100];  
/* THIS CODE IS BROKEN */  
strncpy(dest, source1, sizeof dest);  
strncat(dest, source2, sizeof dest);  
printf("result was %s\n", dest)
```

the above can access memory of out of bounds

...in a bunch of ways

Linux's strncpy manual

```
strncpy(dest, source1, sizeof dest);
```

“Warning: If there is no null byte among the first n bytes of src, the string placed in dest will not be null-terminated.”

exercise: what should the call have been?

Linux's strncat manual

```
strncat(dest, source2, sizeof dest);
```

“If src contains n or more bytes, strncat() writes n+1 bytes to dest (n from src plus the terminating null byte). Therefore, the size of dest must be at least strlen(dest)+n+1.”

exercise: what should the call have been?

better versions?

FreeBSD (and Linux via libbsd): `strlcpy`, `strlcat`

“Unlike [`strncat` and `strncpy`], `strlcpy()` and `strlcat()` take the full size of the buffer and guarantee to NUL-terminate the result...”

```
strlcpy(dest, source1, sizeof dest);  
strlcat(dest, source2, sizeof dest);
```

Windows: `strncpy_s`, `strcat_s` (same idea, different name)

C++/Rust bounds checking

```
#include <vector>
```

```
...
```

```
std::vector<int> data;
```

```
data.resize(50);
```

```
// undefined behavior:
```

```
data[60] = 0;
```

```
// throws std::out_of_range exception
```

```
data.at(60) = 0;
```

```
let data: Vec<i32> = ...;
```

```
data.resize(50, 0);
```

```
// undefined behavior:
```

```
unsafe { *data.get_unchecked_mut(60) = 1; }
```

```
// panics at runtime:
```

```
data[60] = 0;
```

language-level solutions

languages like Python don't have this problem

couldn't we do the same thing in C?

bounds-checking C

there have been many proposals to add bounds-checking to C

including implementations

brainstorm: *why hasn't this happened?*

easy bounds-checking

```
void vulnerable() {  
    char buffer[100];  
    int c;  
    int i = 0;  
    while ((c = getchar()) != EOF && c != '\n') {  
        buffer[i] = c;  
    }  
}  
  
void vulnerable_checked() {  
    char buffer[100];  
    int c;  
    int i = 0;  
    while ((c = getchar()) != EOF && c != '\n') {  
        FAIL_IF(i >= 100 || i < 0);  
        buffer[i] = c;  
    }  
}
```

harder bounds-checking

```
void vulnerable(char *buffer) {
    char buffer[100];
    int c;
    int i = 0;
    while ((c = getchar()) != EOF && c != '\n') {
        buffer[i] = c;
    }
}

void vulnerable_checked(char *buffer) {
    int c;
    int i = 0;
    while ((c = getchar()) != EOF && c != '\n') {
        FAIL_IF(i >= UNKNOWN || i < UNKNOWN);
        buffer[i] = c;
    }
}
```

adding bounds-checking — fat pointers

```
struct MyPtr {  
    char *pointer; /* "raw" pointer value */  
    char *minimum; /* first byte of buffer pointed to */  
    char *maximum; /* last byte of buffer pointed to */  
};
```

adding bounds-checking — fat pointers

```
struct MyPtr {  
    char *pointer; /* "raw" pointer value */  
    char *minimum; /* first byte of buffer pointed to */  
    char *maximum; /* last byte of buffer pointed to */  
};
```

```
char buffer[100];  
char *p = &buffer[10];
```

becomes

```
char buffer[100];  
MyPtr p = {  
    .pointer = &buffer[10],  
    .minimum = &buffer[0],  
    .maximum = &buffer[99]  
};
```

adding bounds checking — strcpy

```
MyPtr strcpy(MyPtr dest, const MyPtr src) {  
    int i;  
    do {  
        CHECK(src.pointer + i <= src.maximum);  
        CHECK(src.pointer + i >= src.minimum);  
        CHECK(dest.pointer + i <= dest.maximum);  
        CHECK(dest.pointer + i >= dest.minimum);  
        dest.pointer[i] = src.pointer[i];  
        i += 1;  
        CHECK(src.pointer + i <= src.maximum);  
        CHECK(src.pointer + i >= src.minimum);  
    } while (src.pointer[i] != '\0');  
    return dest;  
}
```


speed of bounds checking

two comparisons for every pointer access?

three times as much space for every pointer?

unfortunate things C programmers do (1)

from FreeBSD's bootpd (server for machines that boot from the network):

```
struct shared_string {
    unsigned int linkcount;
    char        string[1]; /* Dynamically extended */
};
...
s = (struct shared_string *) smalloc(
    sizeof(struct shared_string) + length
);
...
```

unfortunate things C programmers do (2)

from perl's source code:

```
sv_setuv(my_pool_sv, PTR2UV(my_poolp));
```

```
...
```

```
/* later, in another function: */
```

```
my_pool_t *my_poolp = INT2PTR(my_pool_t*, SvUV(my_pool_sv));
```

PTR2UV: pointer to Unsigned int Value

INT2PTR: integer to pointer value

unfortunate things C programmers do (3)

```
struct SuperClass;  
struct SubClass {  
    struct SuperClass super;  
    ...  
}
```

```
struct SubClass sub;  
struct SuperClass *super = &sub.super;  
some_function(super);  
...  
some_function(struct SuperClass *super) {  
    ...  
    struct SubClass *sub = (struct SubClass *)super;  
    ...  
}
```

example: CCured

Necula et al, "CCured: Type-Safe Retrofitting of Legacy Code"
(2002)

extension to C to add fat pointers

actually three different types of pointers:

- SAFE: point to single object (not array) or NULL

- SEQUENCE: pointer to array with known bounds (like "fat" pointers)

- DYNAMIC: extra to handles type-casting

needs source changes to annotate some pointer usage
especially to allow library function calls

1-**2.5x** time overhead

research example (2009)

**Baggy Bounds Checking: An Efficient and Backwards-Compatible Defense
against Out-of-Bounds Errors**

baggy bounds checking idea

giant lookup table — one entry for every 16 bytes of memory

table indicates start of object allocated here

check pointer arithmetic:

```
char p = str[i];
```

```
/* becomes: */
```

```
CHECK(START_OF[str / 16] == START_OF[&str[i] / 16])
```

```
char p = str[i];
```

baggy bounds trick

table of pointers to starting locations would be huge

add some restrictions:

- all object sizes are powers of two

- all object starting addresses are a multiple of their size

then, table contains size info only:

- table contains i , size is 2^i bytes:

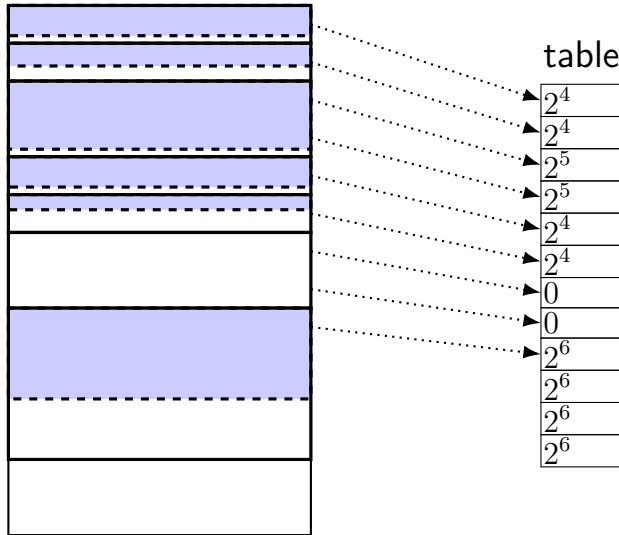
```
char *GetStartOfObject(char *pointer) {  
    return pointer & ~(1 << TABLE[pointer / 16] - 1);  
    /* pointer bitwise-and 2^(table entry) - 1 */  
    /* clear lower (table entry) bits of pointer */  
}
```


allocations and lookup table



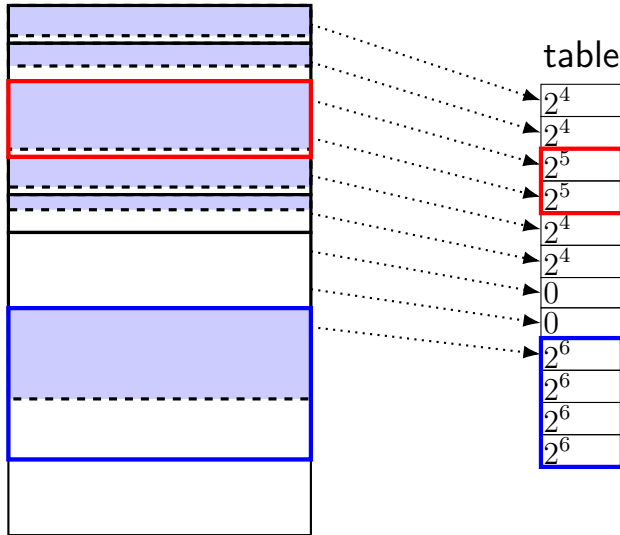
object allocated in
power-of-two 'slots'

allocations and lookup table



object allocated in
power-of-two 'slots'

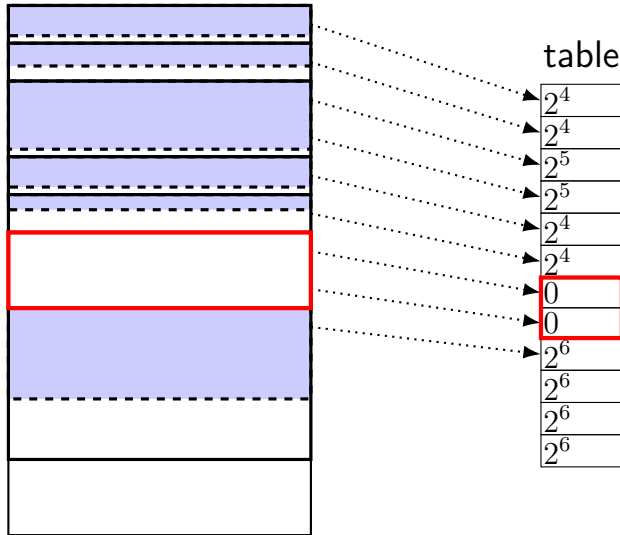
allocations and lookup table



object allocated in
power-of-two 'slots'

table stores sizes
for each 16 bytes

allocations and lookup table

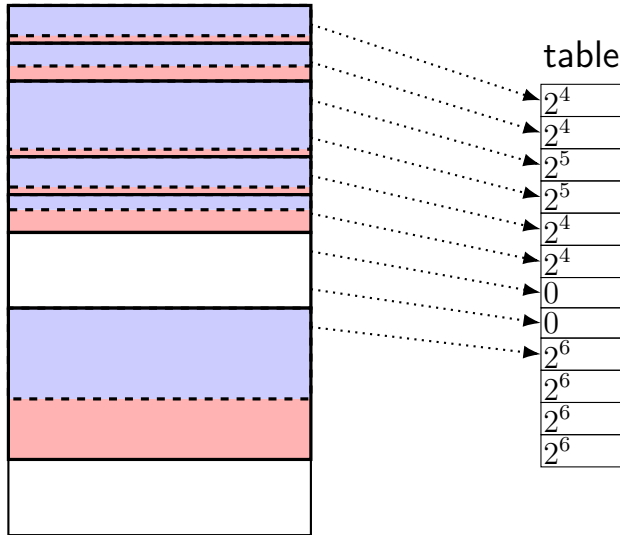


object allocated in
power-of-two 'slots'

table stores sizes
for each 16 bytes

addresses **multiples of size**
(may *require padding*)

allocations and lookup table



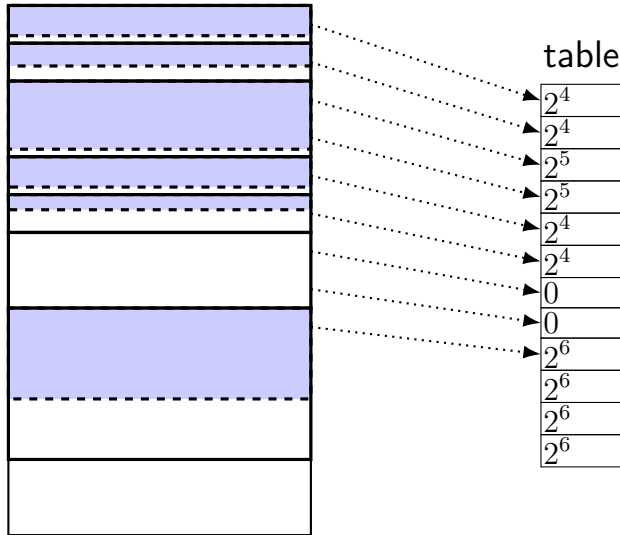
object allocated in
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table stores sizes
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addresses multiples of size
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sizes are **powers of two**
(may *require padding*)

allocations and lookup table



object allocated in
power-of-two 'slots'

table stores sizes
for each 16 bytes

addresses multiples of size
(may *require padding*)

sizes are powers of two
(may *require padding*)

managing the table

not just done malloc()/new

vulnerable:

also for stack allocations:

```
void vulnerable() {  
    char buffer[100];  
    gets(vulnerable);  
}
```

```
// make %rsp a multiple  
// of 128 (2^7)
```

```
andq $0xFFFFFFFFFFFFFFF80, %rsp
```

```
// allocate 128 bytes
```

```
subq $0x80, %rsp
```

```
// rax <- rsp / 16
```

```
movq $rsp, %rax
```

```
shrq $4, %rax
```

```
movb $7, TABLE(%rax)
```

```
movb $7, TABLE+1(%rax)
```

```
...
```

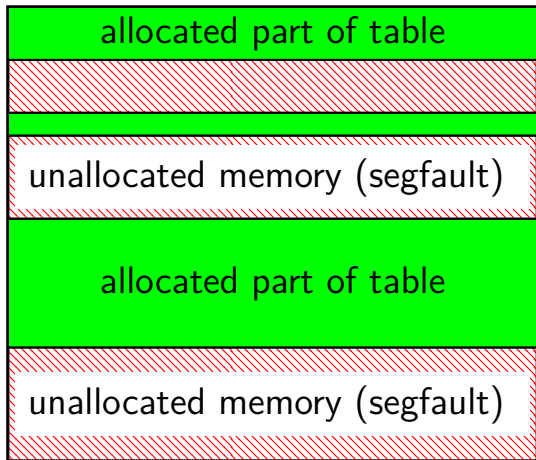
```
movq %rsp, %rdi
```

```
call gets
```

```
ret
```

sparse lookup table

lookup table



baggy bounds check: added code

bounds lookup	{ mov eax, buf shr eax, 4 mov al, byte ptr [TABLE+eax]
pointer arithmetic	{ char *p = buf[i];
bounds check	{ mov ebx, buf xor ebx, p shr ebx, al jz ok p = slowPath(buf, p) ok:

Figure 5: Code sequence inserted to check unsafe pointer arithmetic.

baggy bounds check: added code

```
/* bounds lookup */
    mov buf, %rax
    shr %rax, 4
    mov LOOKUP_TABLE(%rax), %al
/* array element address computation */
    ...    // char * p = buf[i];
/* bound check */
    mov buf, %rbx
    xor p, %rbx
    shr %al, %rbx
    jz ok
    ...    // handle possible violation
```

ok:

avoiding checks

code not added if not array/pointer accesses to object

code not added when pointer accesses “obviously” safe

author's implementation: only checked within function

exercise: overhead of baggy bounds (1)

suppose program allocates:

1000 100 byte objects

1 10000 byte object

using baggy bounds, estimate:

space required for padding

space required for table

exercise: overhead of baggy bounds (1)

suppose program allocates:

1000 100 byte objects

1 10000 byte object

using baggy bounds, estimate:

space required for padding

$$(128 - 100) \cdot 1000 + (16384 - 10000) = 34384$$

space required for table

$$(128 \cdot 1000 + 16384) \div 16 = 9024$$

exercise: overhead of baggy bounds (2)

```
char *strcat(char *d, char *s) {  
    int i;  
    for (i = 0; s[i] != '\0'; i += 1) {  
        d[i] = s[i];  
    }  
    d[i] = '\0';  
    return d;  
}
```

estimate:

- number of bounds checks needed

- very rough number of instructions run w/o bounds check

thought question:

with bounds checking, what's fastest possible code?

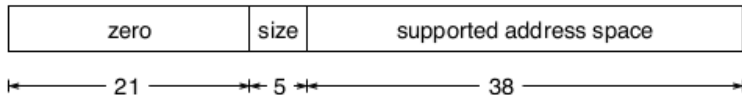
alternate approach: pointer tagging

some bits of *address* are size
replaces table entry/lookup

change code to allocate objects this way

works well on 64-bit — plenty of addresses to use

(c) Tagged pointer



baggy bounds performance

table: 4–72% time overhead (depends on benchmark suite)

table: 11–21% space overhead (depends on benchmark suite)

tagged pointers: slightly better on average

baggy bounds performance

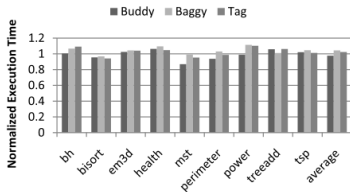


Figure 19: Normalized execution time on AMD64 with Olden benchmarks.

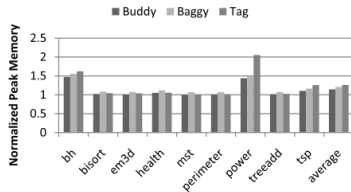


Figure 21: Normalized peak memory use on AMD64 with Olden benchmarks.

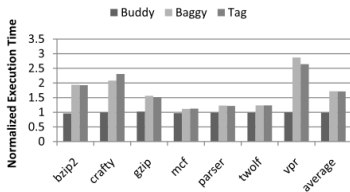


Figure 20: Normalized execution time on AMD64 with SPECINT 2000 benchmarks.

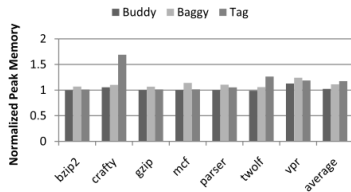


Figure 22: Normalized peak memory use on AMD64 with SPECINT 2000 benchmarks.

problem: within object

```
struct foo {  
    char buffer[1024];  
    int *pointer;  
};  
struct foo array_of_foos[1024];  
...  
char *p = &array_of_foos[4].buffer[4]
```

exercise: what are the bounds for p?

unfortunate things C programmers do (4)

in code generated by f2c (Fortran to C translator)

(cleaned up slightly)

```
float sum(int size, float *arr) {  
    arr = arr - 1; /* <-- deliberately out-of-bounds pointer */  
    float result = 0.f;  
    for (i = 1; i <= size; ++i) {  
        result += arr[i]  
    }  
    return result;  
}
```

AddressSanitizer

like baggy bounds:

- big lookup table

- lookup table set by memory allocations

- compiler modification: change stack allocations

unlike baggy bounds:

- check reads/writes (instead of pointer computations)

- only detect errors that read/write *between objects*

- object sizes not padded to power of two

- table has info for every single byte (more precise)

adding bounds-checking example

```
void vulnerable(long value, int offset) {  
    long array[10] = {1,2,3,4,5,6,7,8,9,10};  
    // generated code: (added by AddressSanitizer)  
    if (!lookup_table[&array[offset]] == VALID) FAIL();  
    array[offset] = value;  
    do_something_with(array);  
}
```

AddressSanitizer: crashes only if array[offset] isn't part of any object

but no extra space — single-byte precision

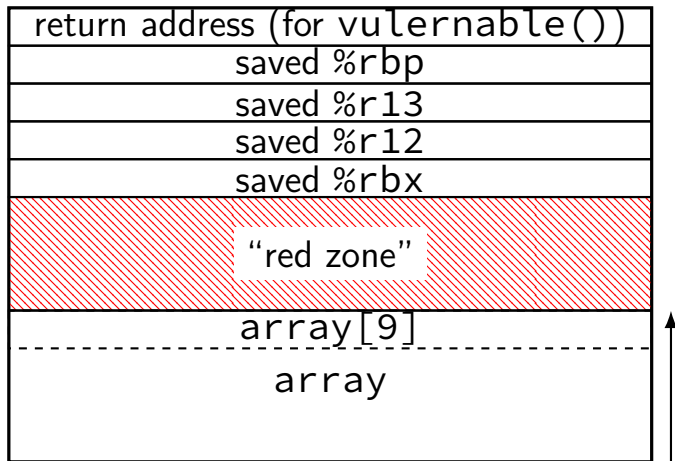
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    array[offset] = value;  
    do_something_with(array);  
}
```

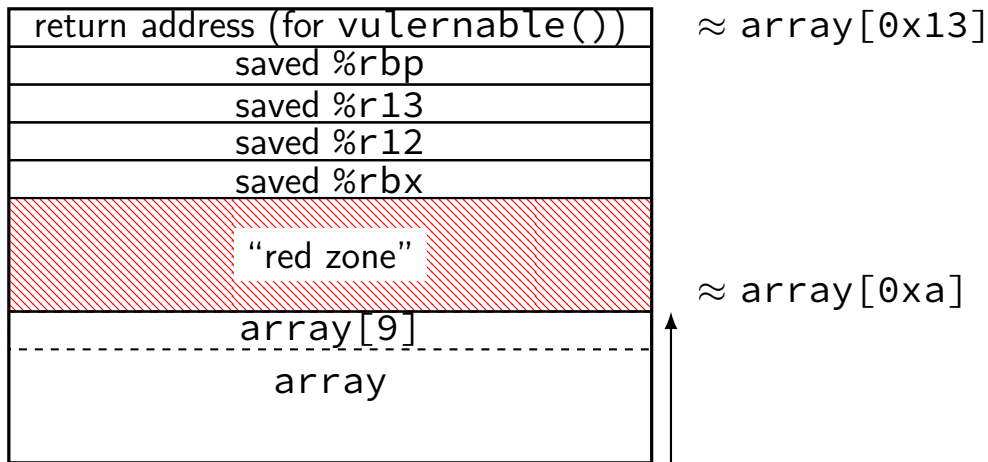
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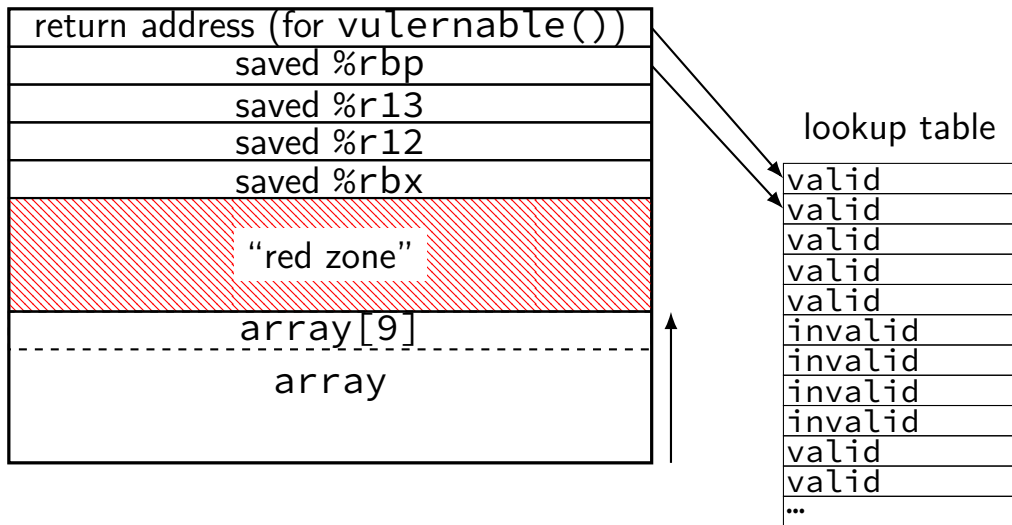
AddressSanitizer stack layout



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AddressSanitizer: crashes only if array[offset] isn't part of any object

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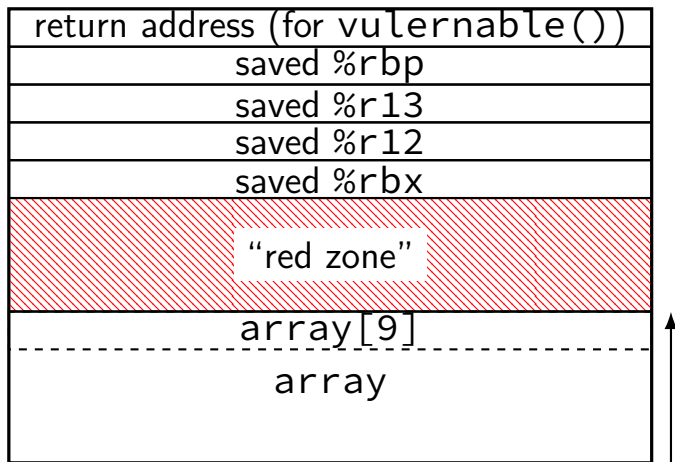
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    if (!lookup_table[&array[offset]] == VALID) FAIL();  
    array[offset] = value;  
    do_something_with(array);  
}
```

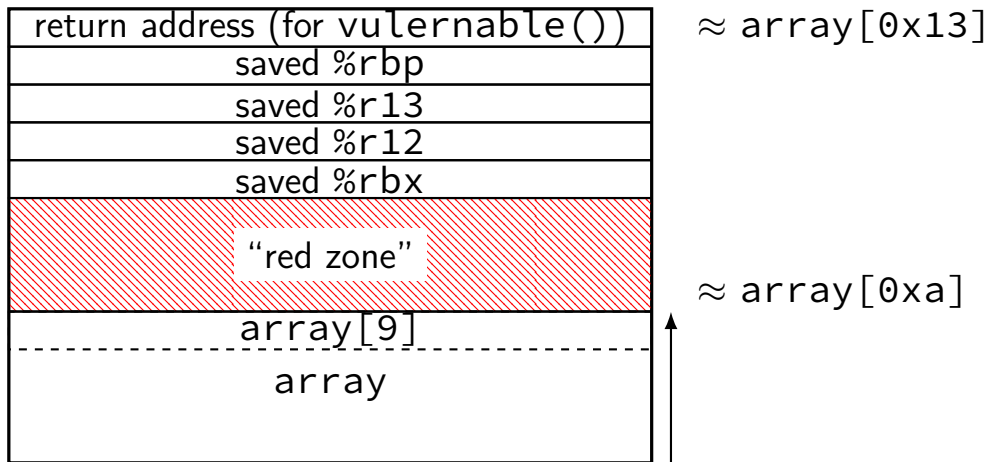
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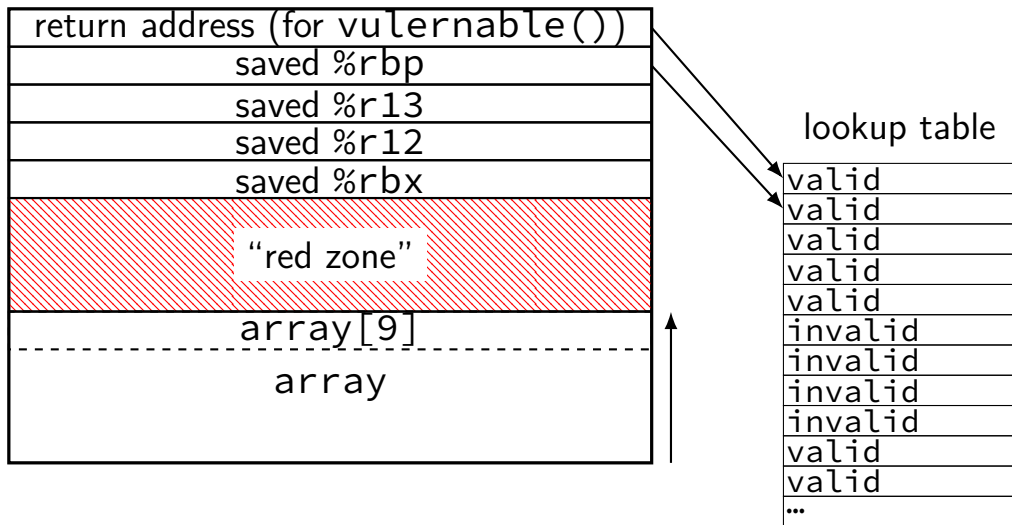
AddressSanitizer stack layout



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AddressSanitizer stack layout



revisted: within object

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};  
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...  
char *p = &array_of_foos[4].buffer[4]
```

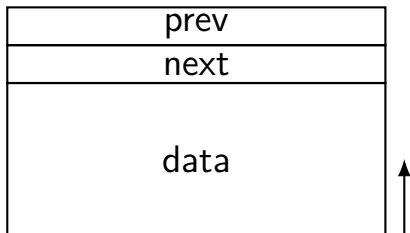
exercise: What out-of-bounds accesses to 'p' can AddressSanitizer detect?

how does that compare to baggy bounds? To the 'fat pointers' strategy?

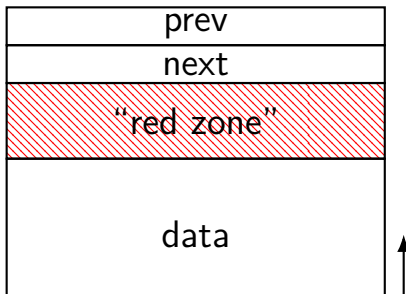
changing object layout?

```
struct string_list {  
    char data[100];  
    struct string_list *prev;  
    struct string_list *next;  
};
```

actual layout



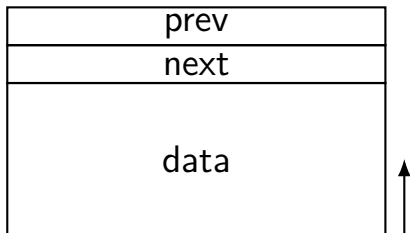
layout wanted for error-finding



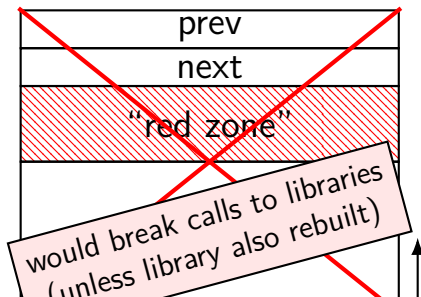
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```

actual layout



layout wanted for error-finding



AddressSanitizer versus Baggy Bounds

pros vs baggy bounds:

- you can actually use it (comes with GCC/Clang)

- byte-level precision — no “padding” on objects

- detects use-after-free a lot of the time

cons vs baggy bounds:

- doesn't prevent out-of-bounds “targetted” accesses

- requires extra space between objects

- usually slower

Valgrind Memcheck

similar to AddressSanitizer — but no compiler modifications

instead: is an emulator (plus alternate malloc/new implementation)

implemented using binary translation (just-in-time compilation)

only (reliably) detects errors on heap

but works on *unmodified* binaries

binary translation

compile assembly to new assembly

works without instruction set support

early versions of VMWare on x86 (before x86 added virtualisation support)

can be used to run one platform on another

binary translation idea

```
0x40FE00: addq %rax, %rbx
movq 14(%r14,4), %rdx
addss %xmm0, (%rdx)
...
0x40FE3A: jne 0x40F404
subss %xmm0, 4(%rdx)
...
je 0x40F543
ret
```

binary translation idea

```
0x40FE00: addq %rax, %rbx  
movq 14(%r14,4), %rdx  
addss %xmm0, (%rdx)  
...  
0x40FE3A: jne 0x40F404
```

```
subss %xmm0, 4(%rdx)  
...  
je 0x40F543
```

```
ret
```

divide machine code
into *basic blocks*
(= “straight-line” code)
(= code till
jump/call/etc.)

binary translation idea

```
0x40FE00: addq %rax, %rbx
movq 14(%r14,4), %rdx
addss %xmm0, (%rdx)
...
0x40FE3A: jne 0x40F404
subss %xmm0, 4(%rdx)
...
je 0x40F543
ret
```

generated code:

```
// addq %rax, %rbx
movq rax_location, %rdi
movq rbx_location, %rsi
call checked_addq
movq %rax, rax_location
...
// jne 0x40F404
... // get CCs
je do_jne
movq $0x40FE3F, %rdi
jmp translate_and_run
do_jne:
movq $0x40F404, %rdi
jmp translate_and_run
```


a binary translation idea

- convert whole *basic blocks*

 - code upto branch/jump/call

- end with call to `translate_and_run`

 - compute new *simulated PC* address to pass to call

making binary translation fast

- cache converted code

 - `translate_and_run` checks cache first

- patch calls to `translate_and_run` to refer directly to cached code

- do something more clever than `movq rax_location, ...`

 - map (some) registers to registers, not memory

- ends up being “just-in-time” compiler

binary translation? really?

early VMWare: for instructions without hardware virtualization support

- only needed for little bits of OS code

used by Apple to handle changing CPU designs

Rosetta 2: run Intel on ARM (current)

Rosetta: run Power PC on Intel (2005–2011)

Mac 68k emulator: Run Motorola 680x0 on Power PC (1994–2005)

which scheme prevents...?

which schemes detect or prevent from being harmful...?

1. call to assembly code that goes beyond buffer?
2. allowing attacker to insert 150 bytes in 100 byte buffer on heap?
3. allowing attacker to insert 120 bytes in 100 byte buffer on stack?
4. attacker exploiting code that does `array[attacker_index]` to overwrite something outside heap array?

of:

- A. “fat pointers” approach
- B. Baggy Bounds checking
- C. AddressSanitizer
- D. Valgrind Memcheck

answer (1)

which schemes detect or prevent from being harmful...?

1. call to assembly code that goes beyond buffer?

only Valgrind Memcheck handles assembly code

other techniques require C compiler to produce different assembly

answer (2)

which schemes detect or prevent from being harmful...?

2. allowing attacker to insert 150 bytes in 100 byte buffer on heap?

schemes:

- A. “fat pointers” approach — yes
- B. Baggy Bounds checking —yes, detect + crash
- C. AddressSanitizer — yes, detect + crash
- D. Valgrind Memcheck — yes, detect + rash

answer (3)

which schemes detect or prevent from being harmful...?

3. allowing attacker to insert 120 bytes in 100 byte buffer on stack?

schemes:

- A. “fat pointers” approach — yes
- B. Baggy Bounds checking — prevent from being harmful / no crash
- C. AddressSanitizer — yes, detect + crash (red zone)
- D. Valgrind Memcheck — no — no memory to mark invalid

answer (3)

which schemes detect or prevent from being harmful...?

4. attacker exploiting code that does `array[attacker_index]` to overwrite something outside heap array?

schemes:

- A. “fat pointers” approach — yes
- B. Baggy Bounds checking — yes
- C. AddressSanitizer — no — attacker index can find valid memory
- D. Valgrind Memcheck — no — (same as AddressSanitizer)