bounds checking (2) / testing (1)

last time

use-after-free vulnerabilities

- after free: old pointer still "works" if new thing allocated there
- attacker can get control of memory of object they didn't use
- info leak (read from object you shouldn't)
- code execution (replace VTable/function pointer/etc.)

FORTIFY_SOURCE: gcc/clang/etc.'s sometimes bounds checking

- special `chk` version of library functions
- works when compilers can find bounds easily
- compiler can't find bounds: no fallback

unfortunate design of strncpy, strncat

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 gaurenteeto NUL-terminate the result...”

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

Windows: `strcpy_s`, `strcat_s` (same idea, differentname)

C++ 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;
```

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

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    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:

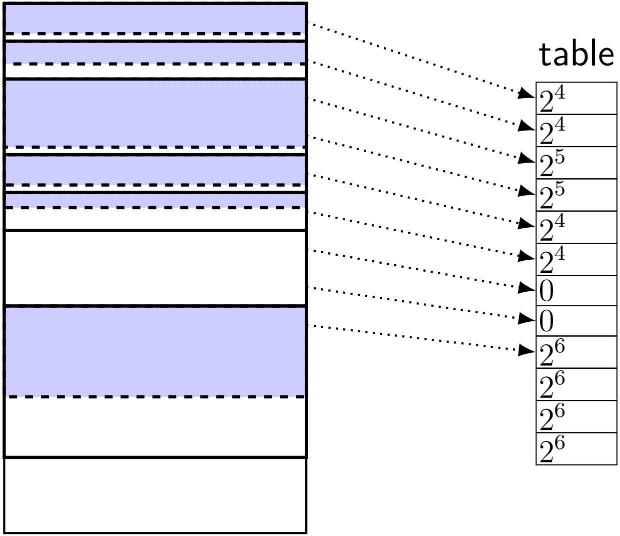
- table contains i, size is 2^i bytes:

```
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

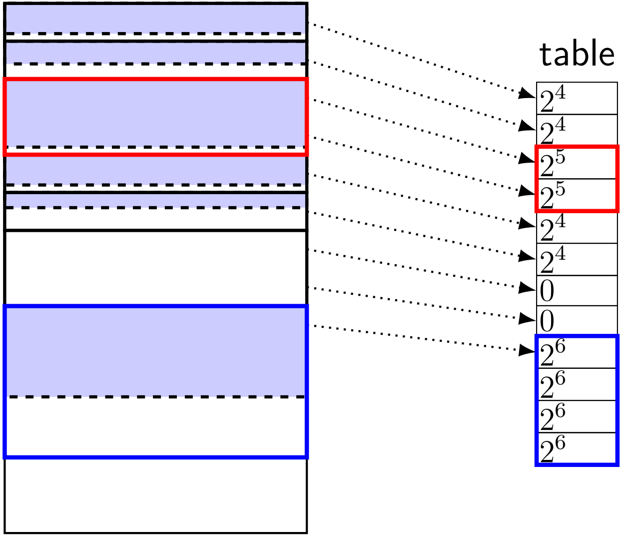
object allocated in
power-of-two 'slots'

allocations and lookup table



object allocated in power-of-two ‘slots’

allocations and lookup table



object allocated in
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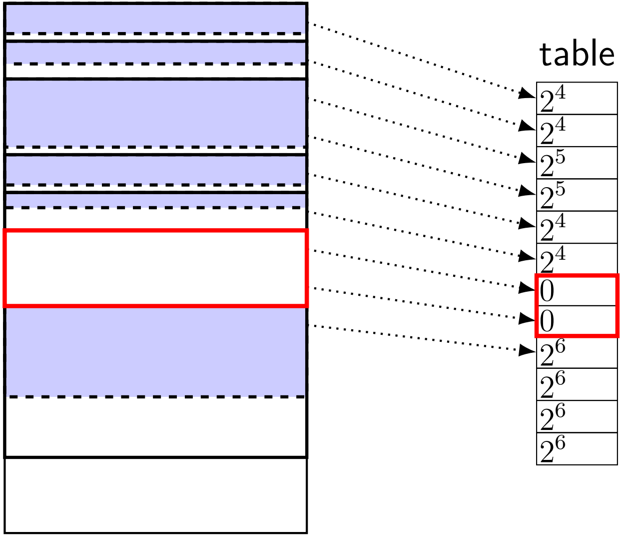
table stores sizes
for each 16 bytes

allocations and lookup table

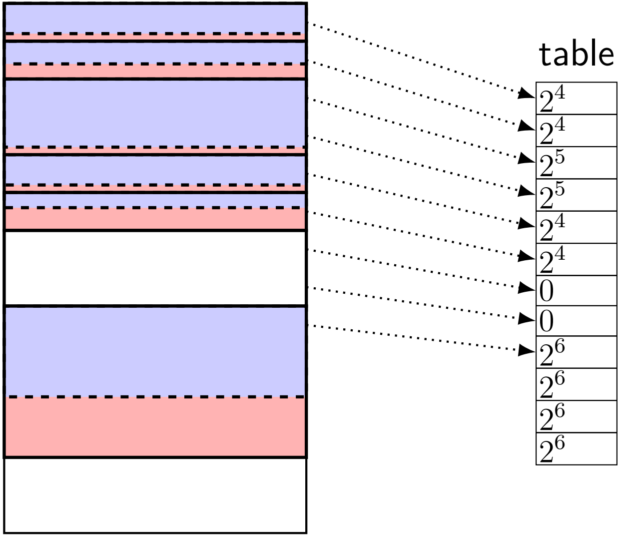


object allocated in power-of-two 'slots'

table stores sizes for each 16 bytes

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

allocations and lookup table



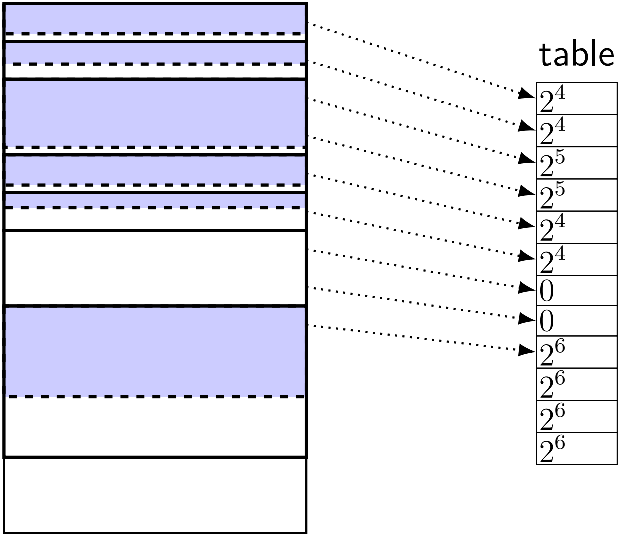
object allocated in power-of-two 'slots'

table stores sizes for each 16 bytes

addresses multiples of size (may require padding)

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

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

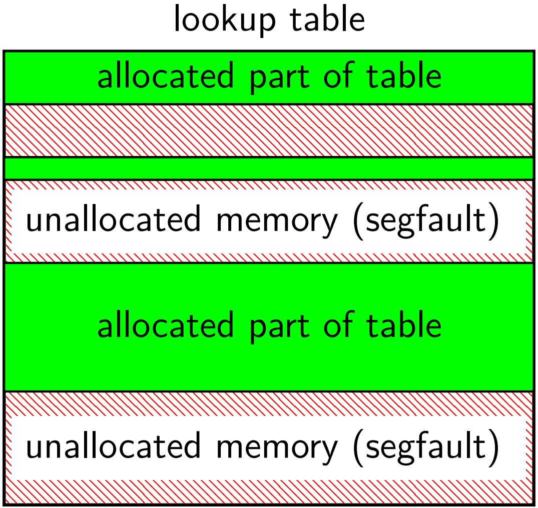
not just done `malloc()/new`

also for stack allocations:

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

```
vulnerable:
  // make %rsp a multiple
  // of 128 (2^7)
  andq $0xFFFFFFFFFFFFFF80, %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



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:
```

adapted from paper figure

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

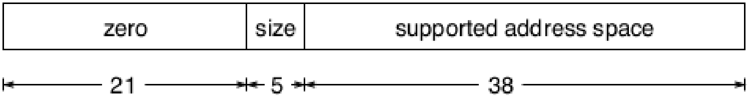
some bits of address are size

- 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

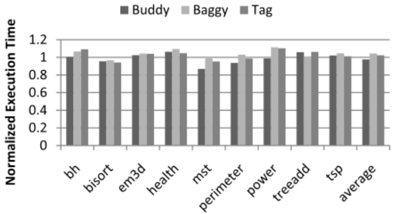


Figure 19: Normalized execution time on AMD64 with Olden benchmarks.

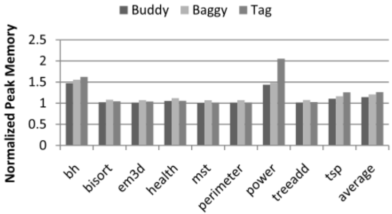


Figure 21: Normalized peak memory use on AMD64 with Olden benchmarks.

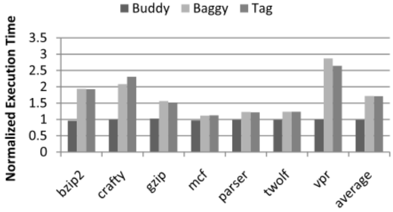


Figure 20: Normalized execution time on AMD64 with SPECINT 2000 benchmarks.

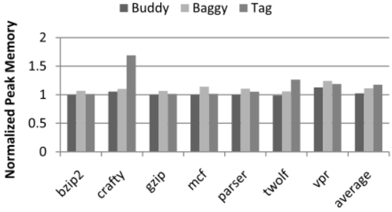


Figure 22: Normalized peak memory use on AMD64 with SPECINT 2000 benchmarks.

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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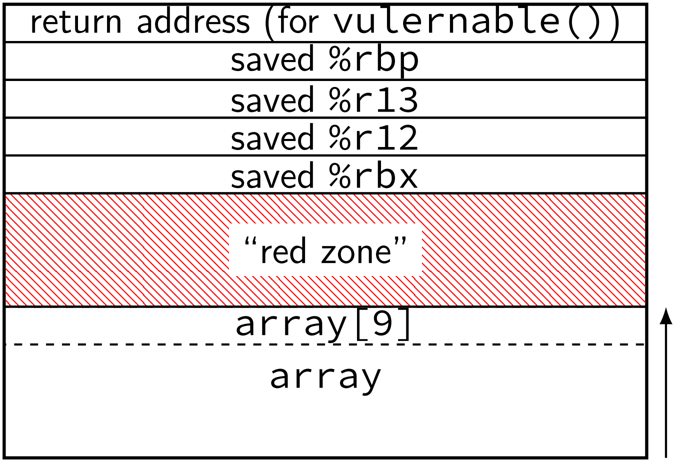
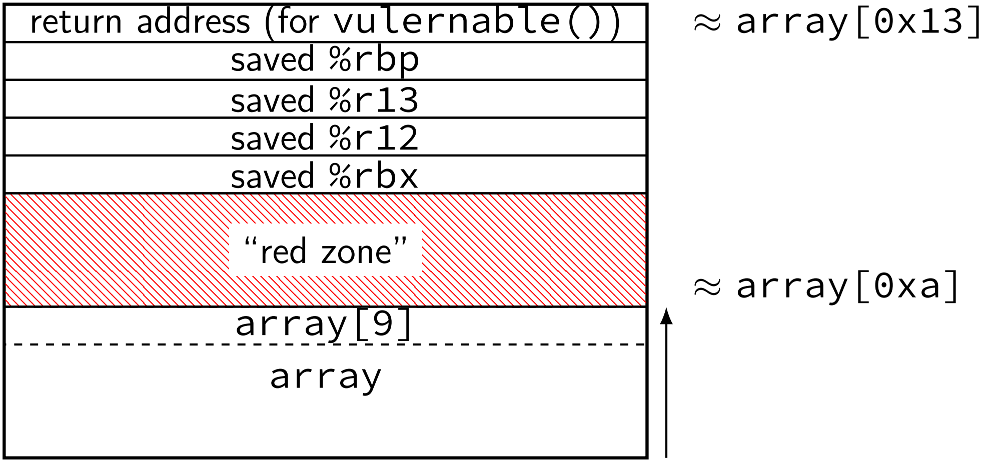
AddressSanitizer stack layout



AddressSanitizer stack layout



AddressSanitizer stack layout