COMP 737011 - Memory Safety and Programming Language Design

Lecture 3: Heap Attack and Protection

徐 辉
xuh@fudan.edu.cn

Outline

- 1. Heap Analysis
- 2. Heap Attack
- 3. Protection Techniques

1. Heap Analysis

Target Program

- How many chunks will be allocated?
- What happens to the bins?

```
void main(void)
{
    char *p[10];
    for(int i=0; i<10; i++){
        p[i] = malloc (10 * i);
        strcpy(p[i], "nowar!!!");
    }

    for(int i=0; i<10; i++)
        free(p[i]);
}
```

Analyze the Program with GEF

- Install GEF (GDB Enhanced Features):
  - https://gef.readthedocs.io/en/master/
- Add two break points

break 1

break 2

```
void main(void)
{
    char *p[10];
    for(int i=0; i<10; i++){
        p[i] = malloc (10 * i);
        strcpy(p[i], "nowar!!!");
    }

    for(int i=0; i<10; i++)
        free(p[i]);
}
```

Checkout What Happens

- Recall the structure of chunks

prev_size	
size	PREV_INUSE
forward pointer	
unused space	
size	

```
gef➤  break *main+65
Breakpoint 1 at 0x401191
gef➤  r
gef➤  search-pattern nowar
[+] Searching 'nowar' in memory
…
[+] In '[heap]'(0x405000-0x426000),
  0x4052a0 - 0x4052a8  →   "nowar!!

gef➤  x/10g 0x405290
0x405290:       0x0     0x21
0x4052a0:       0x212121726177f6e      0x0
0x4052b0:       0x0     0x20d51
0x4052c0:       0x0     0x0
0x4052d0:       0x0     0x0
```

10-byte header for x86-64:
Header content: 0x21,
- chunk size: 0x20 byte
- previous in use: 1 (last byte)

More Chunks

- After several iterations…

```
gef➤  heap chunks
Chunk(addr=0x405010, size=0x290, flags=PREV_INUSE)
    [0x0000000000405010     00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................]
Chunk(addr=0x4052a0, size=0x20, flags=PREV_INUSE)
    [0x00000000004052a0     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x4052c0, size=0x20, flags=PREV_INUSE)
    [0x00000000004052c0     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x4052e0, size=0x20, flags=PREV_INUSE)
    [0x00000000004052e0     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x405300, size=0x30, flags=PREV_INUSE)
    [0x0000000000405300     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x405330, size=0x30, flags=PREV_INUSE)
    [0x0000000000405330     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x405360, size=0x40, flags=PREV_INUSE)
    [0x0000000000405360     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x4053a0, size=0x50, flags=PREV_INUSE)
    [0x00000000004053a0     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x4053f0, size=0x50, flags=PREV_INUSE)
    [0x00000000004053f0     6e 6f 77 61 72 21 21 21 00 00 00 00 00 00 00 00    nowar!!!........]
Chunk(addr=0x405440, size=0x20bd0, flags=PREV_INUSE)
    [0x0000000000405440     00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................]
Chunk(addr=0x405440, size=0x20bd0, flags=PREV_INUSE)  ←  top chunk
```

View the Bins (tcachebins)

- Freed chunks are added to tcachebins (new in libc 2.6)

```
gef➤  heap bins
───────── Tcachebins for thread 1 ──────────────────────
Tcachebins[idx=0, size=0x20, count=3] ←  Chunk(addr=0x4052e0, size=0x20, flags=PREV_INUSE)
←  Chunk(addr=0x4052c0, size=0x20, flags=PREV_INUSE)  ←  Chunk(addr=0x4052a0, size=0x20,
flags=PREV_INUSE)
Tcachebins[idx=1, size=0x30, count=2] ←  Chunk(addr=0x405330, size=0x30, flags=PREV_INUSE)
←  Chunk(addr=0x405300, size=0x30, flags=PREV_INUSE)
Tcachebins[idx=2, size=0x40, count=1] ←  Chunk(addr=0x405360, size=0x40, flags=PREV_INUSE)
Tcachebins[idx=3, size=0x50, count=2] ←  Chunk(addr=0x4053f0, size=0x50, flags=PREV_INUSE)
←  Chunk(addr=0x4053a0, size=0x50, flags=PREV_INUSE)
Tcachebins[idx=4, size=0x60, count=1] ←  Chunk(addr=0x405440, size=0x60, flags=PREV_INUSE)
Tcachebins[idx=5, size=0x70, count=1] ←  Chunk(addr=0x4054a0, size=0x70, flags=PREV_INUSE)

───────── Fastbins for arena at 0x7ffff7fadb80 ───────────
Fastbins[idx=0, size=0x20] 0x00
Fastbins[idx=1, size=0x30] 0x00
Fastbins[idx=2, size=0x40] 0x00
...
```

Characteristics of Tcachebins

- Single-linked list
- First-in-last-out
- Max length of the list in each bin: 7
- Exceeding chunks will be put into fastbins

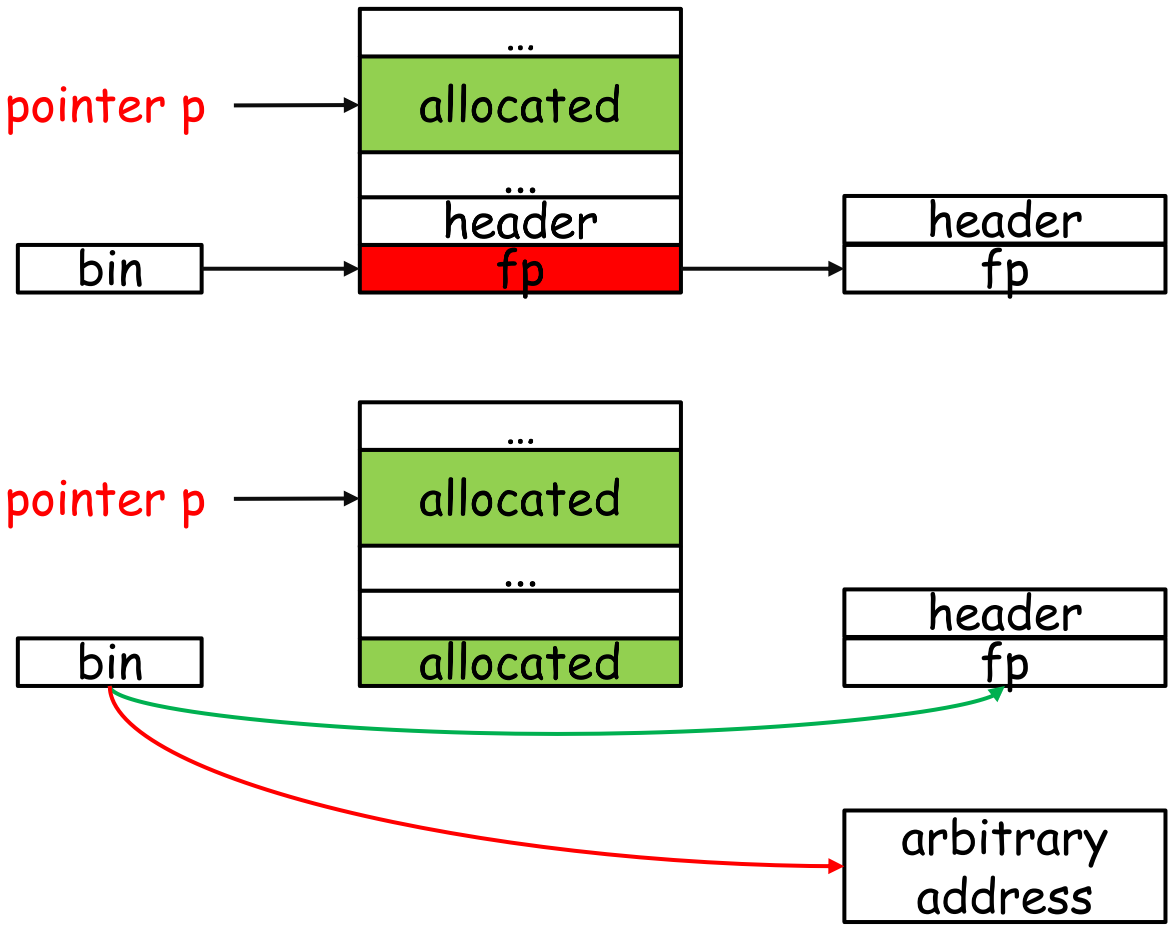
2. Heap Attack

Heap Vulnerablilities

- Heap overflow
- Use after free
- Double free

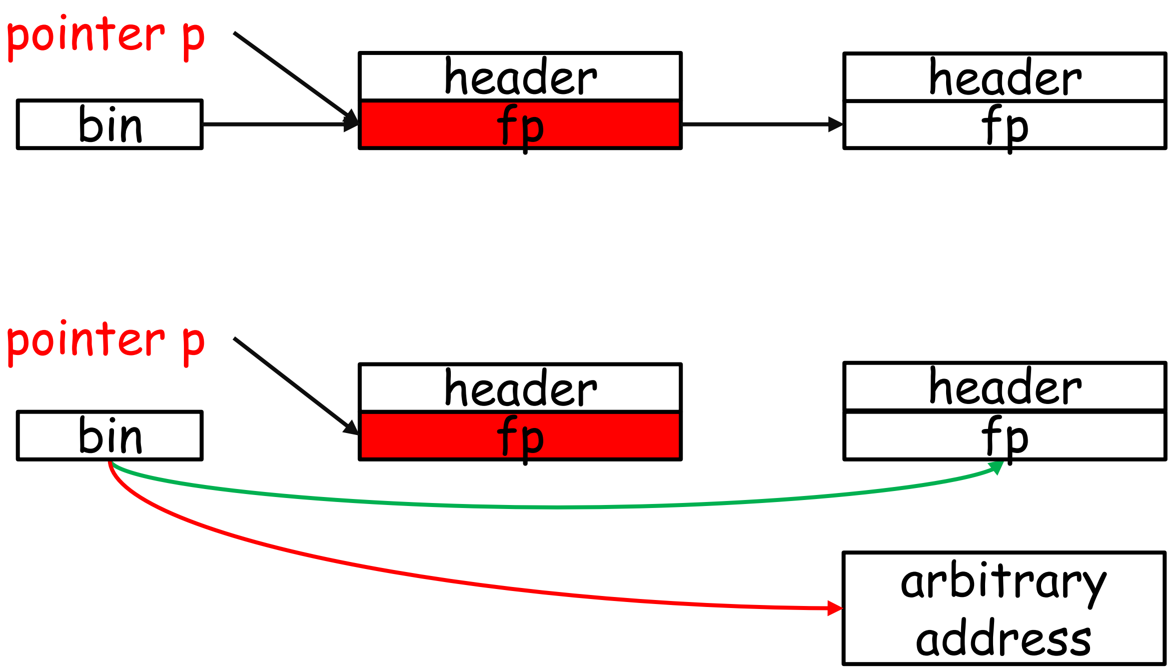
Heap Overflow

- Change the forward pointer of the top free chunk.
- What happens when allocating the chunk?



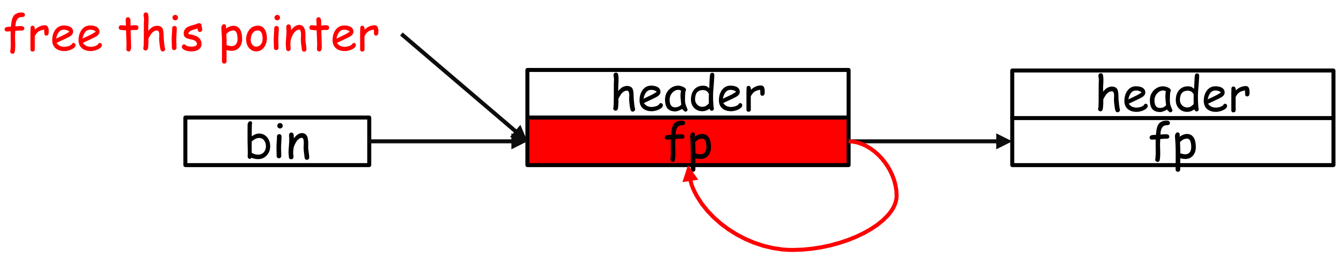
Use After Free Is Easier

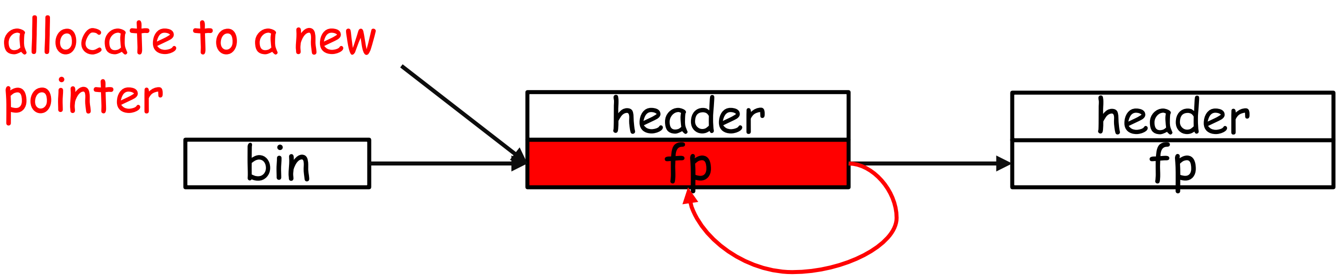
- Directly change the forward pointer of the top free chunk



What About Double Free?

- The forward pointer points to the chunk itself
- After allocation, the chunk is still in the list





Address of Attacking Interest

- Return Address:
  - similar as buffer overflow
- Global Offset Table (GOT):
  - a table for dynamic linkage or position-independent code
  - update the table entries during startup or when symbols are accessed
  - e.g., change the address of function “strcpy()”
- Virtual Method Table (vtable):
  - abstract functions of C++/Rust

In Class Practice

- Write a C program and demonstrate UAF
- Write a C program and demonstrate Double Free
  - You may encounter some detection techniques

3. Protection Techniques

Detecting Bugs in Allocator?

- Detecting double free is easier
  - there are a limited number of chunks
  - pointer address should be valid
  - e.g., fasttop, e-key in tcachebin
  - trade of between efficiency and resillience
- Detecting dangling/invalid pointer is difficult
  - offset could be used
  - difficult to determine whether an address is valid
- Sample papers to read:
  - Akritidis. "Cling: A memory allocator to mitigate dangling pointers." *USENIX Security 2010*.
  - Sam, *et al*. "Freeguard: A faster secure heap allocator." CCS 2017.

Static Analysis

- Analyze whether a pointer being used is dangling
- Should infer the alias of pointers
  - The chunk could be freed via other variables
- General alise analysis problem is NP-hard
- Several typical performance issues to consider
  - Flow-sensitivity: consider the order of statements?
  - Path-sensitivity: analyze the result for each path?
  - Context-sensitivity: inter-procedural issues
  - Field-sensitivity: how to model the members of objects
- Sample papers to read:
  - Lee, et al. "Preventing Use-after-free with Dangling Pointers Nullification." *NDSS*. 2015.
  - Van Der Kouwe, et al. "Dangsan: Scalable use-after-free detection." *EuroSys 2017*.

Programming Language Design

- Rust ownership-based mechanism
- Preventing shared mutable aliases
- Shared mutable aliases should be wrapped with RC type
  - similar to shared_ptr in C++

```
let b = B:new();
let r1: &B = &b;
let r2: &B = &b;
```

b owns the object
r1 borrows the ownership immutably
r2 borrows the ownership immutably

Immutable borrow

```
let b = B:new();
let r1: &mut B = &mut b;
```

b owns the object
r1 borrows the ownership mutably
b temporily lost the ownership

Mutable borrow

More Reference

- https://guyinatuxedo.github.io
- https://doc.rust-lang.org/book/ch15-04-rc.html
- Akritidis. "Cling: A memory allocator to mitigate dangling pointers." *USENIX Security 2010*.
- Sam, et al. "Freeguard: A faster secure heap allocator." CCS 2017.
- Lee, et al. "Preventing Use-after-free with Dangling Pointers Nullification." *NDSS*. 2015.
- Van Der Kouwe, et al. "Dangsan: Scalable use-after-free detection." *EuroSys 2017*.

Solution: Use After Free

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

void main(void)
{
    char* p1 = malloc (22);
    char* p2 = malloc (22);
    free(p2);
    free(p1);
    *(int *) p1 = 0x411112;
    p1 = malloc(22);
    p2 = malloc(22);
    printf("Allocated memory address: %x\n", p2);
}
```

Solution: Double Free

```
void main(void)
{
    char* p1 = malloc (22);
    free(p1);
    p1[9] = 0x0; //overwrite e-key for double check
    free(p1);
    *(int *) p1 = 0x411112;
    p1 = malloc(22);
    p1 = malloc(22);
    printf("Allocated memory address: %x\n", p1);
}
```