CMPSC 447
Heap Attacks

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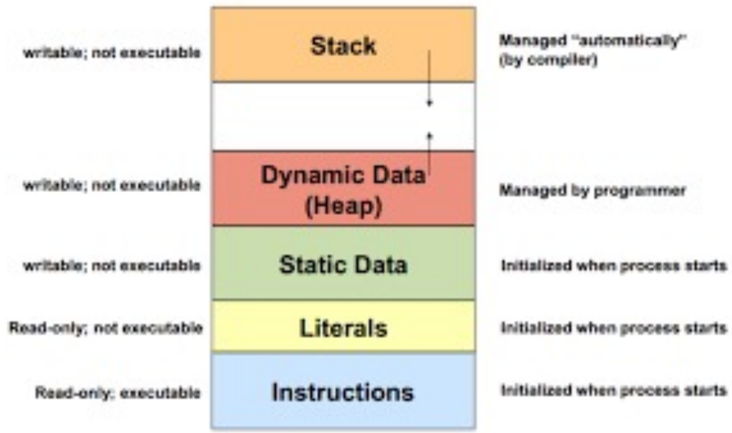
Heap Memory

- What is heap memory?



Heap Memory

- Another region of memory that may be vulnerable to attacks is heap memory
  - Attacks similar to those on stack memory, such as buffer overflows, are possible
    - Although the attack techniques differ somewhat
      - Target metadata – kinds of similar, but different effect
      - Target data – we didn't do that on the stack yet

Heap Memory

- Another region of memory that may be vulnerable to attacks is heap memory
  - However, the complexity of managing heap memory brings other attacks into consideration
    - While these attacks are also possible on stack memory in theory, exploitable flaws are much less likely on the stack
- Today, we will look at the new attack types and attack techniques for the heap

Heap Memory

- What is heap memory?
  - The heap memory region is where dynamic memory allocations take place
  - It is a contiguous region of virtual memory (can expand)

Heap Low

Heap High

Heap Memory

- What is heap memory?
  - The heap memory region is where dynamic memory allocations take place
  - An allocation is assigned a contiguous range of virtual memory within the heap (e.g., on malloc)

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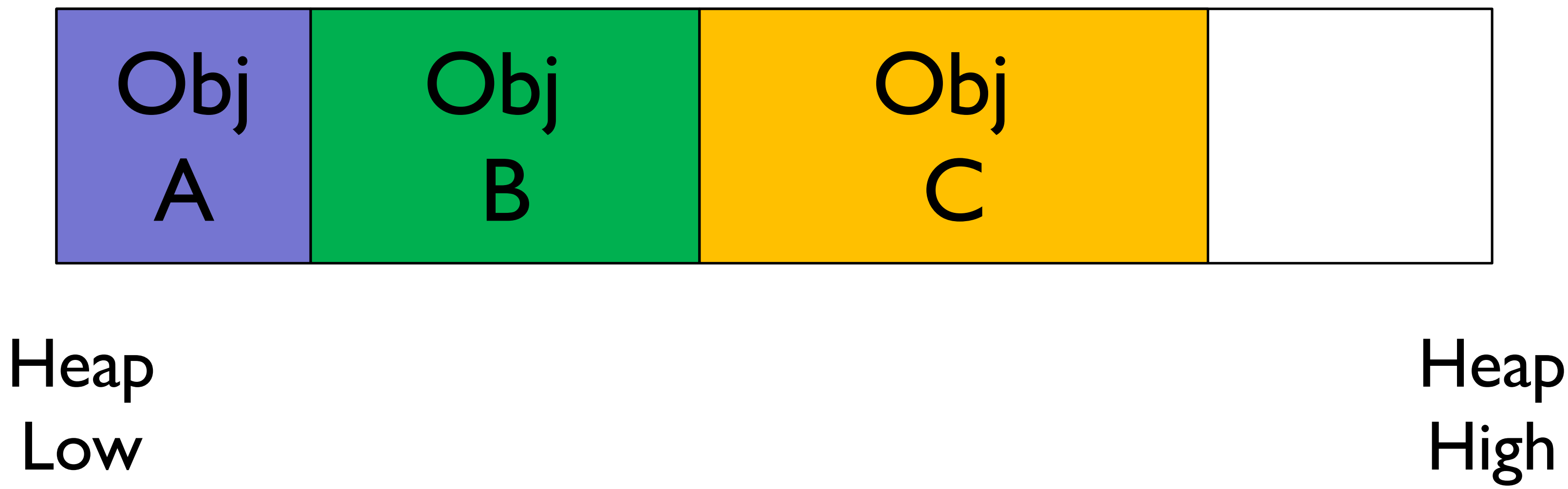
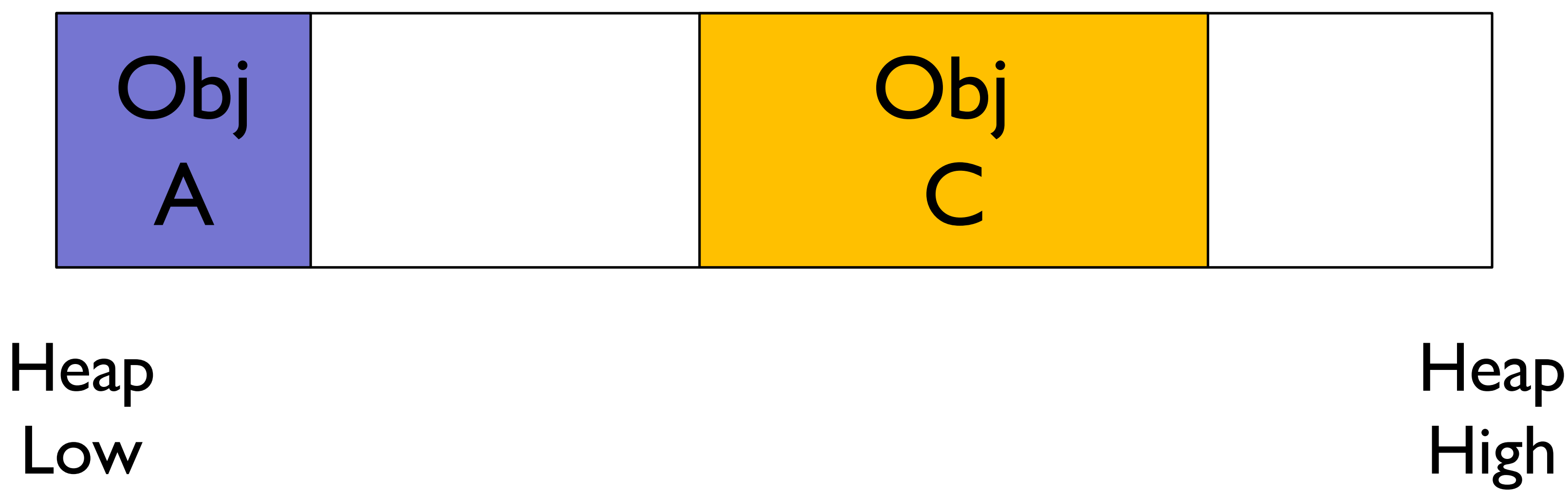
  - An allocation is assigned a contiguous range of virtual memory within the heap (e.g., on malloc)



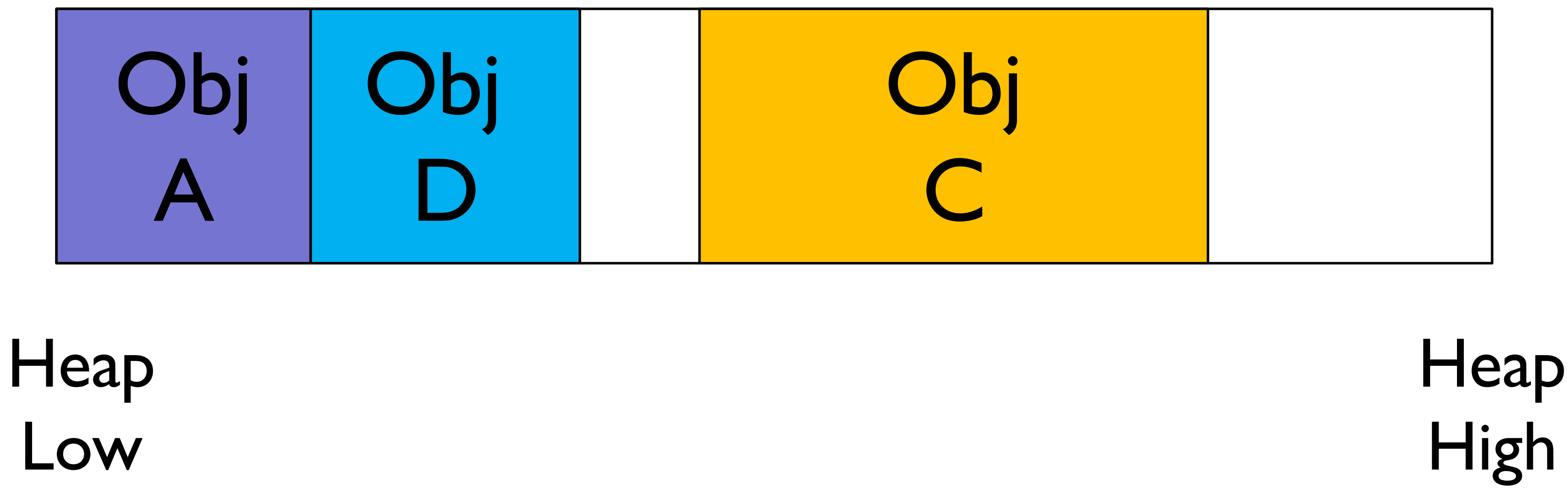
Heap Memory

- What is heap memory?
  - The heap memory region is where dynamic memory allocations take place
  - Memory from a specific allocation may be reclaimed when no longer needed (e.g., on "free")



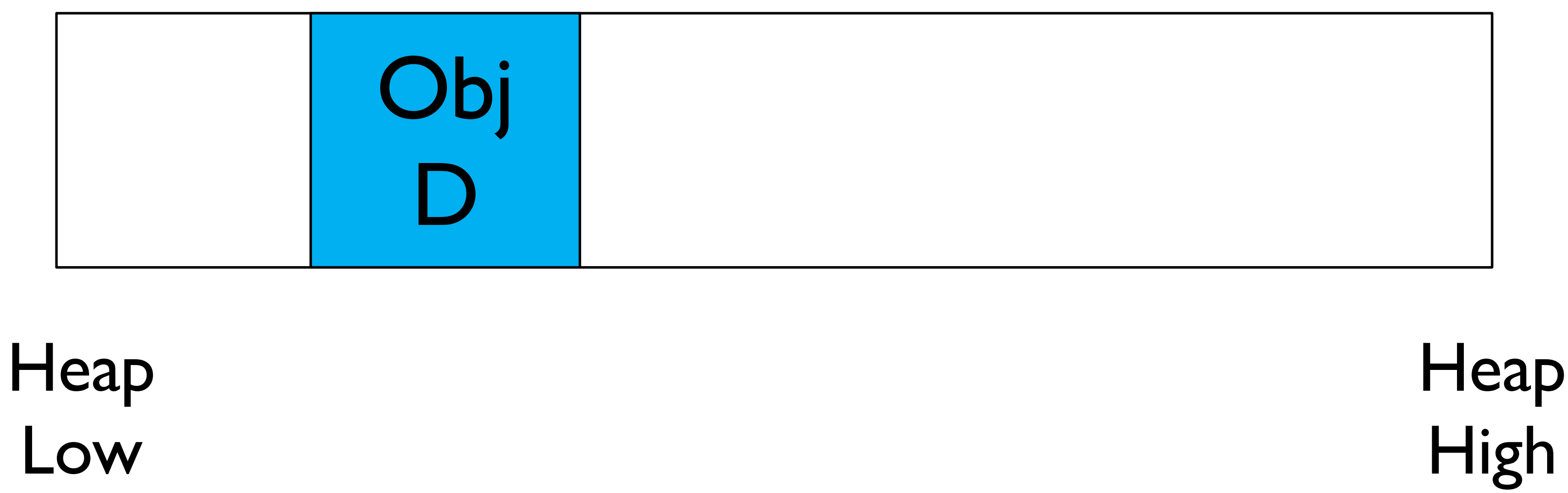
Heap Memory

- What is heap memory?
  - The heap memory region is where dynamic memory allocations take place
  - Memory from a specific allocation may be reclaimed when no longer needed (e.g., on “free”) and reused



Heap Memory

- What is heap memory?
  - The heap memory region is where dynamic memory allocations take place
  - If you forget to reclaim memory no longer in use, that memory region is lost (i.e., memory leak)



Review: Stack Buffer Overflow

- Suppose that PacketRead causes an overflow on the memory region of the variable "packet" below
  - What is the potential impact?

```
int authenticated = 0;
char packet[1000];

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
 if (authenticated)
   ProcessPacket(packet);
```

Stack Buffer Overflow

- Suppose that PacketRead causes an overflow on the memory region of the variable “packet” below
  - What is the potential impact? ”authenticated” may be set

```
int authenticated = 0;
char packet[1000];

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
 if (authenticated)
   ProcessPacket(packet);
```

Heap Buffer Overflow

- What happens if we allocate "packet" on the heap?
  - A buffer overflow of a buffer allocated on the heap is called a heap overflow – Impact?

```
int authenticated = 0;
char *packet = (char *)malloc(1000);

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
 if (authenticated)
   ProcessPacket(packet);
```

Heap Buffer Overflow

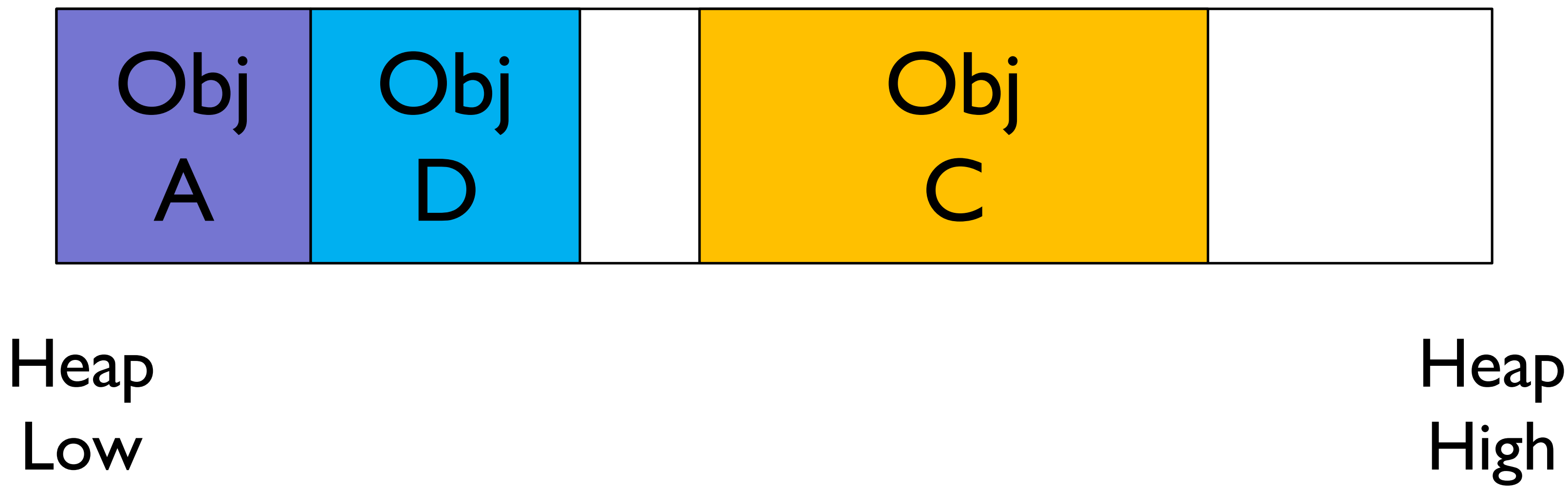
- While a heap overflow may impact heap memory regions, it won't impact stack memory (directly)
  - "authenticated" is unaffected, but something else may be affected

```
int authenticated = 0;
char *packet = (char *)malloc(1000);

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
 if (authenticated)
   ProcessPacket(packet);
```

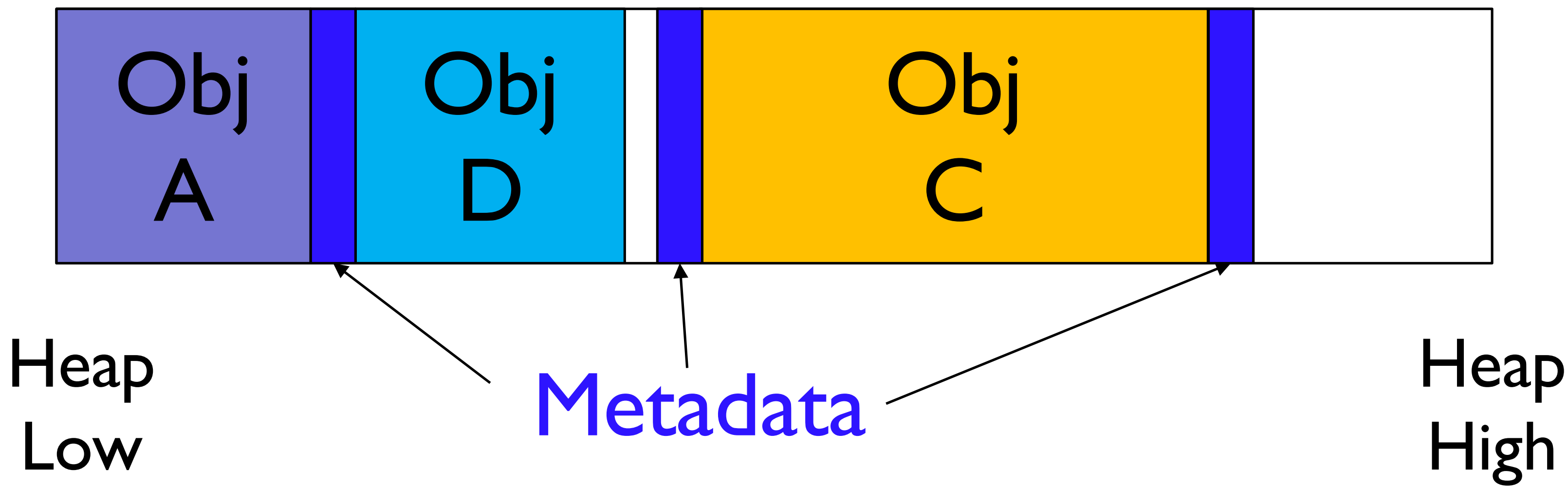
Heap Memory Layout

- The Heap Memory Layout below is idealized
  - Depends on the heap allocator
  - Many heap allocators store metadata with objects on the heap to manage the heap region



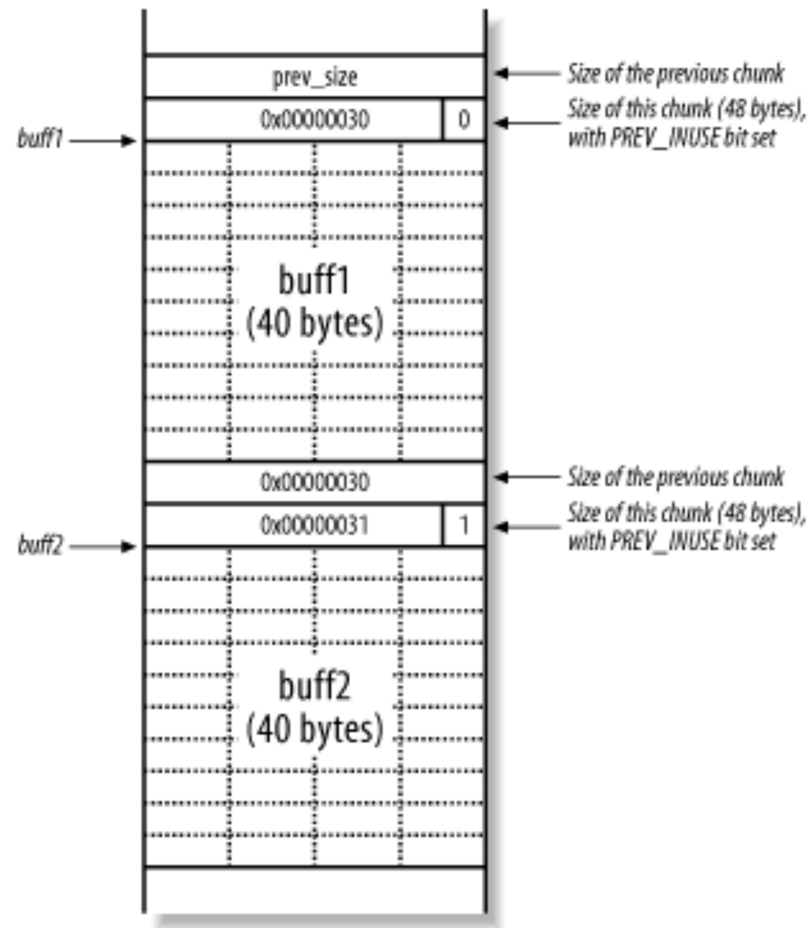
Heap Memory Layout

- The Heap Memory Layout often includes metadata
  - Depends on the heap allocator
  - Often placed between objects to store information needed to manage allocation state – e.g., sizes and status



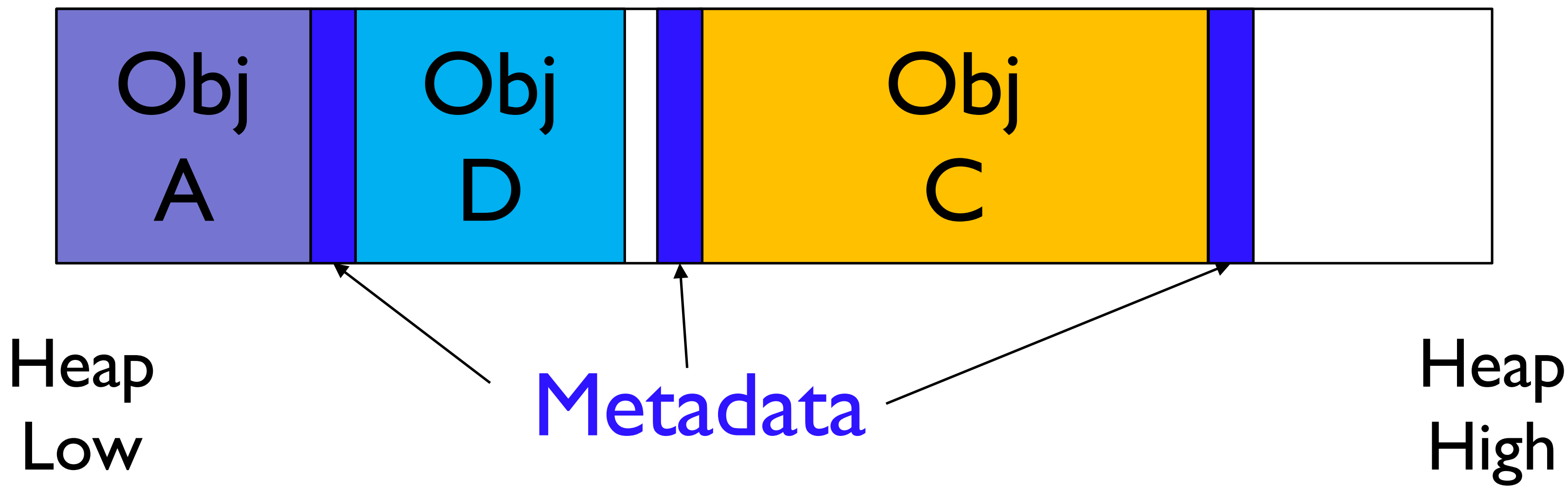
Heap Memory Layout

- The Heap Memory Layout often includes metadata
  - Depends on the heap allocator
  - Often placed between objects to store information like the "size of chunk," "size of allocation," "in use bit," and reference to the previous or next chunk



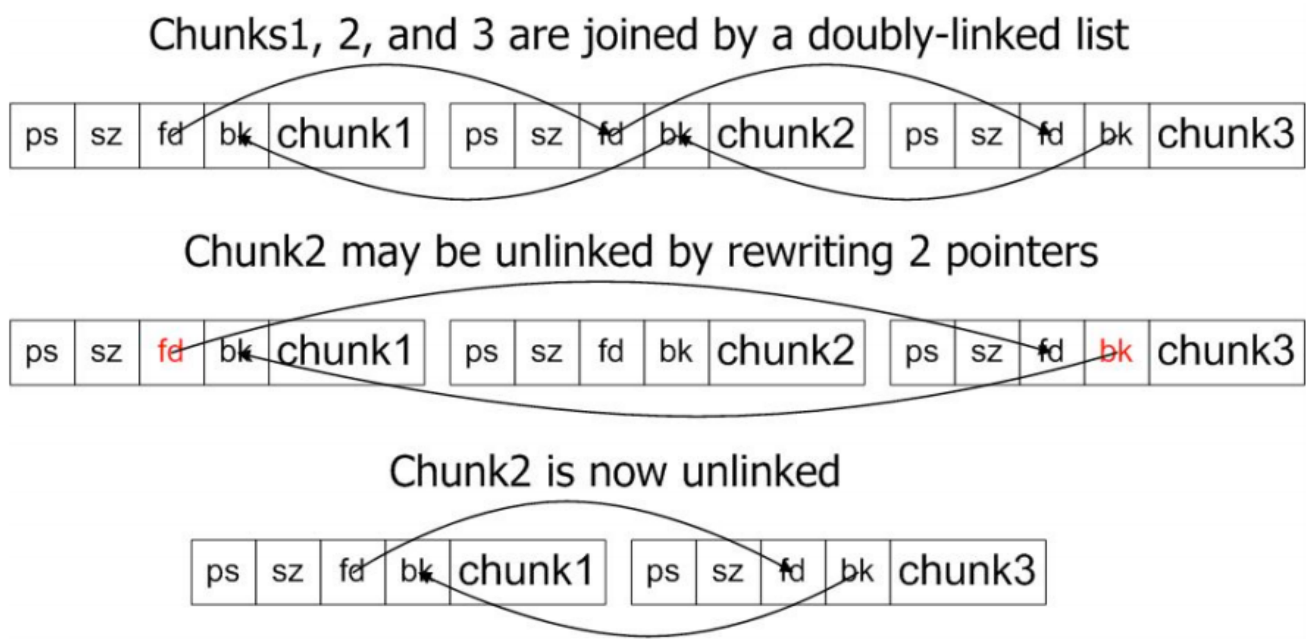
Heap Memory Layout

- The Heap Memory Layout often includes metadata
  - Depends on the heap allocator
  - So, what are the potential impacts of a heap overflow?



Heap Overflows

- Heap allocators maintain a doubly-linked list of allocated and free chunks
- **`malloc`**() and **`free`**() modify this list



Heap Overflows

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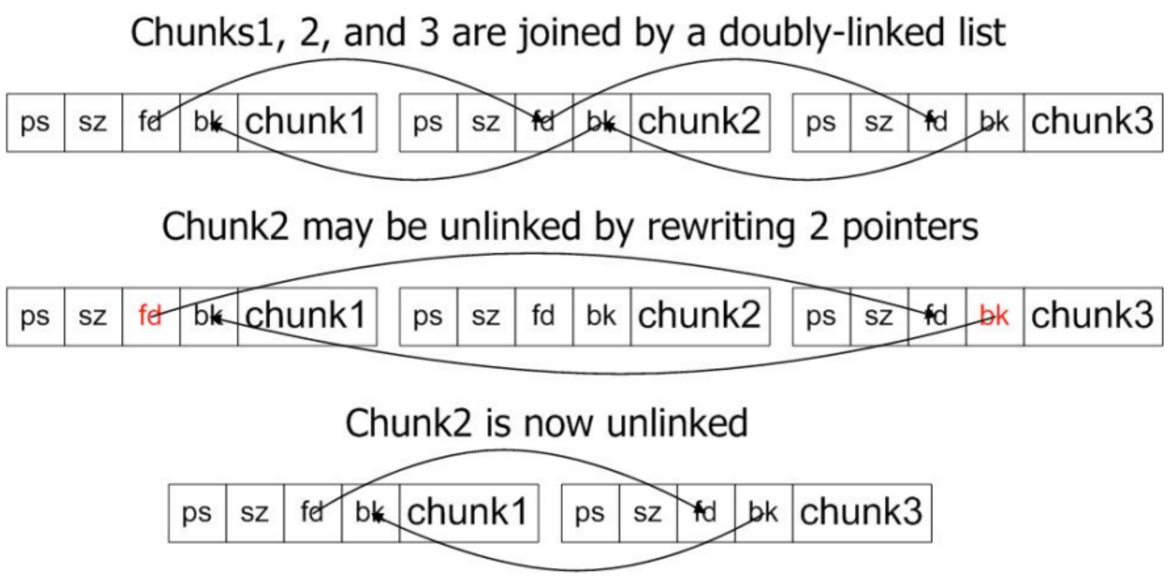
- free() removes a chunk from allocated list

```
chunk2->bk->fd = chunk2->fd
chunk2->fd->bk = chunk2->bk
```

- By overflowing chunk1, attacker controls bk and fd
  - Controls both *where* and *what* data is written!
    - Arbitrarily change memory



Heap Overflows

- By overflowing chunk1, attacker controls bk and fd
  - Controls both *where* and *what* data is written!
    - Assign chunk2->fd to value to want to write
    - Assign chunk2->bk to address X (where you want to write)
      - Less an offset of the fd field in the structure
- Free() removes a chunk from allocated list

```
chunk2->bk->fd = chunk2->fd
chunk2->fd->bk = chunk2->bk
```

- What's the result?

Heap Overflows

- By overflowing chunk2, attacker controls bk and fd
  - Controls both *where* and *what* data is written!
    - Assign chunk2->fd to value to want to write
    - Assign chunk2->bk to address X (where you want to write)
      - Less an offset of the fd field in the structure
- Free() removes a chunk from allocated list

```
chunk2->bk->fd = chunk2->fd
addrX->fd = value
chunk2->fd->bk = chunk2->bk
value->bk = addrX
```

- What's the result?
  - Change a memory address to a new pointer value (in data)

Heap Overflow Defenses

- Separate data and metadata
  - e.g., OpenBSD's allocator (Variation of **`PHKmalloc`**)
- Sanity checks during heap management

```
free(chunk2) -->
    assert(chunk2->fd->bk == chunk2)
    assert(chunk2->bk->fd == chunk2)
```

  - Added to GNU **`libc`** 2.3.5

Other Heap Attacks

- Other Types of Attacks
  - Buffer Overread or Disclosure
  - Use-After-Free
  - Type Confusion
- While these are all also possible attacks on stack objects, they are often more significant attacks on heap objects
  - We will take a look

Buffer Overread/Disclosure

- A buffer overread (disclosure) attack enables an adversary to read memory outside of a region

Buffer Overread/Disclosure

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- A buffer overread (disclosure) attack enables an adversary to read memory outside of a region
  - Benign task: Copy from "buffer X" to "buffer Y"
  - Read beyond the memory region of "buffer X"
  - To access other objects' data
  - And copy into "buffer Y"
- Why would that be a problem?

Buffer Overread/Disclosure

- A buffer overread (disclosure) attack enables an adversary to read memory outside of a region
  - Benign task: Copy from "buffer X" to "buffer Y"
  - Read beyond the memory region of "buffer X"
  - To access other objects' data
  - And copy into "buffer Y"
- While also possible for stack objects, often more sensitive data is stored on the heap
  - Heap data is longer lived (more than a function) and often more diverse and complex (structures)

Heartbleed

- The Heartbleed vulnerability was a significant threat to the security of OpenSSL
  - OpenSSL – crypto library for the SSL/TLS protocols
  - Buffer overread vulnerability in the library that allowed an adversary to steal web servers' private keys
  - About 500,000 secure web servers were at risk

Heartbleed

- The Heartbleed vulnerability was a significant threat to the security of OpenSSL
  - OpenSSL – crypto library for the SSL/TLS protocols
- Caused by a heap overread
  - Send a message of length K, but say its length is N > K
  - Allocate N-byte buffer, but only copy K bytes into the buffer from the original message
  - Return all the memory in the N-byte buffer

Attacks on Memory Reuse

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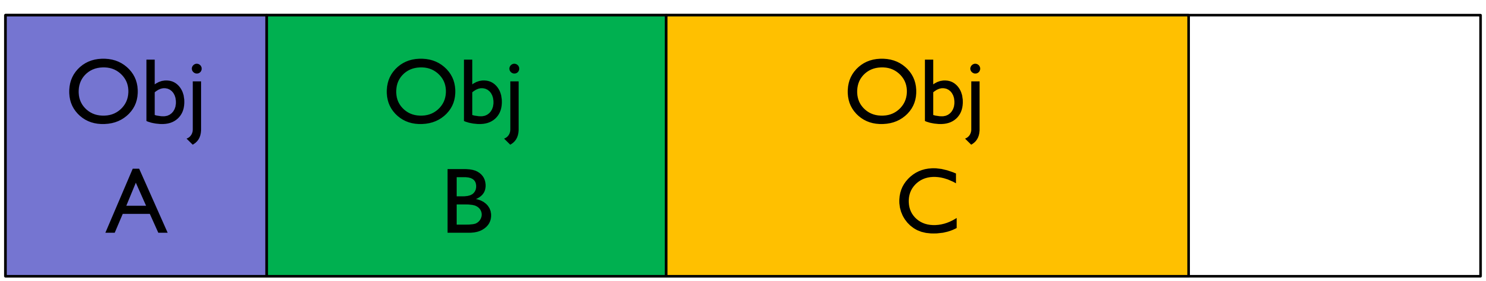
- Attacks also exploit the inconsistencies caused in the reuse of memory on the heap
- Inconsistencies
  - Your program may reclaim memory
    - And reuse that memory region for another object
  - But, the pointers to the original object (i.e., memory location prior to reclamation) may remain
    - And be used after the reuse
- Examples
  - Use-after-free and type confusion

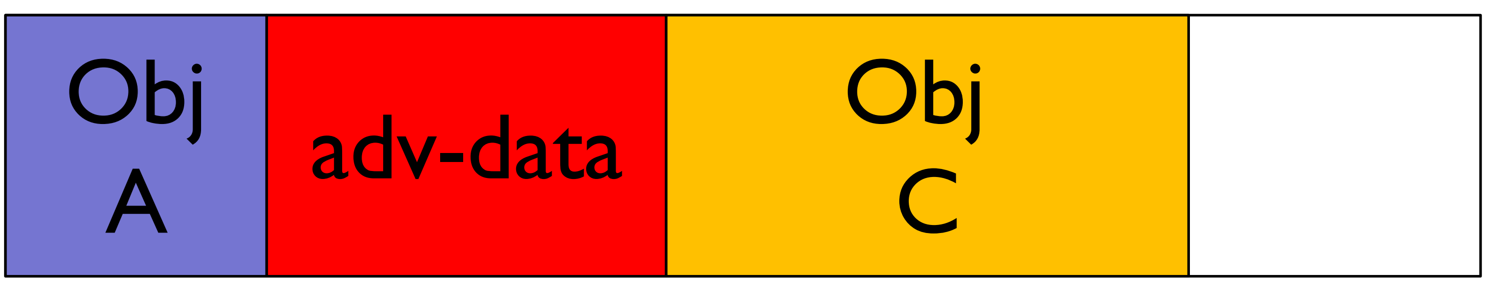
Use After Free

- Flaw: Program frees data on the heap, but then references that memory as if it were still valid
  - E.g., pointer to Obj B (say "b")
- Accessible: Adversary can control data written using the freed pointer
  - memcpy(b, adv-data, size);
- Exploit: Obtain a "write primitive"



Use After Free

- Flaw: Program frees data on the heap, but then references that memory as if it were still valid
  - E.g., pointer to Obj B (say "b")
- Accessible: Adversary can control data written using the freed (stale) pointer
  - memcpy(b, adv-data, size);
- Exploit: Obtain a "write primitive"



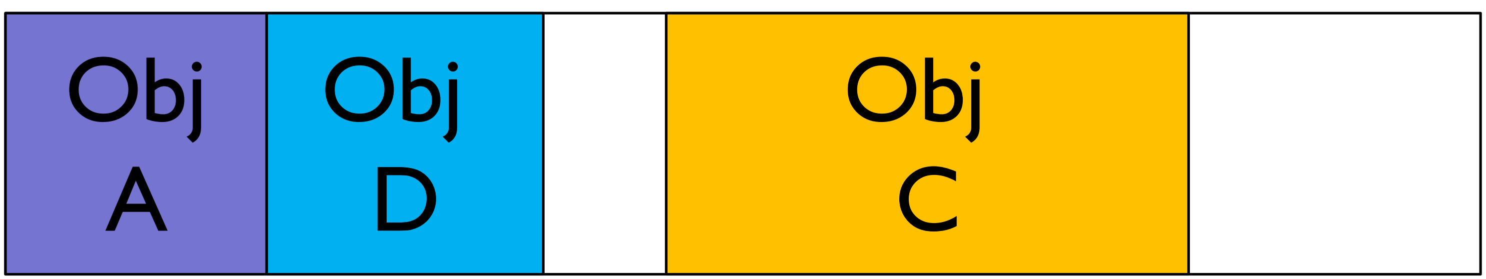
Use After Free

- Flaw: Program frees data on the heap, but then references that memory as if it were still valid
- Accessible: Adversary can control data written using the freed pointer
- Exploit: Obtain a "write primitive"

- Hold on: just using a reference to freed memory isn't really a problem, is it?
  - What is missing from above?

Use After Free

- Flaw: Program frees data on the heap, but then references that memory as if it were still valid
  - E.g., pointer to Obj B (say "b")
- Accessible: Adversary can control data written using the freed pointer
  - memcpy(b, adv-data, size);
- Exploit: Obtain a "write primitive" to a new object



Use After Free

- What happens here?

```
int main(int argc, char **argv) {
    char *buf1R1;
    char *buf2R1;
    char *buf2R2;
    char *buf3R2;

    buf1R1 = (char *) malloc(BUFSIZER1);
    buf2R1 = (char *) malloc(BUFSIZER1);

    free(buf2R1);

    buf2R2 = (char *) malloc(BUFSIZER2);
    buf3R2 = (char *) malloc(BUFSIZER2);

    strncpy(buf2R1, argv[1], BUFSIZER1-1);
    free(buf1R1);
    free(buf2R2);
    free(buf3R2);
}
```

Use After Free

- When the second R1 buffer (buf2R1) is freed that memory is available for reuse right away

```
buf1R1 = (char *) malloc(BUFSIZER1);
buf2R1 = (char *) malloc(BUFSIZER1);

free(buf2R1);
```

- Then, the R2 buffers could be allocated within that memory region (buf2R1s)

```
buf2R2 = (char *) malloc(BUFSIZER2);
buf3R2 = (char *) malloc(BUFSIZER2);
```

- Finally, the write using the freed pointer will overwrite the R2 buffers (and metadata between)

```
strncpy(buf2R1, argv[1], BUFSIZER1-1);
```

Type Confusion Attacks

- A type confusion attack exploits when a program uses a pointer one type to reference a memory region of another type
  - A common way of utilizing a use-after-free vulnerability to go from a "write primitive" to an "arbitrary write primitive"
  - Let's see how…

Type Confusion

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- Most effective attacks exploit data of another type

```
struct A {
    struct C *c;
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

Type Confusion

- Free A and allocate B – assume in A's location

```
struct A {
    struct C *c;
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));
```

Type Confusion

- How do you think you exploit this?

```
struct A {
    struct C *c;
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));
```

Type Confusion

- Arbitrary write primitive!

```
struct A {
    struct C *c;
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));
y->B1 = address_of_where_to_write;
x->c->field = value_to_write;
```

Use After Free

- Flaw: program frees data on the heap, but then references that memory as if it were still valid
- Accessible: Adversary can control data written using the freed pointer
- Exploit: Obtain an "arbitrary write primitive"
- Become a popular vulnerability to exploit – over 60% of CVEs
  - http://blog.tempest.com.br/breno-cunha/perspectives-on-exploit-development-and-cyber-attacks.html

Type Confusion

- How do you think you exploit this?

```
struct A {
    void (*fnptr)(char *arg);
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));
```

Type Confusion

- Arbitrary code reuse!

```
struct A {
    void (*fnptr)(char *arg);
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));
y->B1 = execve@PLT;
x->fnptr("/bin/sh");
```

Type Confusion

- Adversary chooses function pointer value (set as int)
- Adversary may also be able to choose value for “arg”
- To implement arbitrary code reuse

```
struct A {
    void (*fnptr)(char *arg);
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));
y->B1 = execve@PLT;
x->fnptr(“/bin/sh”);
```

Heap Spraying

- How do adversaries use such flaws?
  - May be hard to get an object of ”struct Y” in the location of the freed “struct X” object
- Use heap spraying to fill the heap with lots of “struct Y” objects
  - Eventually, one will be placed in the location of the freed “struct X” object, so we can use the pointer to access to target memory or code

Type Confusion

- Does type confusion require a use-after-free?
  - What other C operation enables a programmer to reference data one location via multiple type signatures?

Type Casts

- Does type confusion require a use-after-free?
  - What other C operation enables a programmer to reference data one location via multiple type signatures?
- Type Cast
  - A type cast enables you to create a pointer of a different type to the same memory region
    - Also, reasoning about multiple types is common in object-oriented languages (C++)

Type Confusion Via Casts

- Cause the program to process data of one type when it expects data of another type
  - Provides same affect as we did with use-after-free
  - But, without the "free" – just need an ambiguous "use"
    - Where's the error below?

```
class Ancestor { int x; }

class Descendent : Ancestor { int y; }

Ancestor *A = new A;
Descendant *D = static cast <Ancestor *> A;

D->y = 7;
```

HexType – Jeon et al. ACM CCS 2017

Type Confusion

- Cause the program to process data of one type when it expects data of another type
  - Provides same affect as we did with use-after-free
  - But, without the "free" – just need an ambiguous "use"
    - Where's the error below?

```
class Ancestor { int x; }

class Descendent : Ancestor { int y; }

Ancestor *A = new A;
Descendant *D = static cast <Ancestor *> A;

D->y = 7;  // not within memory region allocated to A
```

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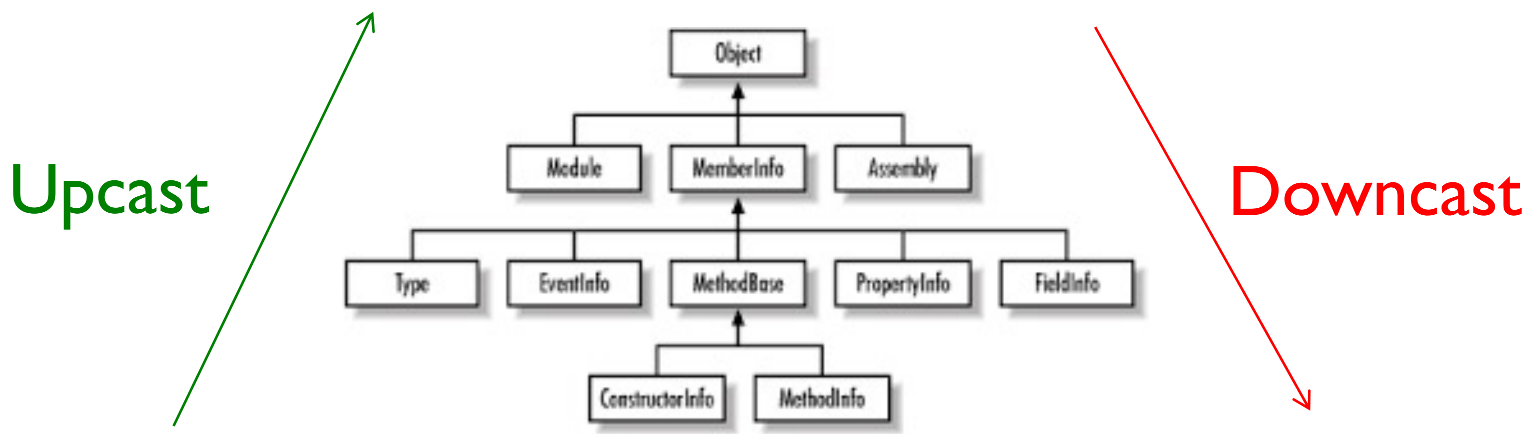
Type Hierarchies

- C++ allows you to construct type hierarchies



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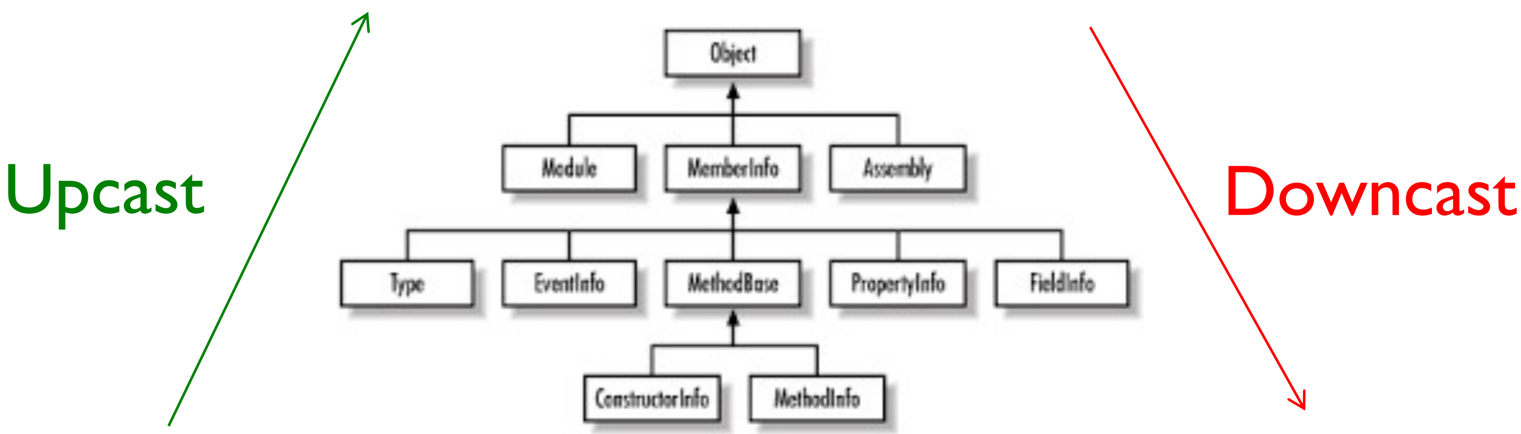
Type Hierarchies

- C++ allows you to construct type hierarchies
  - Which type of cast is safe and why?



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Un/Safe Type Casts

- Upcasts are always safe because they only reduce the type structure
  - That is, only subtypes extend the structure definitions
- Thus, downcasts (as in the example) and arbitrary casts (that do not follow the hierarchy) are unsafe
  - However, programming environments trust programmers to do the right thing

Take Away

- Heaps provide a wide variety of options for adversaries, depending on the software flaw
- Can attack either heap metadata or other heap data, including pointers to access arbitrary memory
- Heaps are susceptible to more types of powerful attacks than stacks
  - Disclosure attacks, use-after-free, and type confusion
  - These attacks are all somewhat related
- We will explore defenses for all of these