Memory Corruption Vulnerabilities, Part II

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Integer Overflow Vulnerabilities

* slides adapted from those by Seacord

Integer Overflows

- An **integer overflow** occurs when an integer is increased beyond its maximum value or decreased beyond its minimum value
- Standard integer types (signed)
  - signed char, short int, int, long int, long long int
- Signed overflow vs unsigned overflow
  - An unsigned overflow occurs when the underlying representation can no longer represent an integer value.
  - A signed overflow occurs when a value is carried over to the sign bit

Overflow Examples

```
unsigned int ui;
signed int si;
ui = UINT_MAX; // 4,294,967,295;
ui++;
printf("ui = %u\n", ui);

si = INT_MAX; // 2,147,483,647
si++;
printf("si = %d\n", si);
```

ui = 0

si = -2,147,483,648

Overflow Examples, cont'd

```
ui = 0;
ui--;
printf("ui = %u\n", ui);
```

ui = 4,294,967,295

```
si = INT_MIN; // -2,147,483,648;
si--;
printf("si = %d\n", si);
```

si = 2,147,483,647

Integer Overflow Example

```
int main(int argc, char *const *argv) {
    unsigned short int total;
    total = strlen(argv[1]) + strlen(argv[2]) + 1;
    char *buff = (char *) malloc(total);
    strcpy(buff, argv[1]);
    strcat(buff, argv[2]);
}
```

What if the total variable is overflowed because of the addition operation?

Vulnerability: JPEG Example

- Based on a real-world vulnerability in the handling of the comment field in JPEG files

```
void getComment(unsigned int len, char *src) {
    unsigned int size;
    size = len - 2;
    char *comment = (char *)malloc(size + 1);
    memcpy(comment, src, size);
    return;
}
```

size is interpreted as a large positive value of 0xffffffff

size+1 is 0

What if I do “getComment(1, "Comment ");”?

Possible to cause an overflow by creating an image with a comment length field of 1

Vulnerability: Negative Indexes

```
int *table = NULL;
int insert_in_table(int pos, int value){
    if (!table) {
        table = (int *)malloc(sizeof(int) * 100);
    }
    if (pos > 99) {
        return -1;
    }
    table[pos] = value;
    return 0;
}
```

What if pos is negative?

Vulnerability: Truncation Errors

```
int func(char *name, long cbBuf) {
    unsigned short bufSize = cbBuf;
    char *buf = (char *)malloc(bufSize);
    if (buf) {
        memcpy(buf, name, cbBuf);
        …
        free(buf);
        return 0;
    }
    return 1;
}
```

What if we call the function with cbBuf greater than 2^{16} -1?

Heap Overflow

*adapted from slides by Trent Jaeger

Heap Overflows

- Another region of memory that may be vulnerable to overflows is heap memory
  - A buffer overflow of a buffer allocated on the heap is called a heap overflow

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

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

Overflowing Heap Critical User Data

```
/* record type to allocate on heap */
typedef struct chunk {
    char inp[64];                /* vulnerable input buffer */
    void (*process)(char *);   /* pointer to function */
} chunk t;

void showlen(char *buf) {
    int len; len = strlen(buf);
    printf("buffer5 read %d chars\n", len);
}

int main(int argc, char *argv[]) {
    chunk t *next;
    setbuf(stdin, NULL);
    next = malloc(sizeof(chunk t));
    next->process = showlen;
    printf("Enter value: ");
    gets(next->inp);
    next->process(next->inp);
    printf("buffer5 done\n");
}
```

example by Stallings

- Overflow the buffer on the heap so that the function pointer is changed to an arbitrary address

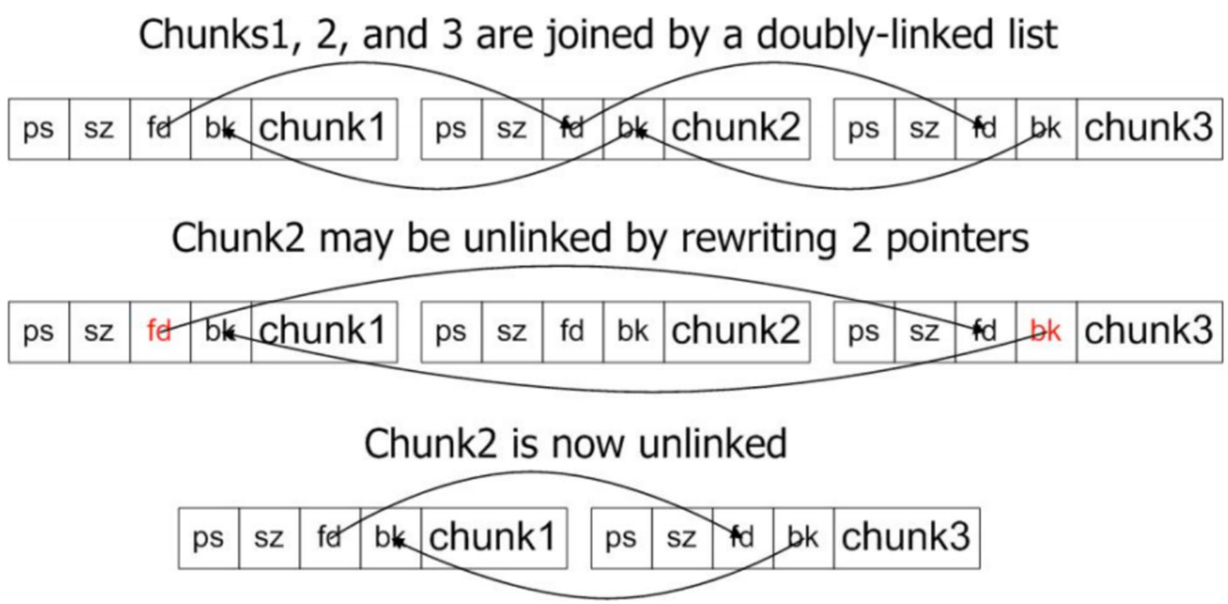
Overflow Heap Meta-Data

- Heap allocators (AKA memory managers)
  - What regions have been allocated and their sizes
  - What regions are available for allocation
- Heap allocators maintain metadata such as chunk size, previous, and next pointers
  - Metadata adjusted during heap-management functions
    - malloc() and free()
  - Heap metadata often inlined with heap data

Example Heap Allocator

- Maintain a doubly-linked list of allocated and free chunks
- malloc() and free() modify this list

An Example of Removing a Chunk



- free() removes a chunk from allocated list
  - chunk2->bk->fd = chunk2->fd
  - chunk2->fd->bk = chunk2->bk

Attacking the Example Heap Allocator

- By overflowing chunk2, attacker controls bk and fd of chunk2
- Suppose the attacker wants to write value to memory address addr
  - Attacker sets chunk2->fd to be value
  - Attacker sets chunk2->bk to be addr-offset, where offset is the offset of the fd field in the structure

Attacking the Example Heap Allocator

- free() changed in the following way
  - chunk2->bk->fd = chunk2->fd becomes (addr-offset)->fd = value, the same as (*addr)=value
  - chunk2->fd->bk= chunk2->bk becomes value->bk = addr-offset
- The first memory write achieves the attacker’s goal
  - Arbitrary memory writes

Use After Free and Double Free

*adapted from slides by Trent Jaeger

Use After Free

- Error: Program frees memory on the heap, but then references that memory as if it were still valid
  - Adversary can control data written using the freed pointer
- AKA use of dangling pointers

Use After Free

```
int main(int argc, char **argv) {
   char *buf1, *buf2, *buf3;

   buf1 = (char *) malloc(BUFSIZE1);

   free(buf1);

   buf2 = (char *) malloc(BUFSIZE2);
   buf3 = (char *) malloc(BUFSIZE2);
   strncpy(buf1, argv[1], BUFSIZE1-1);
   …

}
```

What happens here?

Use After Free

- When the first buffer is freed, that memory is available for reuse right away
- Then, the following buffers are possibly allocated within that memory region

```
buf2 = (char *) malloc(BUFSIZE2);
buf3 = (char *) malloc(BUFSIZE2);
```

- Finally, the write using the freed pointer may overwrite buf2 and buf3 (and their metadata)

```
strncpy(buf1, argv[1], BUFSIZE1-1);
```

Use After Free

- Most effective attacks exploit data of another type

```
struct A {
    void (*fnptr)(char *arg);
    char *buf;
};

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

Use After Free

- Free A, and allocate B does what?

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

Use After Free

- How can you exploit it?

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

y->B1 = 0xDEADBEEF;
x->fnptr(x->buf);
```

- Assume that
  - The attacker controls what to write to y->B1
  - There is a later use-after-free that performs a call using "x->fnptr"

Use After Free

- Adversary chooses function pointer value
- Adversary may also choose the address in
  x->buf

- Become a popular vulnerability to exploit – over 60% of CVEs in 2018

Exercise: Find the Use-After-Free Error

```
#include <stdlib.h>

struct node {
  struct node *next;
};

void func(struct node *head) {
  struct node *p;
  for (p = head; p != NULL; p = p->next) {
    free(p);
  }
}
```

Prevent Use After Free

- Difficult to detect because these often occur in complex runtime states
  - Allocate in one function
  - Free in another function
  - Use in a third function
- It is not fun to check source code for all possible pointers
  - Are all uses accessing valid (not freed) references?
  - In all possible runtime states

Prevent Use After Free

- What can you do that is not too complex?
  - You can set all freed pointers to NULL
    - Getting a null-pointer dereference if using it
    - Nowadays, OS has built-in defense for null-pointer deference
  - Then, no one can use them after they are freed
  - Complexity: need to set all aliased pointers to NULL

Related Problem: Double Free

```
main(int argc, char **argv)
{
        …
        buf1 = (char *) malloc(BUFSIZE1);
        free(buf1);
        buf2 = (char *) malloc(BUFSIZE2);
        strncpy(buf2, argv[1], BUFSIZE2-1);
        free(buf1);
        free(buf2);
}
```

What happens here?

Double Free

- Free buf1, then allocate buf2
  - buf2 may occupy the same memory space of buf1
- buf2 gets user-supplied data

```
strncpy(buf2, argv[1], BUFSIZE2-1);
```

- Free buf1 again
  - Which may use some buf2 data as metadata
  - And may mess up buf2's metadata
- Then free buf2, which uses really messed up metadata

What's Wrong? Fix?

```
#include <stdlib.h>

int f(size_t n) {
  int error_condition = 0;

  int *x = (int *)malloc(n * sizeof(int));
  if (x == NULL)
    return -1;

  /* Use x and set error_condition on error. */
  …

  if (error_condition == 1) {
    /* Handle error */
    free(x);
  }

  free(x);
  return error_condition;
}
```

What's Wrong? Fix?

```
#include <stdlib.h>

/* p is a pointer to dynamically allocated memory. */
void func(void *p, size_t size) {
  /* When size == 0, realloc(p,0) is the same as free(p).*/
  p2 = realloc(p, size);
  if (p2 == NULL) {
    free(p);
    return;
  }
}
```

Double Free

- So, "double free" can achieve the same effect as some heap overflow vulnerabilities
  - So, can be addressed in the same way
  - But, you can also save yourself some headache by setting freed pointers to NULL
  - Some new heap allocators nowadays have built-in defense for double free

Previous Lectures

- Memory corruption vulnerabilities in C/C++
  - Corrupting critical data in memory
  - E.g., return addresses, function pointers, authentication data, heap meta data
- Examples
  - Stack overflow
  - Integer overflow
  - Heap overflow
  - Use after free
  - Double free

Type Confusion

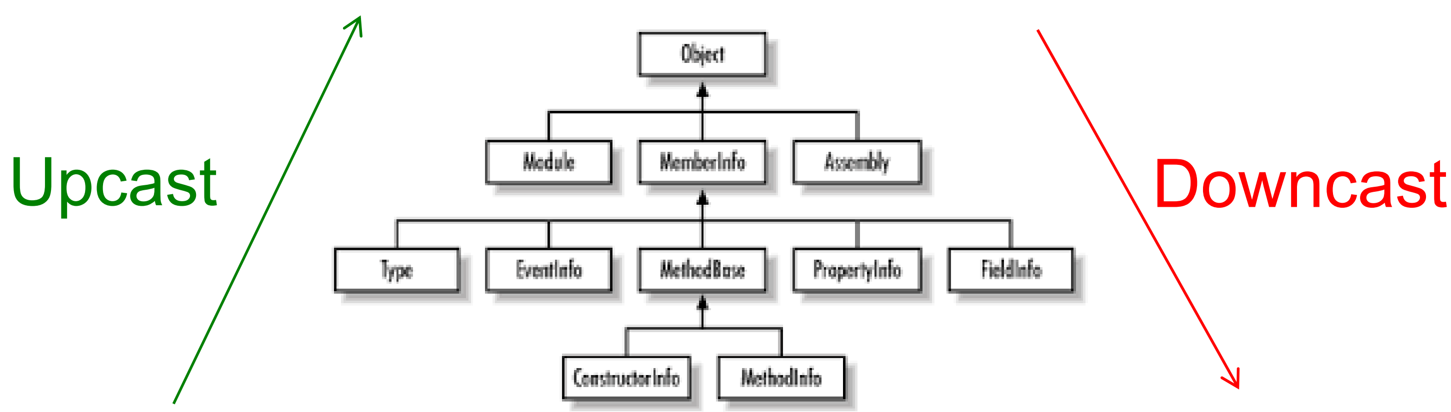
*adapted from slides by Trent Jaeger

Type Confusion

- Cause the program to process data of one type when it expects data of another type
  - Provides the same affect as we did with use-after-free
- Use-after-free is an instance of type confusion
  - But type confusion can be caused by other ways, not necessarily requiring a “free” operation
  - For example, C allows casts from type A to any arbitrary type B

Type Hierarchies

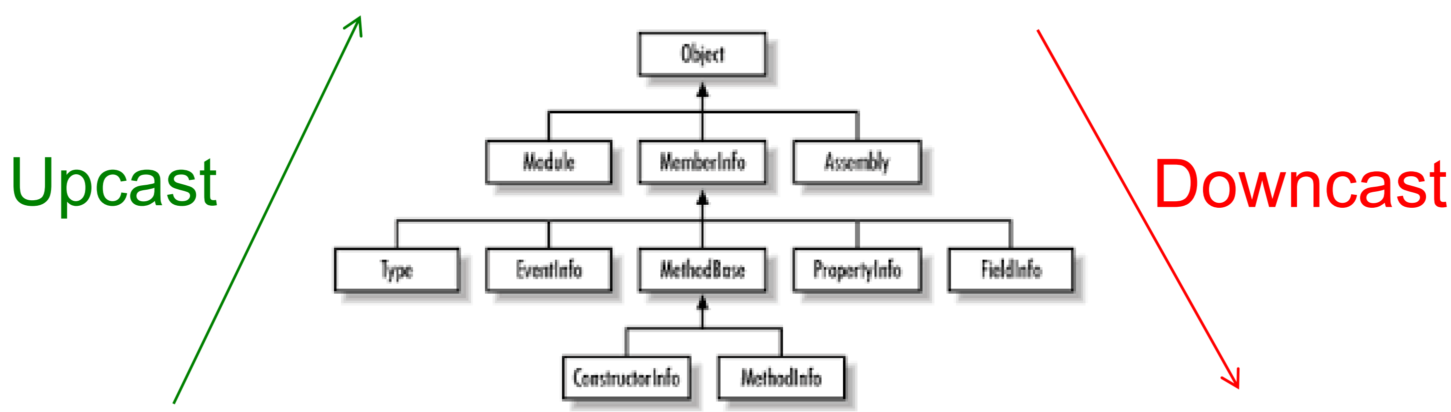
- C++ allows you to construct type hierarchies



HexType – Jeon et al. ACM CCS 2017

Type Hierarchies

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



Type Confusion Safety

- Upcasts are always safe because they only reduce the type structure
  - That is, subtypes extend the structure definitions only
- 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

Preventing Type Confusion

- Casts may be checked at runtime to verify that they are safe
  - Research project: HexType converts all static checks to runtime checks

Format String Attacks

Format String Attacks

- Public since 1999
  - first thought as harmless programming errors
- Format string refers to the argument that specifies the format of a string to functions like printf
- Example

```
int i;
printf (“i = %d with address %16lx\n", i, &i);
```

format string

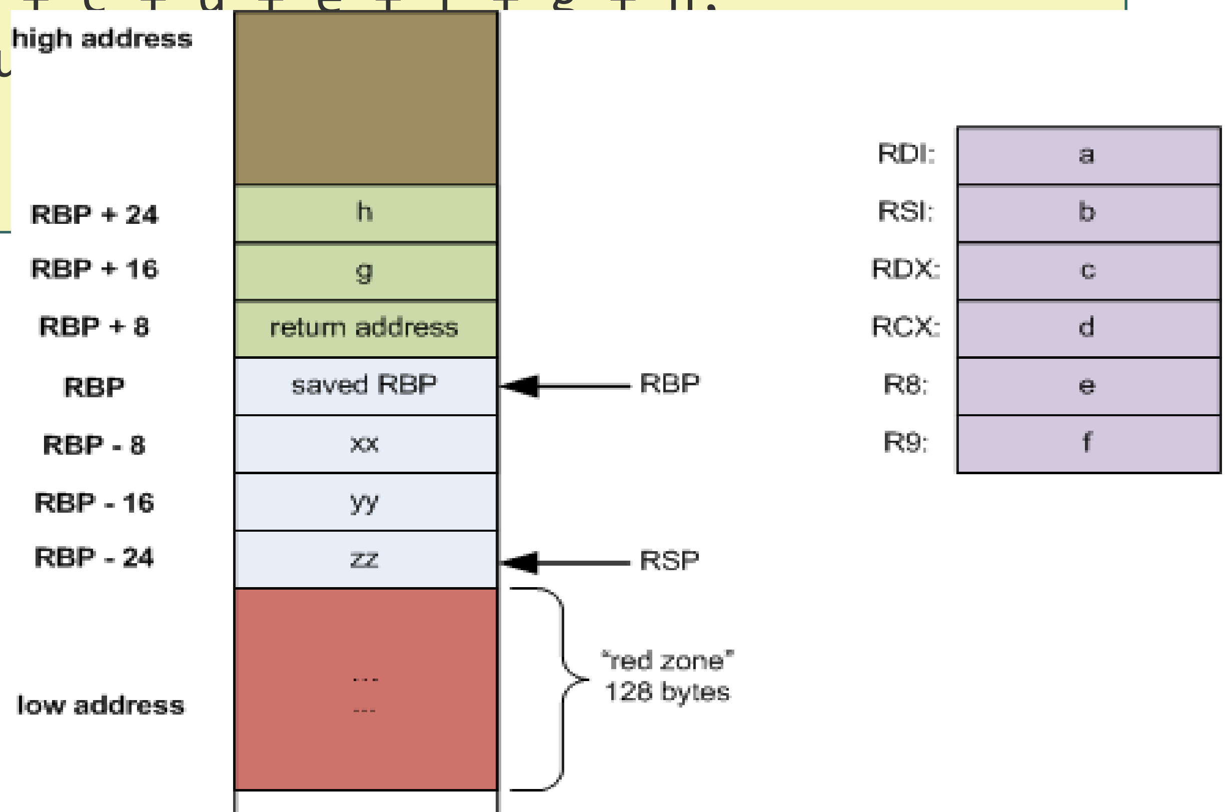
Argument Passing in x86-64

- Arguments (up to the first six) are passed to procedures via registers
  - The rest passed through the stack

Operand size (bits)	Argument Number 1	2	3	4	5	6
64	%rdi	%rsi	%rdx	%rcx	%r8	%r9
32	%edi	%esi	%edx	%ecx	%r8d	%r9d
16	%di	%si	%dx	%cx	%r8w	%r9w
8	%dil	%sil	%dl	%cl	%r8b	%r9b

Example of Argument Passing

```
long myfunc(long a, long b, long c, long d,
            long e, long f, long g, long h) {
   long xx = a * b * c * d * e * f * g * h;
   long yy = a + b + c + d + e + f + g + h;
   long zz = utilfu
   return zz + 20;
}
```



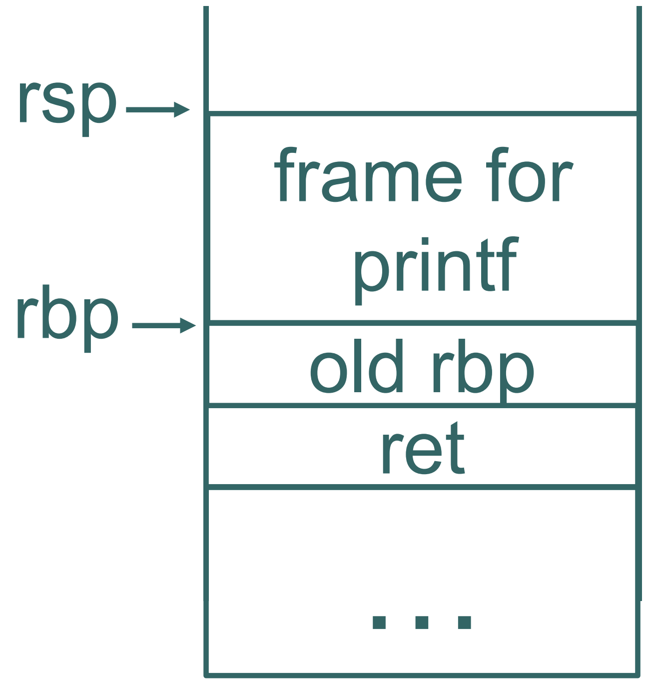
* Example from https://eli.thegreenplace.net/2011/09/06/stack-frame-layout-on-x86-64/

How Does printf Work in C?

int i;

printf (“i = %d with address %08x\n", i, &i);

- Pass string addr pointer, i, &i through registers rdi, rsi, rdx, and invokes printf
- When control is inside printf, the function looks for arguments in those registers
  - Or on the stack if more than 6 arguments

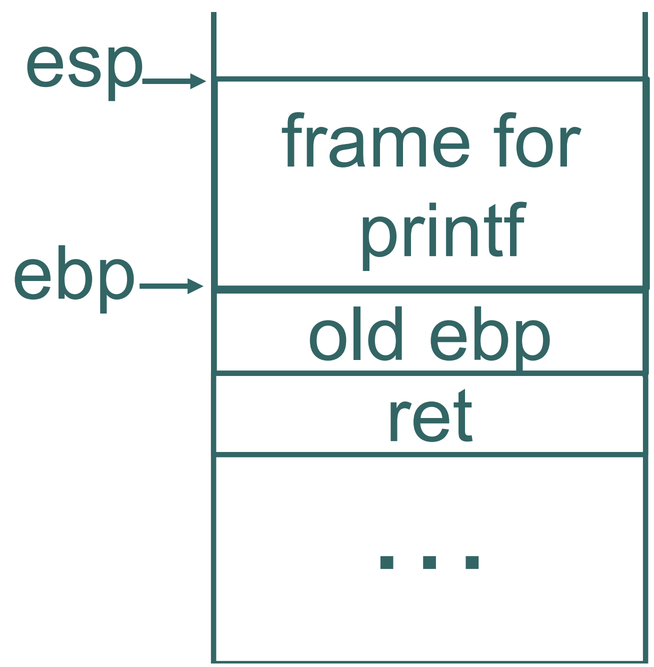


How Does printf Work in C?

- What happens for the following program?

  int i;

  printf (“i = %d with address %08x\n");
- The C compiler would not complain
  - pretending that the required arguments were at the right place



Format String Attacks

- What about the following simple program for echoing user input?

```
int main(int argc, char *argv[]) {
    if (argc>0) printf(argv[1]);
}
```

- Appears to be safe
- However, what would happen if the input is
  - hello%d%d%d%d%d%d
  - Essentially, it runs printf(“hello%d%d%d%d%d%d”)
    - printf with only one format-string argument
  - It would print numbers from argument-passing regs and the stack
  - An attacker can view memory this way
- What if the arg[1] is “hello%s”?
  - Likely segmentation fault (denial of service)

Format String Attacks

- Getting fancier
  - There is a \`%n‘ specifier, which writes the number of bytes already printed, into a variable of our choice.

```
int i;
printf ("foobar%n\n", (int *) &i);
printf ("i = %d\n", i);
```

  - i gets 6 at the end
- For the echo program, what if the user input is “foobar%n”?
  - It will take an address from rsi, and write 6 to the memory slot with that address
  - What about “foobar%10u%n”?
    - Write possibly 16 to a memory location
  - How to write to an arbitrary address?
    - Put that address at the right place (in the right reg or stack slot)
- Therefore, an attacker can update any memory with arbitrary contents
  - How about overwriting a function pointer and hijacking the control flow (and installing some worm code)?

Format String Attacks

```
int main(int argc, char *argv[]) {
    char buf[512];
    fgets(buf, sizeof(buf), stdin);


    printf("The input is:");
    printf(buf);
   return 0
}
```

No buffer overblow here

But, format string attacks

- An attacker can
  - view/change any part of the memory
  - execute arbitrary code
    - Just put the code into buf
- More details see paper
  - "Exploiting Format String Vulnerabilities"

Format String Attacks: Fixes

- Most of time: quite easy to fix

```
int main(int argc, char *argv[]) {
        ~~printf(argv[1]);~~
        printf("\n");
}
```

printf("%s", argv[1])

- But not always so obvious
  - sometimes not easy to find

```
void foo(char *user) {
    char outbuf[512];
    char buffer[512];
    sprintf (buffer, "ERR Wrong command: %400s", user);
    sprintf (outbuf, buffer);
}
```

Is there a buffer overflow? Is there a forma-string vulnerability?
How to fix it?

Prevent Format String Vulnerabilities

- Preventing format string vulnerabilities means limiting the ability of adversaries to control the format string
  - Hard-coded strings w/ no arguments – when you can
  - Hard-coded format strings at least – no printf(arg)
  - Do not use %n
    - Be careful with other references - %s and sprintf can be used to created disclosure attacks
  - Compiler support to match printf arguments with format string

Summary: Memory-Corruption Vulnerabilities

- Buffer overflow
  - stack smashing: overwrite data on the stack
  - can also overwrite data on the heap
  - Integer overflow makes it easier
- Use after free; double free
- Type confusion
- Format string attacks
- And there are many more …
  - E.g., Mark Dowd showed it was possible to hijack Adobe Flash player based on a null pointer dereference
- Type-safe languages have other kinds of vulnerabilities
  - E.g., SQL injection attacks, …
- Homework 2 on format string attacks