Secure Software Development

Memory Corruption I

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Memory safety - Wikipedia

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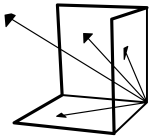
We can distinguish between two types of memory safety violation



Spatial violation: memory access is out of object's bounds

- buffer overflow
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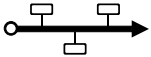

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- use after free
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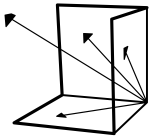

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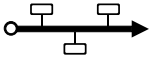

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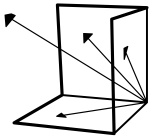

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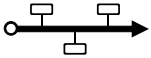

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Memory Safety Violation

- Most "important" bugs are due to violation of memory safety
- Why can't programming languages prevent them?
- There are memory safe languages (e.g., Rust, Java, ...), but...
  - ...most code is still written in C/C++
  - ...C/C++ is supported nearly everywhere
  - ...low-level code (e.g., operating systems) can't easily be implemented in memory safe languages
  - ...memory safe languages are still not mature
- In which language is the runtime of a memory safe language written in?

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Overflow (this lecture)

- Stack overflow
- Heap overflow
- Integer overflow

Invalid Memory (next lecture)

- Use-after-free
- Format string
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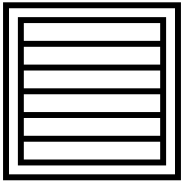
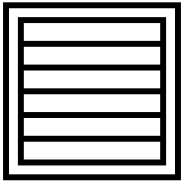
Buffers



- A buffer is a chunk of memory...
  - with boundaries
  - defined by a start address and size
  - storing elements of a certain type
- Example: Arrays in C/C++

```
char buffer[12];
strcpy(buffer, "Hello");
```



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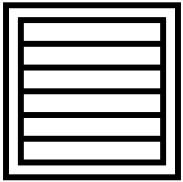

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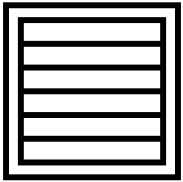

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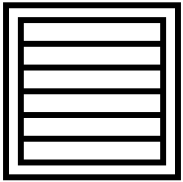

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- Most commonly: array index out of bounds
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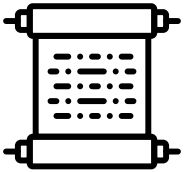

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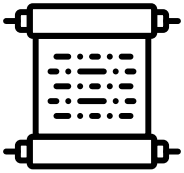

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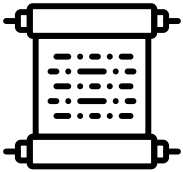

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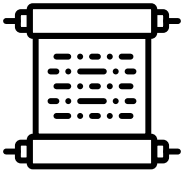

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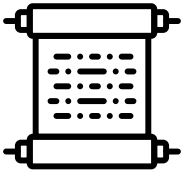

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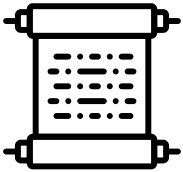

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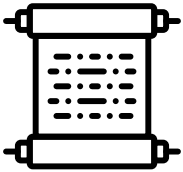

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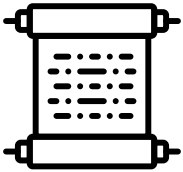

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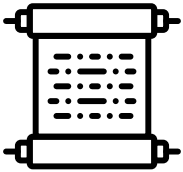

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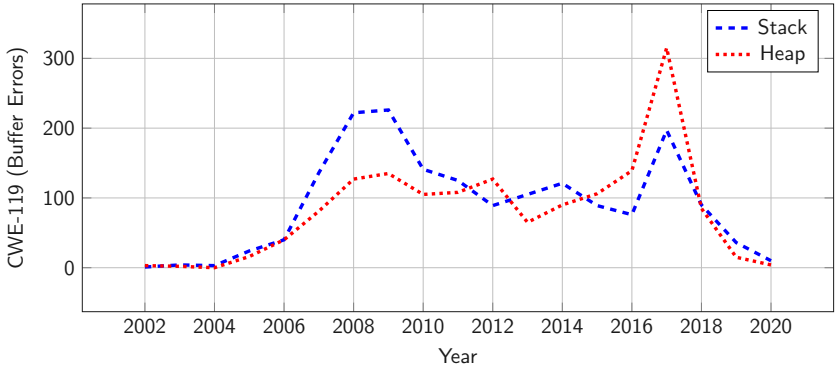

Stack Overflow

- Local buffers are on the stack
- What is next to the buffer?
  - Other variables
  - Function parameters
  - Saved return addresses
- Attacker controls the buffer input, overwrites this data
- Changes control flow or manipulates data

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Practical Example: Stack Overflow


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

void printName(char* buffer) {
  char name[16];
  strcpy(name, buffer);
  printf("Hello %s\n", name);
}

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


```
% gdb --args ./hello Students
(gdb) r
Starting program: /home/hello Students
Hello Students
[Inferior 1 (process 21312) exited normally]
```

```
% gdb --args ./hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
(gdb) r
Starting program: /home/hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA

Program received signal SIGSEGV, Segmentation fault.
0x41414141 in ?? ()
```


```
% gdb --args ./hello Students
(gdb) r
Starting program: /home/hello Students
Hello Students
[Inferior 1 (process 21312) exited normally]
```

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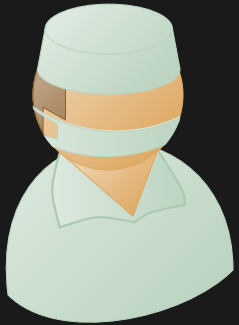

Practical Example Analysis: Stack Overflow


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#include <stdio.h>
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void printName(char* buffer) {
  char name[16];
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}

int main(int argc, char* argv[]) {
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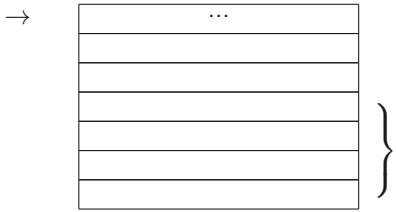
  return 0;
}
```

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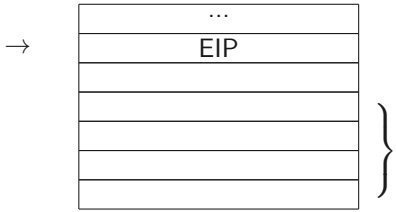

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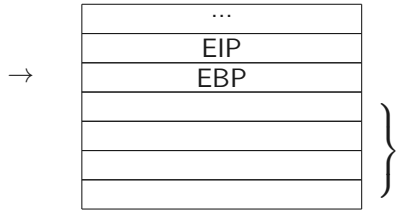


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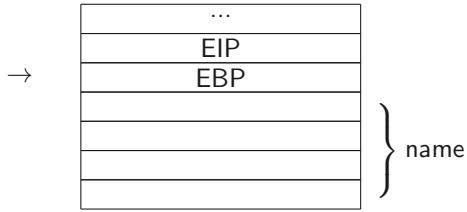


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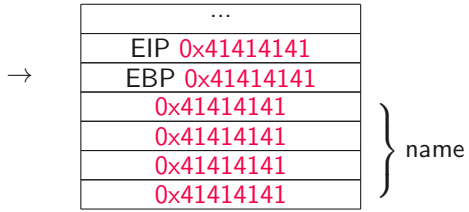


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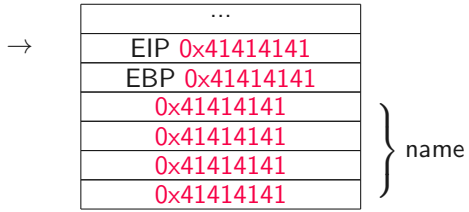

Practical Example Impact: Stack Overflow

- Attacker can jump to arbitrary location in memory
- Every function that is mapped in the address space can be executed
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- Dynamic buffers (e.g., `malloc`'d) are on the heap
- What is next to the buffer?
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Practical Example: Heap Overflow


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

int main(int argc, char* argv[]) {
  char* user = (char*)malloc(8 * sizeof(char));
  char* filename = (char*)malloc(16 * sizeof(char));
  strcpy(filename, "test.txt");
  strcpy(user, argv[1]);

  printf("Hello %s\n", user);
  FILE* f = fopen(filename, "r");
  if(!f) printf("Could not open %s\n", filename);
  fclose(f);
  return 0;
}
```

Buffer Overflow (Heap)


```
% gdb --args ./hello Students
(gdb) r
Starting program: /home/hello Students
Hello Students
[Inferior 1 (process 20744) exited normally]
```

```
% gdb --args ./hello aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
(gdb) r aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
Starting program:
  /home/hello aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
Hello aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
Could not open aaaa

Program received signal SIGSEGV, Segmentation fault.
_IO_new_fclose (fp=0x0) at iofclose.c:53
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[Inferior 1 (process 20744) exited normally]
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  /home/hello aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
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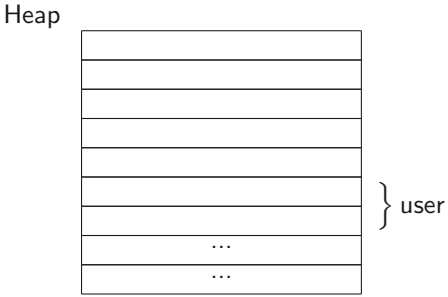

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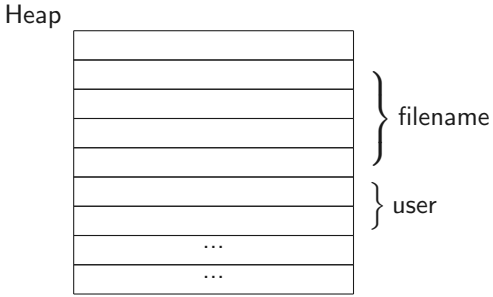


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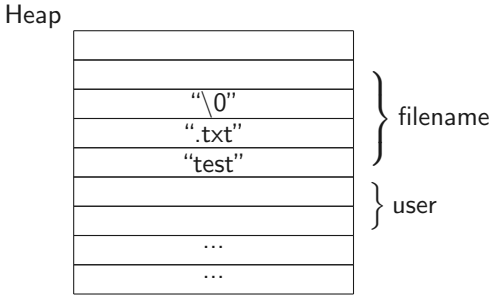

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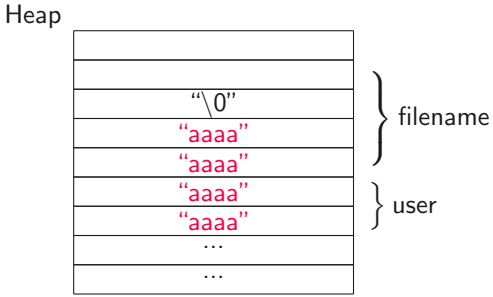

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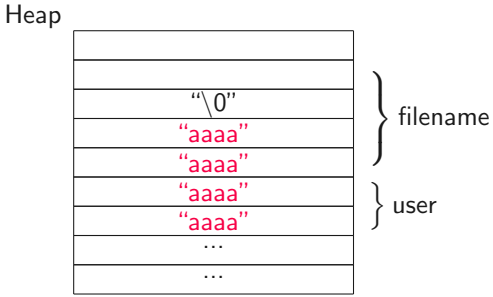

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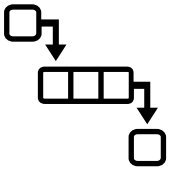
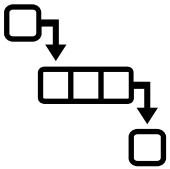


- Lots of different `malloc` implementations
  - `jemalloc` (Android, FreeBSD, Firefox)
  - `tcmalloc` (Chrome)
  - `dlmalloc`/`ptmalloc` (glibc)
- They all handle lists of chunks
- Chunks usually consist of meta data and user data
- There are various techniques to corrupt meta data to
  - achieve arbitrary memory reads/writes
  - get overlapping memory chunks



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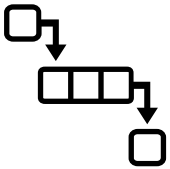

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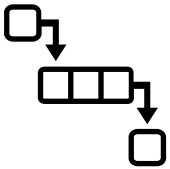

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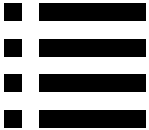

- C++ objects with virtual methods contain a pointer to a vtable
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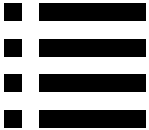
- Controlling the vtable pointers allows to call arbitrary functions

Buffer Overflow (Heap) - vtable



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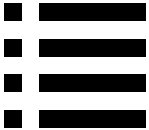

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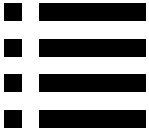

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Fun Example: Heap Overflow with vtable

Buffer Overflow (Heap) - Overwrite vtable

```
#include <iostream>
class A {
  public: virtual const char* name() { return "A"; };
};
const char* secret() {
    return "secret!";
}
int main() {
  size_t* buffer = new size_t[2];
  A* a = new A();
  std::cout << a->name() << std::endl;

  // craft vtable: first entry is pointer to 'secret'
  buffer[0] = (size_t)secret;
  // overflow into 'a', 'buffer' is now our crafted vtable
  buffer[4] = (size_t)buffer;

  std::cout << a->name() << std::endl; // calls first entry in vtable
}
```


```
% ./vtable
A
secret!
```

Heartbleed

- A security bug in the TLS protocol implementation of OpenSSL
- In the heartbeat extension (hence the name)
- A missing bounds check leads to a buffer over-read
- Allows to read up to 64 KB of server memory

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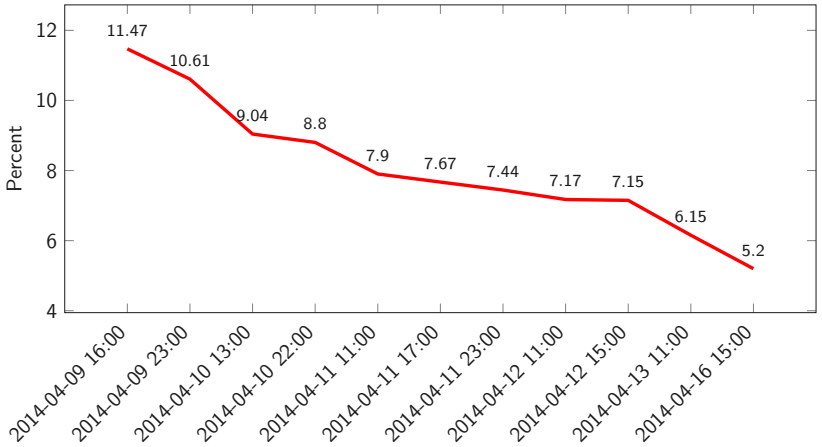
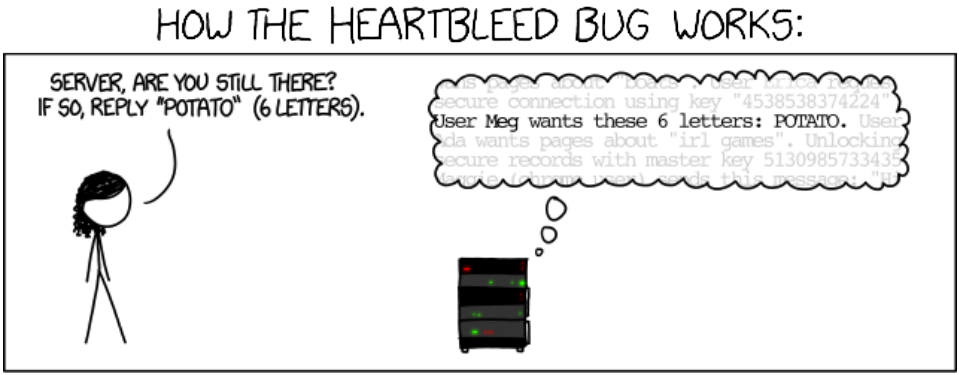
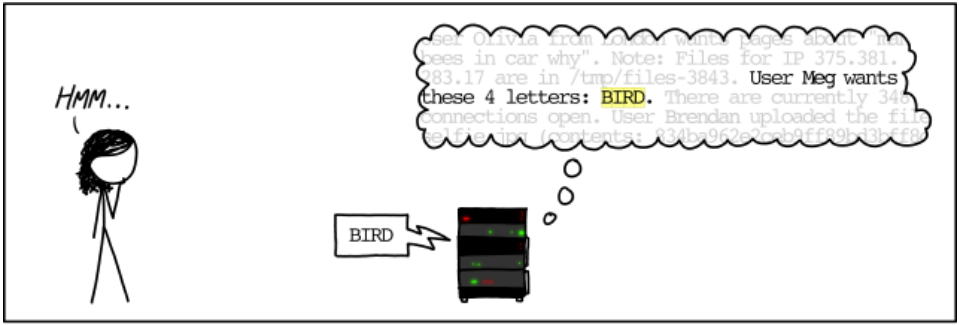
Alexa Top 1 Million Pages - Vulnerable servers

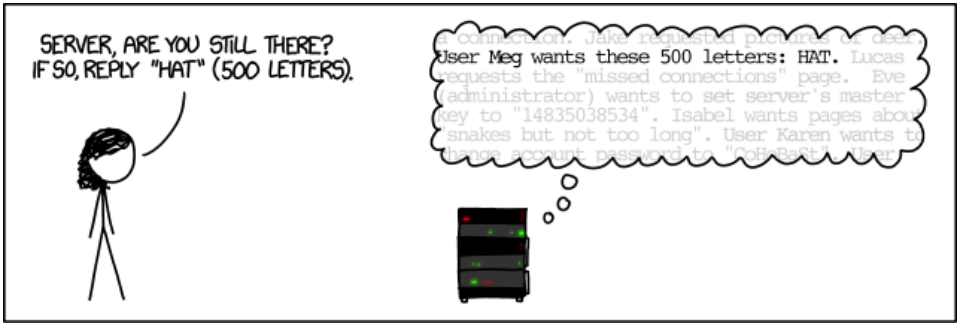


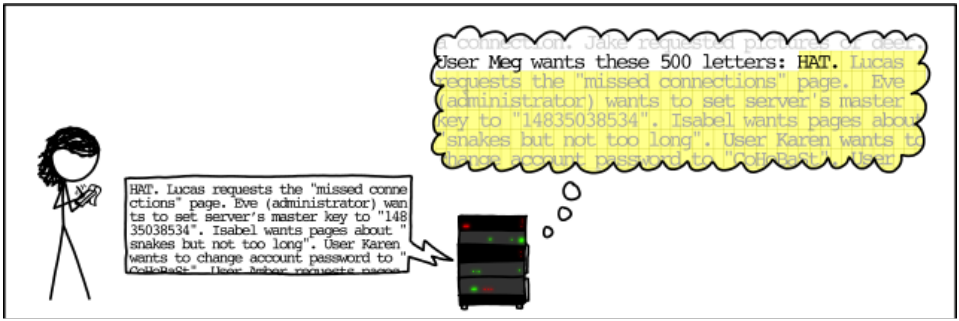

HOW THE HEARTBLEED BUG WORKS:
SERVER, ARE YOU STILL THERE? IF SO, REPLY "POTATO" (6 LETTERS).
User Meg wants these 6 letters: POTATO.


User Meg wants these 6 letters: POTATO.
POTATO


SERVER, ARE YOU STILL THERE? IF SO, REPLY "BIRD" (4 LETTERS).
User Olivia from London wants pages about the bees in car why". Note: Files for IP 375.381. 383.17 are in /tmp/files-3843. User Meg wants these 4 letters: BIRD. There are currently 340 connections open. User Brendan uploaded the file


HMM...
these 4 letters: BIRD.
BIRD


SERVER, ARE YOU STILL THERE? IF SO, REPLY "HAT" (500 LETTERS).
User Meg wants these 500 letters: HAT.


HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to change account password to "
User Meg wants these 500 letters: HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to

Heartbleed Code

```
struct
{
  HeartbeatMessageType type;
  uint16 payload_length;
  opaque payload[HeartbeatMessage.payload_length];
  opaque padding[padding_length];
} HeartbeatMessage;

/* Read type and payload length first */
hbtype = *p++; // message type
n2s( p ,  payload ); // payload = received payload length
pl = p; // pl = content of payload

/* Enter response type, length and copy payload */
*bp++ = TLS1_HB_RESPONSE; // message type
s2n( payload , bp); // payload length to message (bp)
memcpy(bp, pl,  payload ); // copy payload bytes from original content to message
```

Heartbleed Code

```
struct
{
  HeartbeatMessageType type;
  uint16 payload_length;
  opaque payload[HeartbeatMessage.payload_length];
  opaque padding[padding_length];
} HeartbeatMessage;

/* Read type and payload length first */
hbtype = *p++; // message type
n2s( p ,  payload ); // payload = received payload length
pl = p; // pl = content of payload

/* Enter response type, length and copy payload */
*bp++ = TLS1_HB_RESPONSE; // message type
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  HeartbeatMessageType type;
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} HeartbeatMessage;

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Live Demo

Heartbleed - Ubuntu with Apache

- Evil C functions for string handling (`gets`, `strcpy`, ...)
- Off-by-one errors (Null-Byte BOFs)
- Unicode vs ANSI (different size for characters)
- Wrong loop termination (e.g., off-by-one)
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Buffer Overflow - Common Causes

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Integers

- There are different formats for storing numbers
- Binary for unsigned integers, only positive numbers
- Two's complement for signed integers, positive and negative
- Sign bit + Magnitude for floating point numbers

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- An n-bit integer x is represented as

$$x = (x_{n-1}, x_{n-2}, \cdots, x_1, x_0) = \sum_{i=0}^{n-1} 2^i \cdot x_i$$

- The range of representable values is

$$0 \leq x < 2^n$$

- On overflow, the value is reduced modulo 2^n

$$x = \begin{cases} x & x < 2^n \\ x \mod 2^n & x \geq 2^n \end{cases}$$

- An n-bit integer x is represented as

$$x = (x_{n-1}, x_{n-2}, \cdots, x_1, x_0) = -2^{n-1} x_{n-1} + \sum_{i=0}^{n-2} 2^i \cdot x_i$$

- The range of representable values is

$$-2^{n-1} \leq x < 2^{n-1}$$

- Two's complement has a negate operation

$$-x = 2^n - x$$

- A single-precision (IEEE 754-2008) float x is represented as

$$\begin{aligned} x &= (x_{31}, x_{30}, \cdots, x_1, x_0) \\ &= (-1)^{x_{31}} \cdot \left(1 + \sum_{i=1}^{23} x_{23-i} 2^{-i}\right) \cdot 2^{([x_{30}:x_{23}]-127)} \end{aligned}$$

- A single-precision float can encode numbers up to $\approx 3.4 \times 10^{38}$
- All integers with ≤ 6 decimal digits can be encoded
- All values 2^n with $-126 \leq n \leq 127$ can be encoded
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- Example: $x = 3.3125 = 11.0101_b$
- Normalize to $1.bbb \times 2^e = 1.10101_b \times 2^1$
- Sign bit: 0 as it is positive
- Exponent: $e + 127 = 1 + 127 = 128$
- Fraction: $0.bbb \times 2^{23}$
  $= 0.10101_b \times 2^{23} = 0.65625 \times 2^{23} = 5505024$
- Result: $01000000010101000000000000000000_b$

```
int i = 0b01000000010101000000000000000000;
float f = *(float*)&i;
printf("%.4f\n", f); // prints 3.3125
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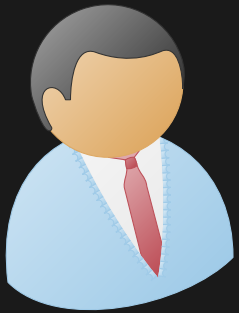
Given the number "`-135253521335.224627`", convert it to IEEE 754 quadruple-precision binary floating-point format (binary128)

- The solution is the decimal interpretation of the fraction part (cf. lecture slides example)
- Example: 9876543210.5 has the decimal interpretation of the fraction part 77770718932167912242925412338892 8
- You can do it manually or use any program you like
- Format description: `https://en.wikipedia.org/wiki/Quadruple-precision_floating-point_format`



Real-world Example: (Abusing) Numbers in Memory

(Abusing) Numbers in Memory

```
float Q_rsqrt( float number )
{
  long i;
  float x2, y;
  const float threehalfs = 1.5F;

  x2 = number * 0.5F;
  y  = number;
  i  = * ( long * ) &y;            // evil floating point bit level hacking
  i  = 0x5f3759df - ( i >> 1 );    // what the fuck?
  y  = * ( float * ) &i;
  y  = y * ( threehalfs - ( x2 * y * y ) );   // 1st iteration
  // y  = y * ( threehalfs - ( x2 * y * y ) );   // 2nd iteration, can be removed

  return y;
}
```

- The infamous fast inverse square root from Quake III Arena
- Computes $\frac{1}{\sqrt{x}}$ with quite good precision
- Origins of the "hack" not fully known
- Also unknown how the magic number 0x5F3759DF was found
- Abusing low-level representation led to algorithm four times faster than all other algorithms

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Integer Overflow

- What happens on an overflow?

Paragraph 5/4, C++11 Standard

If during the evaluation of an expression, the result is not mathematically defined or not in the range of representable values for its type, the behavior is undefined.

This applies only to signed integers, because

Paragraph 3.9.1/4, C++11 Standard

Unsigned integers, declared unsigned, shall obey the laws of arithmetic modulo 2^n where n is the number of bits in the value representation of that particular size of integer [...] unsigned arithmetic does not overflow because a result that cannot be represented by the resulting unsigned integer type is reduced modulo the number that is one greater than the largest value that can be represented by the resulting unsigned integer type.

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- An unsigned n-bit integer can overflow in multiple cases
- Addition: $a + b \geq 2^n \quad (0 \leq a, b < 2^n)$
- Subtraction: $a - b < 0 \quad \text{if } b > a \quad (0 \leq a, b < 2^n)$
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- Addition/Subtraction: $a + b \geq 2^{n-1}$ or $a + b < -2^{n-1}$
  $(-2^{n-1} \leq a, b < 2^{n-1})$
- Negation: $a = -2^{n-1} \Rightarrow -a = 2^{n-1}$
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- Division: $\frac{-2^{n-1}}{-1} = 2^{n-1} \Rightarrow$ Negation

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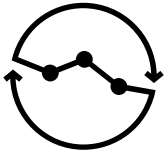

- C has rules to automatically convert types (coercion)
- Type conversion is done by the compiler and can have unintended consequences
  - `float` to `int` causes truncation (removal of the fractional part)
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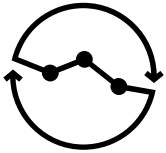
- Similar to type conversion, there is conversion from smaller to larger data types



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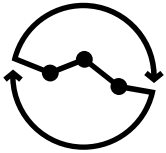

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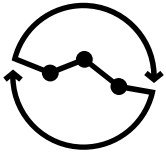

- Converting smaller to larger data types can be done using
  - Sign extension (high bits are set to the sign bit) or
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- If an assignment has two
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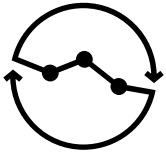

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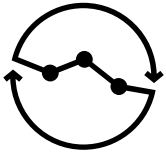

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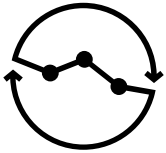

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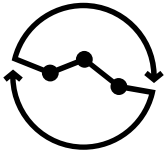

- Converting smaller to larger data types can be done using
  - Sign extension (high bits are set to the sign bit) or
  - Zero extension (high bits are set to '0's)
- If an assignment has two
  - Signed integers ⇒ sign extension
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  - Mixed integers ⇒ it depends...
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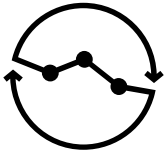

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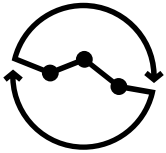

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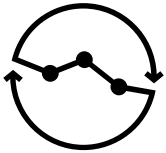

Type conversion for arithmetic operations

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- Different type: complicated...
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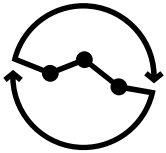

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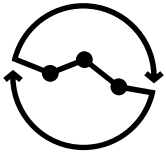

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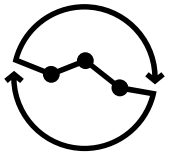

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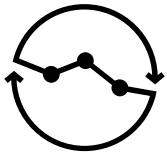

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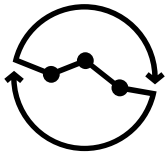

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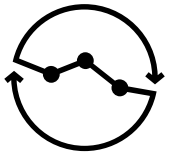

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Fun Example: Implicit Integer Conversion


```
#include <iostream>

signed int s1 = -4;
unsigned int u1 = 2;

signed long int s2 = -4;
unsigned int u2 = 2;

signed long long int s3 = -4;
unsigned long int u3 = 2;

int main() {
  std::cout << (s1 + u1) << "\n";
  std::cout << (s2 + u2) << "\n";
  std::cout << (s3 + u3) << "\n";
}
```


```
% ./conversion
4294967294
-2
18446744073709551614
```


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equal rank, signed converted to unsigned

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```

equal rank, signed converted to unsigned

signed has higher rank and can represent unsigned → signed

signed has higher rank, cannot represent unsigned → unsigned long long

Implicit Integer Conversion

```cpp
#include <iostream>

signed int s1 = -4;
unsigned int u1 = 2;
int main()
{
    if(s1 < u1) {
        std::cout << "In math we trust." << std::endl;
    } else {
        std::cout << "Some men aren't looking for anything logical.";
        std::cout << "Some men just want to watch the world burn." << std::endl;
    }
}
```

```
% ./compare
Some men aren't looking for anything logical. Some men just want
to watch the world burn.
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Practical Example: Integer Overflow

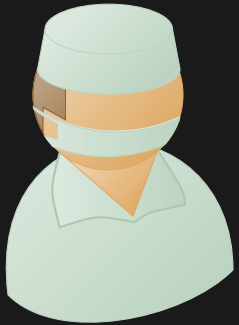

```c
#include <stdio.h>

int main(int argc, char* argv[]) {
    char* val[] = {"Hello", "World"};
    char* secret = "secret";
    char s = atoi(argv[1]);
    if(atoi(argv[1]) >= 0 && s < 2)
        printf("%s\n", val[s]);
    else
        printf("Invalid ID\n");
    return 0;
}
```


```
% ./value 0
Hello
% ./value 1
World
% ./value 2
Invalid ID
% ./value -1
Invalid ID
```

```
% ./value 255
secret
```


```
% ./value 0
Hello
% ./value 1
World
% ./value 2
Invalid ID
% ./value -1
Invalid ID
```

```
% ./value 255
secret
```



Practical Example Analysis: Integer Overflow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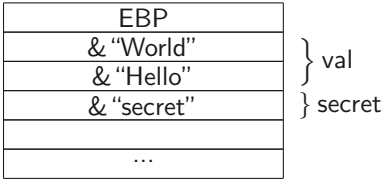


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Practical Example Impact: Integer Overflow

- Integer overflows are not a memory safety violation on their own
- They can lead to a memory safety violation if used...
  - for pointer arithmetic
  - as `malloc` argument
  - as array index
- Lead often to buffer overflows
- Can also result in out-of-bounds read/write

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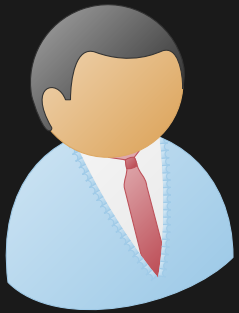

Real-world Example: Integer Overflow


```
public static int binarySearch(int[] a, int key) {
    int low = 0;
    int high = a.length - 1;
    while (low <= high) {
        int mid = (low + high) / 2;
        int midVal = a[mid];
        if (midVal < key)
            low = mid + 1
         else if (midVal > key)
            high = mid - 1;
         else
            return mid; // key found
     }
     return -(low + 1);  // key not found.
}
```


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Fixing Integer Overflow

```
void* new_8bit_image(unsigned int width, unsigned int height)
{
    unsigned int memory = width * height;
    void* data = malloc(memory);
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Fixing Integer Overflow

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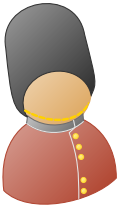
Fixing Integer Overflow

```
void* new_8bit_image(unsigned int width, unsigned int height)
{
    unsigned int memory = width * height;
    if(width * height > UINT_MAX) return NULL;
    void* data = malloc(memory);
    return data;
}
```



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void* new_8bit_image(unsigned int width, unsigned int height)
{
    unsigned int memory = width * height;
    if(UINT_MAX / width < height) return NULL;
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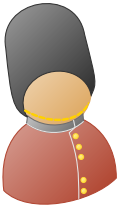
What if `width == 0`?

Fixing Integer Overflow



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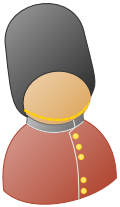

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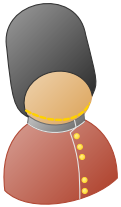

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void* new_8bit_image(unsigned int width, unsigned int height)
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    unsigned int memory;
    if(__builtin_umul_overflow(width, height, &memory)) {
      return NULL;
    }
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}
```
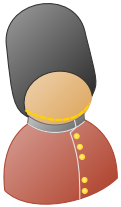

- GCC/clang provide built-in functions to check for overflows
- `__builtin_add_overflow`, `__builtin_sub_overflow`, `__builtin_mul_overflow` for various data types



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Overflow Summary

Overflows...

- are the most common forms of memory safety violation
- are mostly caused by missing bound checks
- can be abused to read from and write to memory
- might occur on buffers and integers
- exist in nearly every programming language (some exceptions)

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COMING UP NEXT ON

SSD

Next on SSD

- More memory corruptions
  - `malloc` allows to read secret data (Use-after-free)
  - A wrong `printf` gives attacker full control (Format Strings)
  - Being confused when casting is dangerous (Type Confusion)
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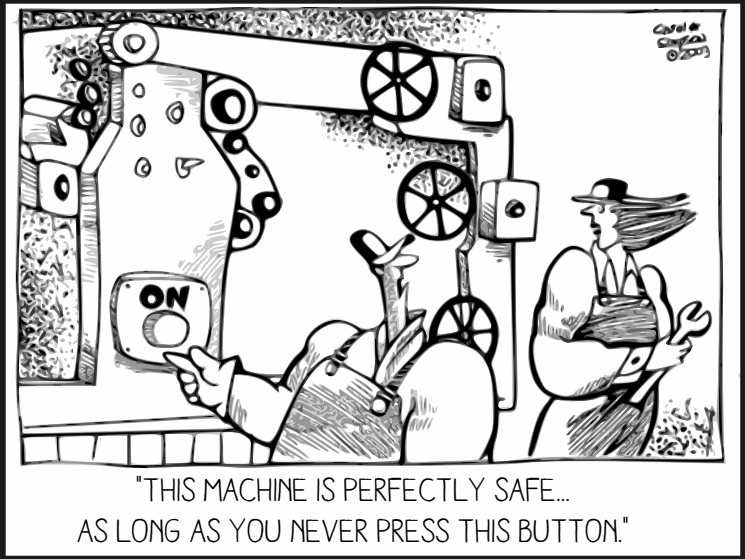
Questions?


ON
"THIS MACHINE IS PERFECTLY SAFE...
AS LONG AS YOU NEVER PRESS THIS BUTTON."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