Secure Software Development

Memory Corruption I

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Winter 2023/24, www.iaik.tugraz.at

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Memory safety is a concern in software development that aims to avoid software bugs that cause security vulnerabilities dealing with random-access memory (RAM) access, such as buffer overflows and dangling pointers.

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  - stack/heap overflow
  - invalid free
  - unwanted aliasing

Memory Safety Violation

We can distinguish between two types of memory safety violation

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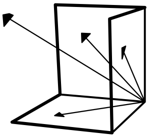

Spatial violation: memory access is out of object's bounds

- buffer overflow
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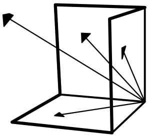

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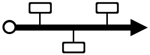

Temporal violation: memory access refers to an invalid object

- use after free
- double free
- use of uninitialized memory

Memory Safety Violation

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  - ...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?

Memory Safety Violation Overview

Overflow (this lecture)

- Stack overflow
- Heap overflow
- Integer overflow

Memory Safety Violation Overview

Overflow (this lecture)

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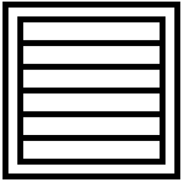
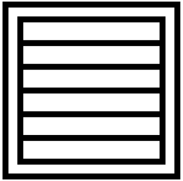
Invalid Memory (next lecture)

- Use-after-free
- Format string
- Type confusion

Buffers



- A buffer is a chunk of memory...



- A buffer is a chunk of memory...
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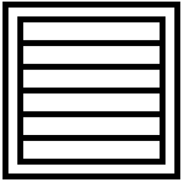
Buffer



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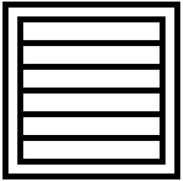

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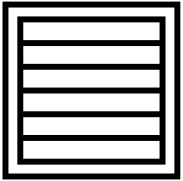
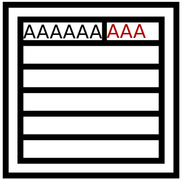


- A buffer is a chunk of memory...
  - with boundaries
  - defined by a start address and size
  - storing elements of a certain type
- Example: Arrays in C/C++

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

Buffer Overflow



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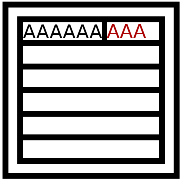

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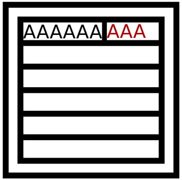

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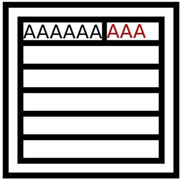

- Not all buffers check their bounds
- Out-of-bounds reads/writes access something
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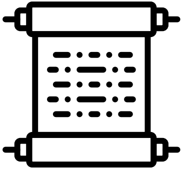
- Example: Buffer overflow in C/C++

```
char buffer[5];
strcpy(buffer, "Hello");
```

1972 First documentation of buffer overflows



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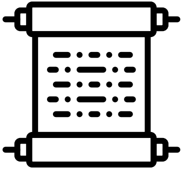

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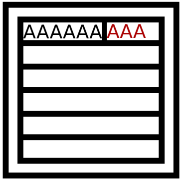
... A lot more buffer overflows

Stack Overflow

Buffer Overflow (Stack)



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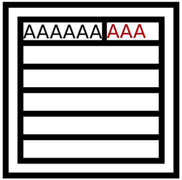

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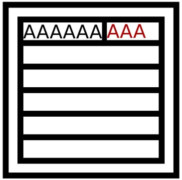

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    - Saved return addresses

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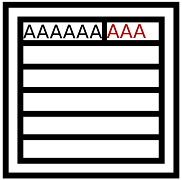

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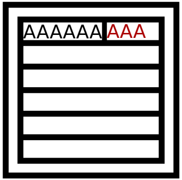

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Practical Example: Stack Overflow

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#include <string.h>

void printName(char* buffer) {
  char name[16];
  strcpy(name, buffer);
  printf("Hello %s\n", name);
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int main(int argc, char* argv[]) {
  if(argc > 1) printName(argv[1]);
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[Inferior 1 (process 21312) exited normally]
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% gdb --args ./hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
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Starting program: /home/hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA

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

Practical Example Analysis: Stack Overflow

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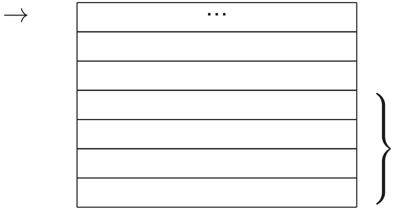

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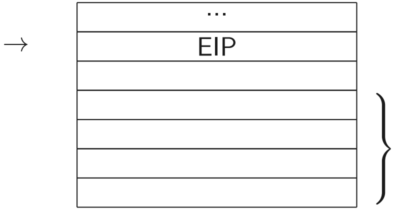

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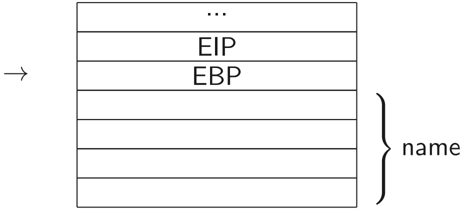

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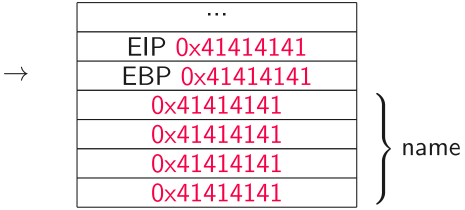

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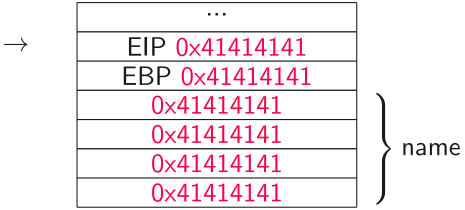

Practical Example Impact: Stack Overflow

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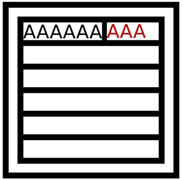

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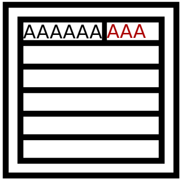

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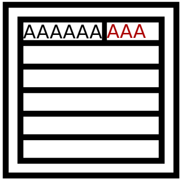
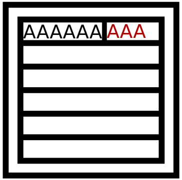


- Attacker can jump to arbitrary location in memory
- Every function that is mapped in the address space can be executed
- Attacker has effectively full control over the program

Heap Overflow

Buffer Overflow (Heap)



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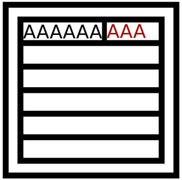

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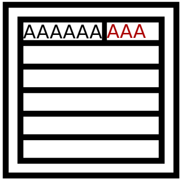

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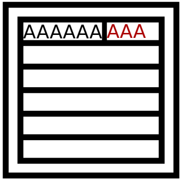

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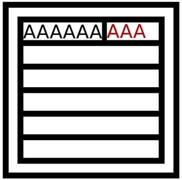

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Practical Example: Heap Overflow

```
#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]
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Buffer Overflow (Heap)

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```
% 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
53      iofclose.c: No such file or directory.
```

Practical Example Analysis: Heap Overflow

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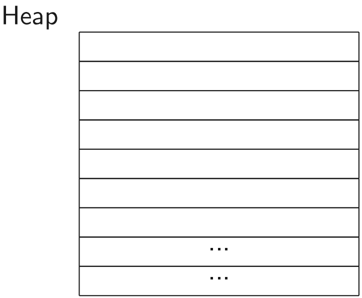

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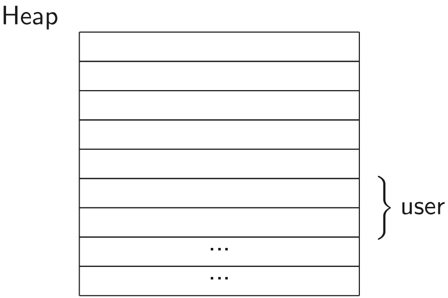

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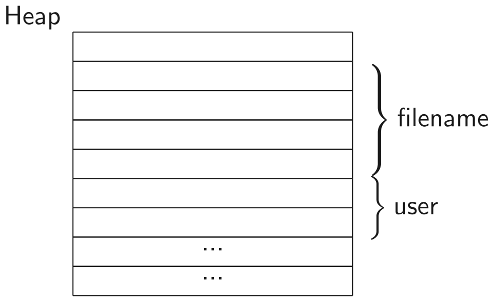

Buffer Overflow (Heap)

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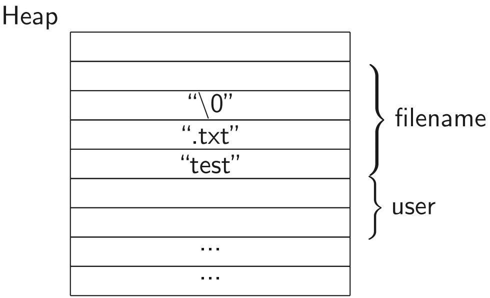

Daniel Gruss, **Vedad Hadzic**, **Lukas Maar**, **Stefan Gast**, **Marcel Nageler** — Winter 2023/24, www.iaik.tugraz.at

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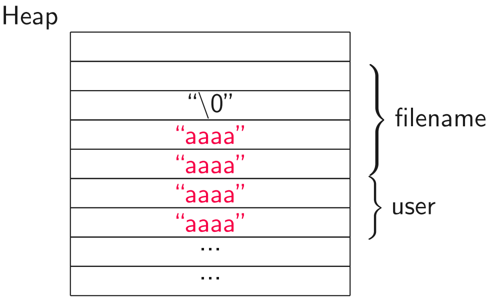

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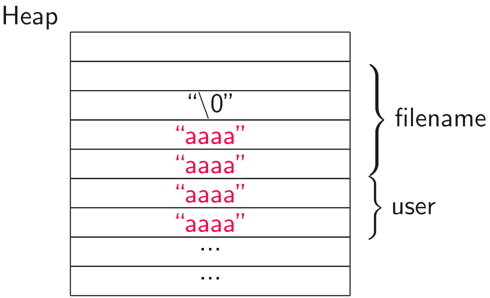

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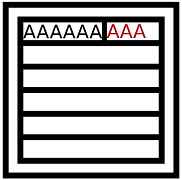
Practical Example Impact: Heap Overflow



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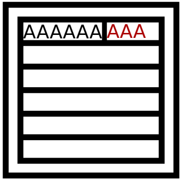

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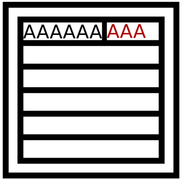

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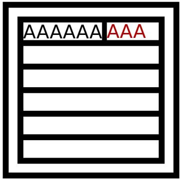

- We changed a different buffer, allowing us to read arbitrary files
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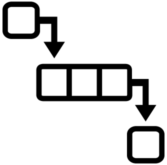
- C++ vtables contain function pointers



- Lots of different `malloc` implementations
  - `jemalloc` (Android, FreeBSD, Firefox)
  - `dlmalloc/ptmalloc` (glibc)
  - `tcmalloc` (former Chrome)
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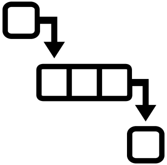

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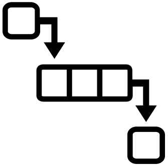

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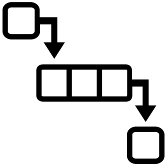

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- They all handle lists of chunks
- Chunks usually consist of meta data and user data
- There are various techniques to corrupt meta data to
  - achieve arbitrary memory reads/writes
  - get overlapping memory chunks

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Buffer Overflow (Heap) - vtable

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- C++ objects with virtual methods contain a pointer to a vtable
- The vtable contains function pointers
- If the buffer is before an object, we can overwrite the vtable pointer to an new, crafted vtable
- Controlling the vtable pointers allows to call arbitrary functions

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
}
```

Buffer Overflow (Heap) - Overwrite vtable

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

Heartbleed

- A security bug in the TLS protocol implementation of OpenSSL

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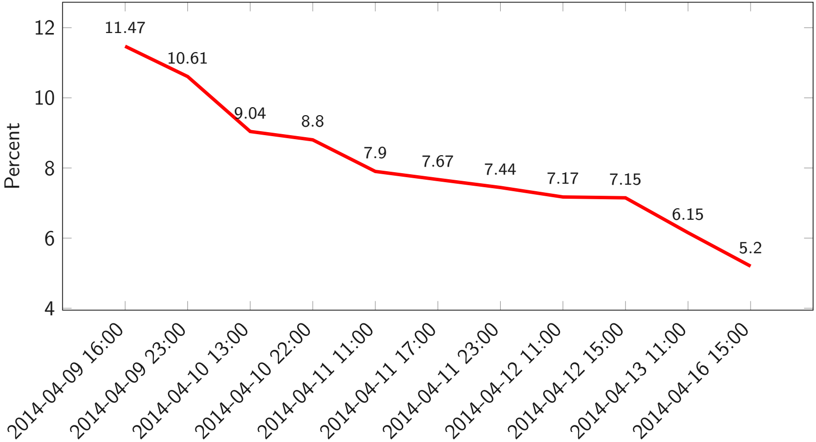
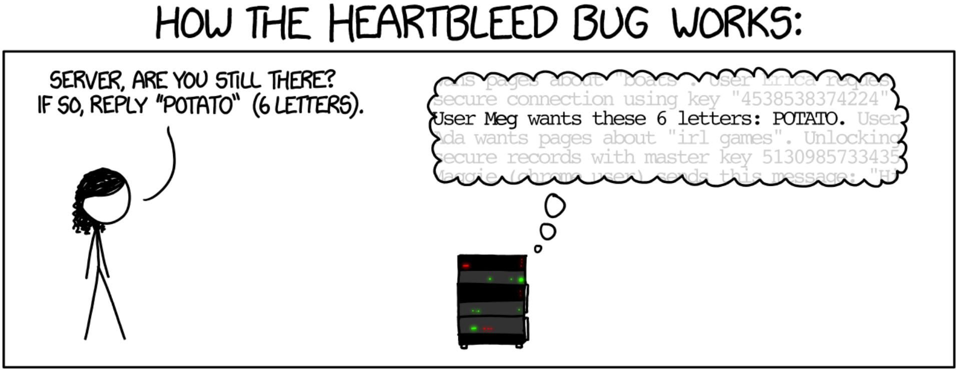
- A missing bounds check leads to a buffer over-read
- Allows to read up to 64 KB of server memory

Alexa Top 1 Million Pages - Vulnerable servers




HOW THE HEARTBLEED BUG WORKS:
SERVER, ARE YOU STILL THERE? IF SO, REPLY "POTATO" (6 LETTERS).
secure connection using key "4538538374224"
User Meg wants these 6 letters: POTATO. User
da wants pages about "irl games". Unlocking
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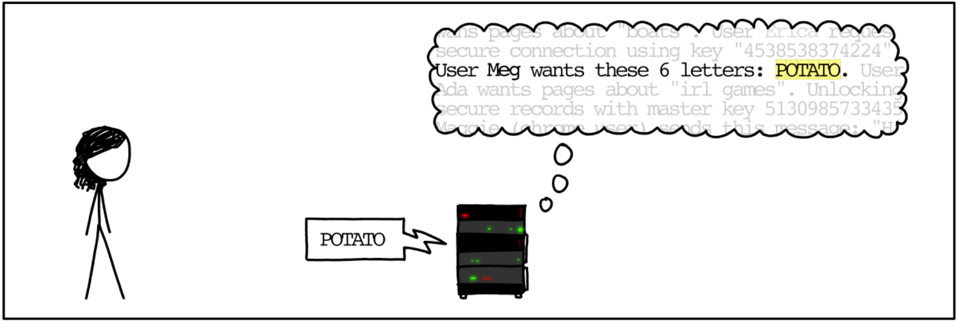
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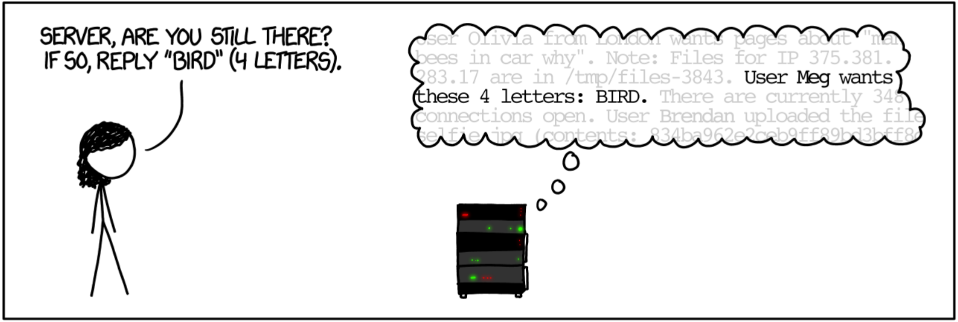
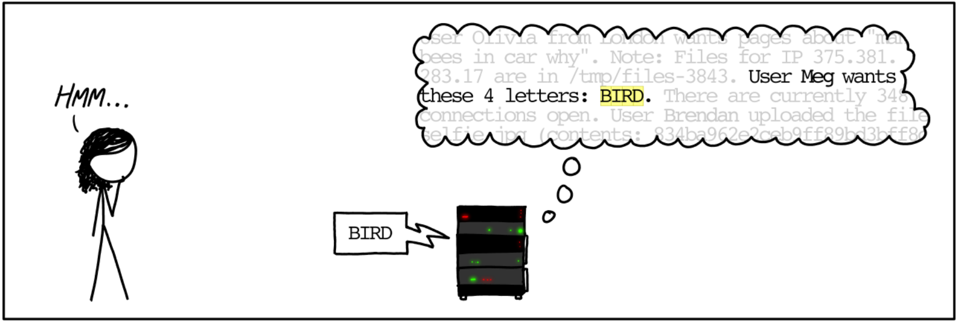

SERVER, ARE YOU STILL THERE? IF SO, REPLY "BIRD" (4 LETTERS).
ser Olivia from London wants pages about "ma
bees in car why". Note: Files for IP 375.381.
283.17 are in /tmp/files-3843. User Meg wants
these 4 letters: BIRD. There are currently 348
connections open. User Brendan uploaded the file
selfie.jpg (contents: 834ba962e2ceb9ff89bd3bff8


HMM...
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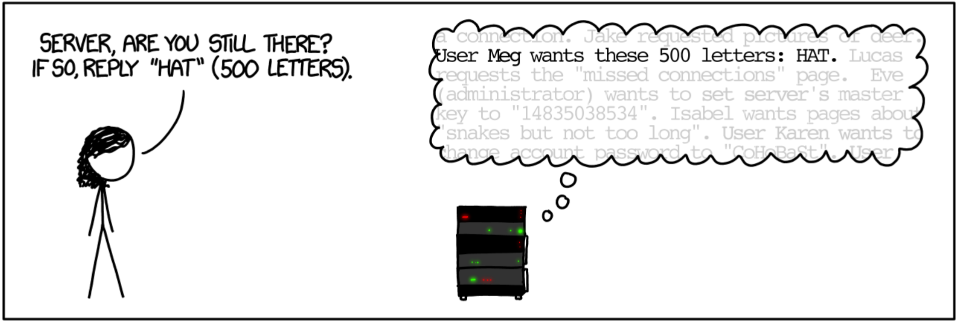
SERVER, ARE YOU STILL THERE? IF SO, REPLY "HAT" (500 LETTERS).
a connection. Jake requested pictures of deer.
User Meg wants these 500 letters: HAT. Lucas
requests the "missed connections" page. Eve
(administrator) wants to set server's master
key to "14835038534". Isabel wants pages abou
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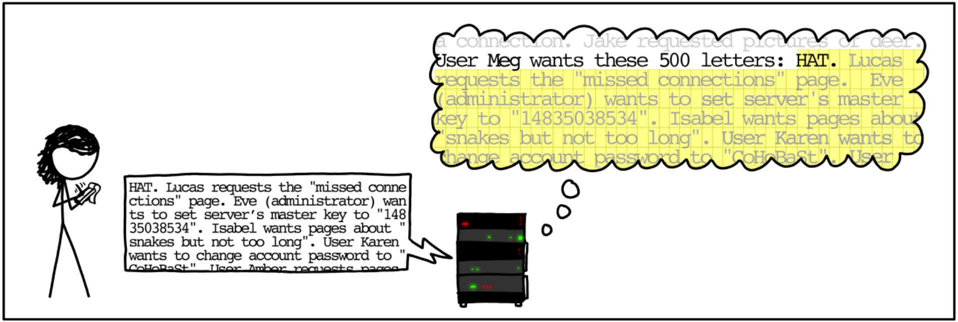
Heartbleed



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Heartbleed Code

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struct
{
  HeartbeatMessageType type;
  uint16 payload_length;
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hbtype = *p++; // message type
n2s( p ,  payload ); // payload = received payload length
pl = p; // pl = content of payload
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/* 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
```

Live Demo

Heartbleed - Ubuntu with Apache

Buffer Overflow - Common Causes

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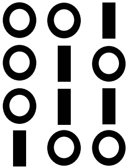
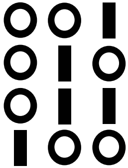
- Unicode vs ANSI (different size for characters)
- Wrong loop termination (e.g., off-by-one)
- Arithmetic errors (e.g., integer overflows)

Integers

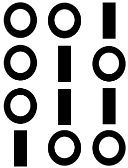


- There are different formats for storing numbers

Numbers in Memory



- There are different formats for storing numbers
- Binary for unsigned integers, only positive numbers



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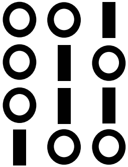
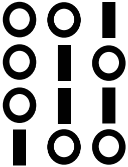
Numbers in Memory



- 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



- An n-bit integer x is represented as

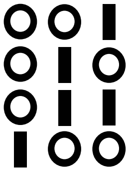
$$x = (x_{n-1}, x_{n-2}, \cdots, x_1, x_0) = \sum_{i=0}^{n-1} 2^i \cdot x_i$$

- The range of representable values is

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

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

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



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

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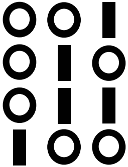
- Two's complement has a negate operation

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

Numbers in Memory - Floats

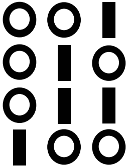


- A single-precision (IEEE 754-2008) float x is represented as

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

- 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

Numbers in Memory - Floats



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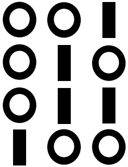
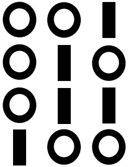
- All integers with ≤ 6 decimal digits can be encoded
- All values 2^n with $-126 \leq n \leq 127$ can be encoded
- Compact: 1 bit (sign), 8 bit (exponent), 23 bit (fraction/mantissa), bias=127 (since stored as unsigned)

- Example: $x = 3.3125$



Numbers in Memory - Floats - Example

- Example: $x = 3.3125 = 11.0101_b$



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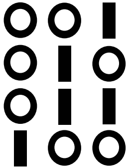

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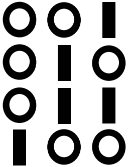

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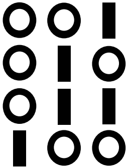
Numbers in Memory - Floats - Example



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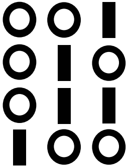

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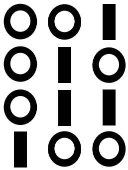
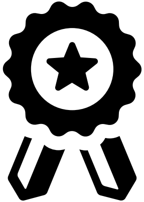
- Fraction: $0.bbb \times 2^{23}$
  $= 0.10101_b \times 2^{23} = 0.65625 \times 2^{23} = 5505024$
- Result: $01000000010101000000000000000000_b$



- 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: $01000000010101000000000000000000_b$

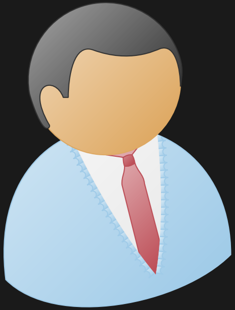
```c
int i = 0b01000000010101000000000000000000;
float f = *(float*)&i;
printf("%.4f\n", f); // prints 3.3125
```

Challenge #2 - Quadruple-precision floating point



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 777707189321679122429254123388928
- 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

```c
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;
}
```

(Abusing) Numbers in Memory

- The infamous fast inverse square root from Quake III Arena

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(Abusing) Numbers in Memory

- 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

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.

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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.

- An unsigned n-bit integer can overflow in multiple cases

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- Subtraction: $a - b < 0 \quad \text{if } b > a \quad (0 \leq a, b < 2^n)$

Integer Overflows - Unsigned integers

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- Addition: $a + b \geq 2^n \quad (0 \leq a, b < 2^n)$
- Stagefright: `uint8_t *buffer = malloc(size + chunk_size);`
- Subtraction: $a - b < 0 \quad \text{if } b > a \quad (0 \leq a, b < 2^n)$
- Multiplication: $a \cdot b \geq 2^n \quad (0 \leq a, b < 2^n)$

Integer Overflows - Signed integers

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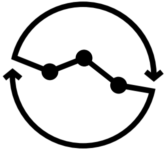
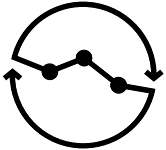
  Multiplication by $-1 \Rightarrow$ Negation
- Division: $\frac{-2^{n-1}}{-1} = 2^{n-1} \Rightarrow$ Negation

  Division by 0

Integer Overflows - Type Conversion



- C has rules to automatically convert types (coercion)



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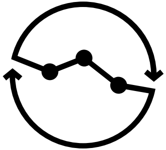
- Type conversion is done by the compiler and can have unintended consequences
  - `float` to `int` causes truncation (removal of the fractional part)
  - `double` to `float` causes rounding of digit



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- 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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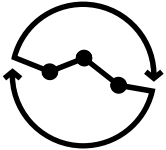
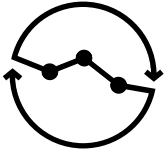
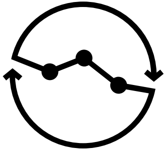
- Similar to type conversion, there is conversion from smaller to larger data types



- Converting smaller to larger data types can be done using



- 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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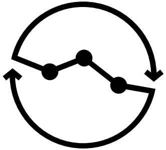
Integer Overflows - Type Conversion



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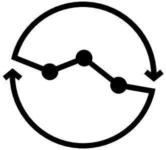
- If an assignment has two
  - Signed integers ⇒ sign extension



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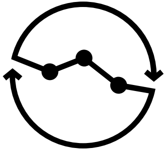

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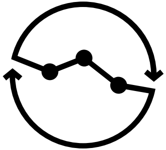

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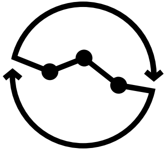
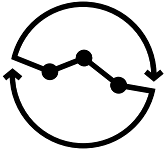
    - Zero extension if source is unsigned
    - Sign extension if source is signed

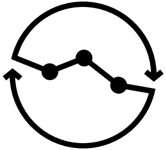
Type conversion for arithmetic operations





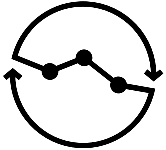
Type conversion for arithmetic operations

- Same type, same rank[†]: no conversion



Type conversion for arithmetic operations

- Same type, same rank†: no conversion
- Same type, different rank: convert smaller to larger data type



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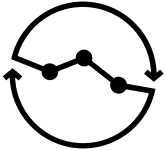

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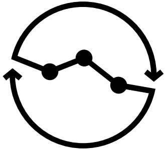
- Different type: complicated...
  - unsigned integer has same or higher rank than signed integer ⇒ convert to unsigned

Daniel Gruss, Vedad Hadzic, Lukas Maar, Stefan Gast, Marcel Nageler — Winter 2023/24, www.iaik.tugraz.at

Integer Overflows - Type Conversion II



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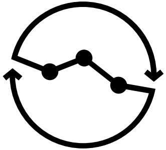
  - else if, signed integer can represent unsigned integer ⇒ convert to signed

Integer Overflows - Type Conversion II



Type conversion for arithmetic operations

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- Different type: complicated...
  - unsigned integer has same or higher rank than signed integer ⇒ convert to unsigned
  - else if, signed integer can represent unsigned integer ⇒ convert to signed
  - else, convert both operands to unsigned with rank of signed integer

† rank is similar to size, an integer contains at least as many bits as the types ranked below it

Fun Example: Implicit Integer Conversion

Implicit Integer Conversion

```cpp
#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";
}
```

Implicit Integer Conversion

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

Implicit Integer Conversion

```
#include <iostream>

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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

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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

```
#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;
    }
}
```

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}
```

```
% ./compare
Some men aren't looking for anything logical. Some men just want
to watch the world burn.
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Implicit Integer Conversion

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equal rank, signed converted to unsigned

```
% ./compare
Some men aren't looking for anything logical. Some men just want
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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;
}
```

Integer Overflow

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

Integer Overflow

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

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

Practical Example Analysis: Integer Overflow

Integer Overflow

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#include <stdio.h>

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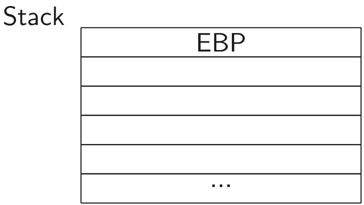
```



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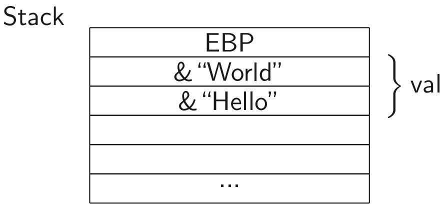

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    if(atoi(argv[1]) >= 0 && s < 2)
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    return 0;
}
```

Practical Example Impact: Integer Overflow

- Integer overflows are not a memory safety violation on their own

Integer Overflow

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- They can lead to a memory safety violation if used...

Integer Overflow

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Integer Overflow

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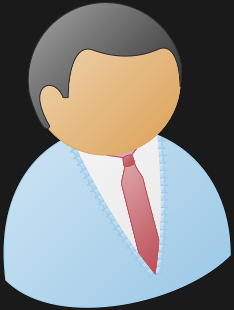
  - as `malloc` argument
  - as array index
- Lead often to buffer overflows

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



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.
}
```

Real-world 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.
}
```

Fixing Integer Overflow

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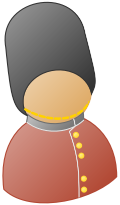
Fixing Integer Overflow

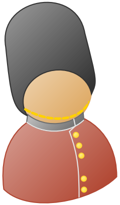
```
void* new_8bit_image(unsigned int width, unsigned int height)
{
    unsigned int memory = width * height;
    if(width * height > UINT_MAX) return NULL;
    void* data = malloc(memory);
    return data;
}
```

Fixing Integer Overflow



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

Fixing Integer Overflow



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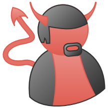
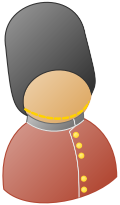


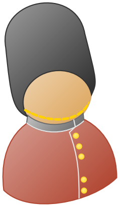
What if `width` == 0?

Fixing Integer Overflow



```c
void* new_8bit_image(unsigned int width, unsigned int height)
{
    unsigned int memory = width * height;
    if(!width || (UINT_MAX / width < height)) return NULL;
    void* data = malloc(memory);
    return data;
}
```

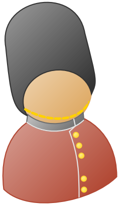
Fixing Integer Overflow



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

- GCC/clang provide built-in functions to check for overflows

Fixing Integer Overflow



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

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

Overflow Summary

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Overflows...

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- 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)

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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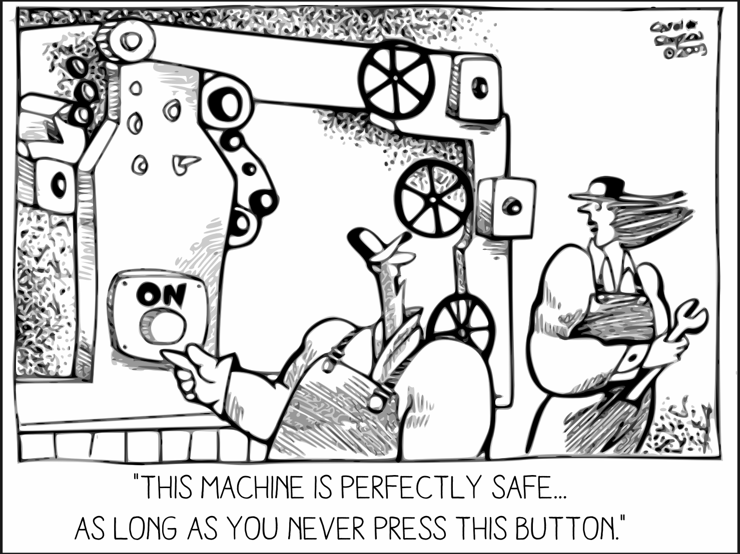
- Outsmart file system permissions

Questions?


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

Further Reading i

- Will Dietz, Peng Li, John Regehr, and Vikram Adve.
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