CS 489 / 698: Software and Systems Security

Module: Common Vulnerabilities

Lecture: memory errors

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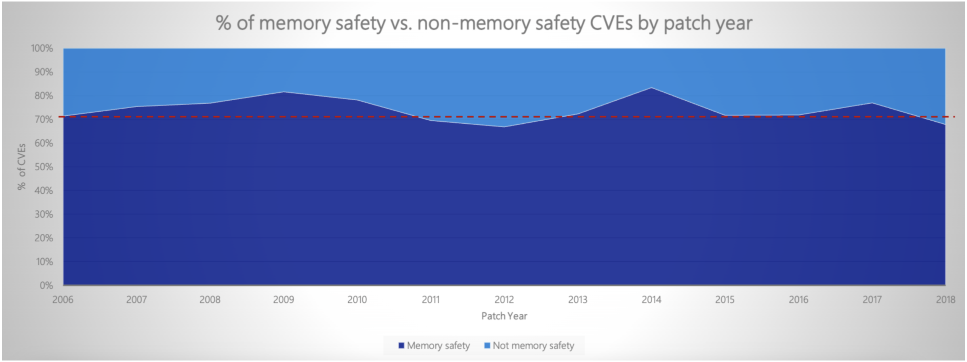
Fall 2024

Outline

1. Why study memory errors?
2. Background: how does a C program execute on a machine?
3. A relatively formal definition of memory errors
4. Case study: Heartbleed vulnerability
5. Concluding remarks

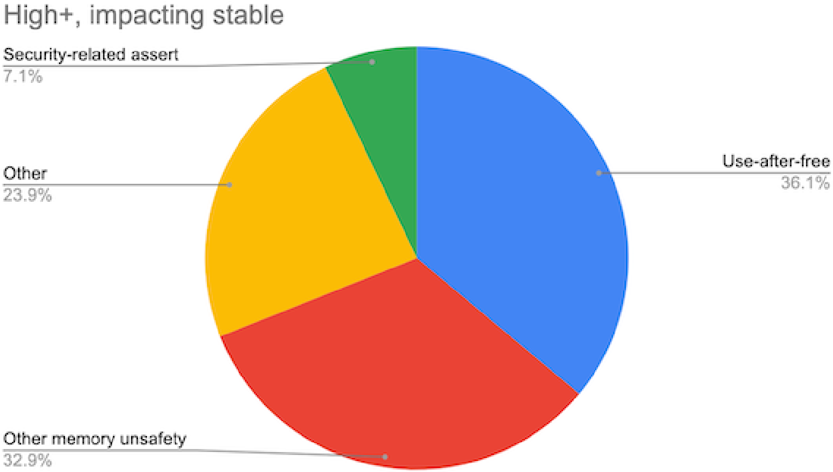
Memory errors are prevalent



Source: BlackHat IL 2019 talk by Matt Miller from Microsoft

Around 70% of all the vulnerabilities in Microsoft products addressed through a security update each year (2006 - 2018) are memory safety issues

Memory errors are prevalent



Source: Chromium Memory Safety Report from Google.

Analysis based on 912 high or critical severity security bugs in Chromium reported in 2015 - 2020

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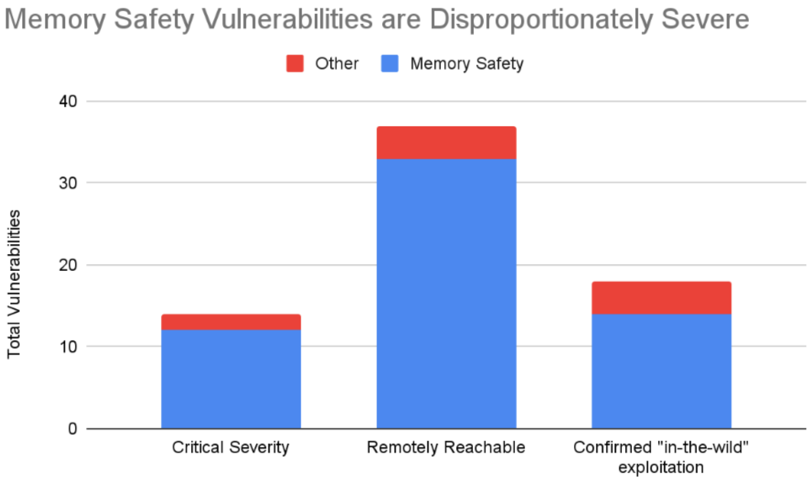


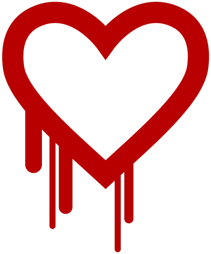
Source: Blog post Memory Safe Languages in Android 13 from Google.

Memory safety vulnerabilities disproportionately represent Android's most severe vulnerabilities

Memory errors can lead to severe consequences

Heartbleed Vulnerability
(CVE-2014-0610)

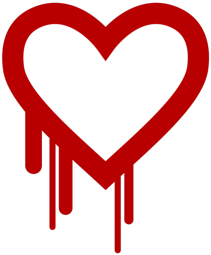
Memory errors can lead to severe consequences



Heartbleed Vulnerability
(CVE-2014-0610)

- A security bug in version 1.0.1 of OpenSSL, which is a widely used implementation of the Transport Layer Security (TLS) protocol
- It was introduced into OpenSSL in 2012 and publicly disclosed in April 2014
- At the time of disclosure, some 17% (around half a million) of the Internet's secure web servers certified by trusted authorities were believed to be vulnerable to the attack

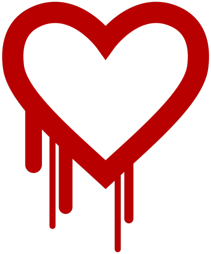
Memory errors can lead to severe consequences



Heartbleed Vulnerability (CVE-2014-0610)

- The Canada Revenue Agency (CRA) reported a theft of social insurance numbers belonging to 900 taxpayers, and said that they were accessed through an exploit of the bug during a 6-hour period on 8 April 2014.
- After the discovery of the attack, the agency shut down its website and extended the taxpayer filing deadline from 30 April to 5 May.

Memory errors can lead to severe consequences



Heartbleed Vulnerability (CVE-2014-0610)

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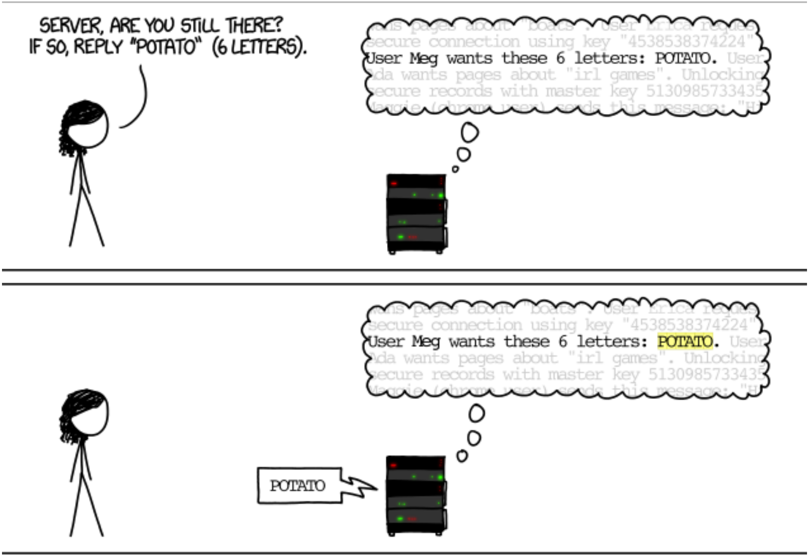
- After the discovery of the attack, the agency shut down its website and extended the taxpayer filing deadline from 30 April to 5 May.
- On 16 April, the RCMP announced they had charged a computer science student in relation to the theft with unauthorized use of a computer and mischief in relation to data.

Heartbleed explanation



Source: https://imgs.xkcd.com/comics/heartbleed_explanation.png

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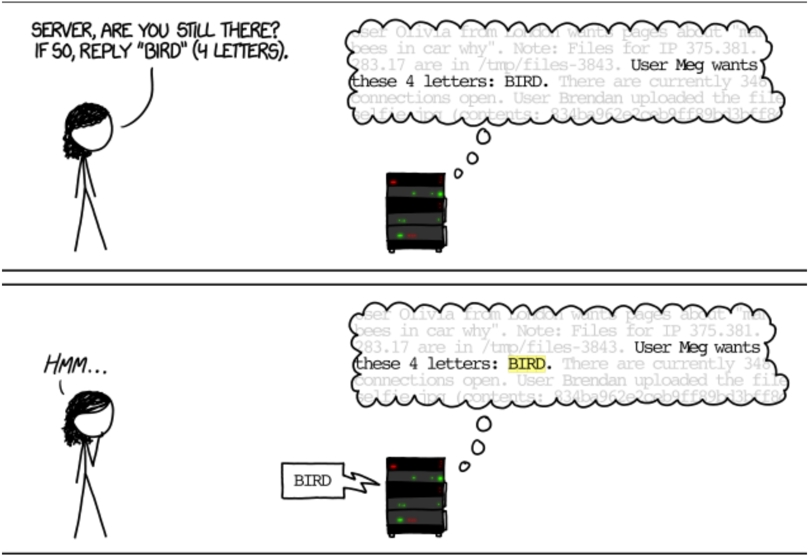

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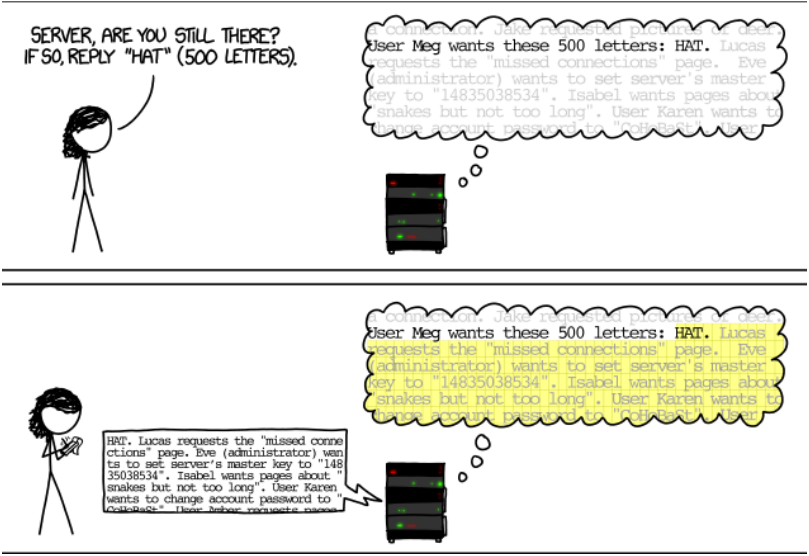

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Outline

A simple C program

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

int main(void) {
  char buff[8];
  int pass = 0;

  printf("Enter the password: ");
  gets(buff);

  if(strcmp(buff, "warriors")) {
    printf("Wrong password\n");
  } else {
    printf("Correct password\n");
    pass = 1;
  }

  if(pass) {
    printf ("Root privileges granted\n");
  }
  return 0;
}
```

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  }
  return 0;
}
```

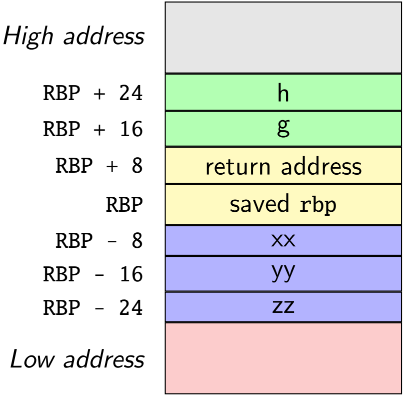
Try with

`gcc -m64 -fno-stack-protector`

And password “golden-hawks”

Stack layout (Linux x86-64 convention)

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

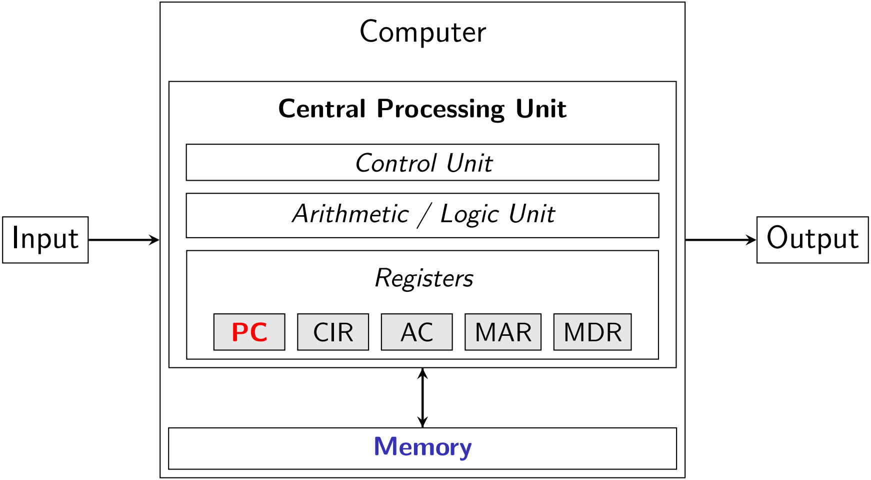


Argument a to `f` passed by registers.

Textbook exploitation of a stack overflow vulnerability

Demo

Von Neumann architecture



Implications of the Von Neumann architecture

- Code and data reside in the same memory space and can be addressed in a unified way
  - If you manage to get the PC register to point to a memory address contains your logic, you have effectively hijacked the control flow.

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- Code and data reside in the same memory space and can be addressed in a unified way
  - If you manage to get the PC register to point to a memory address contains your logic, you have effectively hijacked the control flow.

- There is only one unified memory. It is the job of the compiler / programming language / runtime to find a way to utilize the memory efficiently.
  - Variables declared in a program (e.g., `int i = 0;`) need to be mapped to an address in the memory, and the mapping logic needs to be (ideally) consistent on the same architecture.

Definition: memory

Q: What is a conventional way of dividing up the “memory”?

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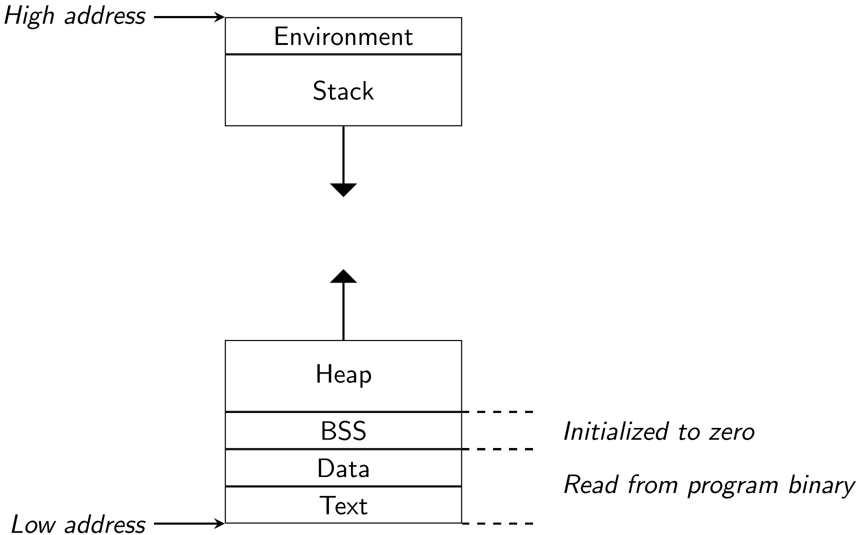
A: Four types of memory on a conceptual level:

- Text (where program code is initially loaded to)
- Stack
- Heap
- Global (a.k.a., static)

Memory layout (Linux x86-64 convention)



Example

```c
#include <stdlib.c>

//! where is this variable hosted?
const char *HELLO = "hello";

//! where is this variable hosted?
long counter;

void main() {
    //! where is this variable hosted?
    int val;

    //! where is this variable hosted?
    //! where is its content allocated?
    char *msg = malloc(120);

    //! what is freed here?
    free(msg);

    //! what is freed here (at end of function)?
}

//! what is freed here (at end of execution)?
```

Example (and answers)

```c
#include <stdlib.c>

// this is in the data section
const char *HELLO = "hello";

// this is in the BSS section
long counter;

void main() {
    // this is in the stack memory
    int val;

    // the msg pointer is in the stack memory
    // the msg content is in the heap memory
    char *msg = malloc(120);

    // msg content is explicitly freed here
    free(msg);

    // the val and msg pointer is implicitly freed here
}

// the global memory is only destroyed on program exit
```

What is heap and why do we need it?

In C/C++, the heap is used to manually allocate (and free) new regions of process memory during program execution.

Heap vs stack

```
typedef struct Response {
  int status;
  char message[40];
} response_t;

response_t *say_hello() {
  response_t* res =
    malloc(sizeof(response_t));
  if (res != NULL) {
    res->status = 200;
    strncpy(res->message, "hello", 6);
  }
  return res;
}
void send_back(response_t *res) {
  // implementation omitted
}
void process() {
  response_t *res = say_hello();
  send_back(res);
  free(res);
}
```

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}
void send_back(response_t *res) {
  // implementation omitted
}
void process() {
  struct Response res;
  say_hello(&res);
  send_back(&res);
}
```

A stack-based implementation of (roughly) the same functionality

Heap: what happens after `malloc()`?

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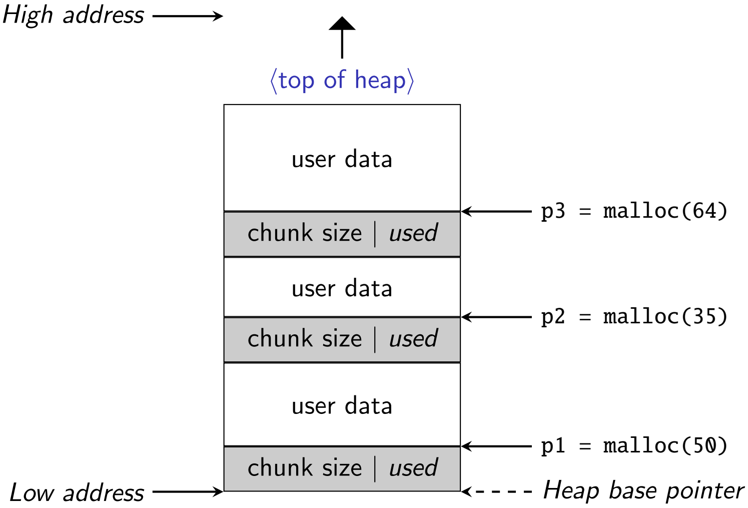
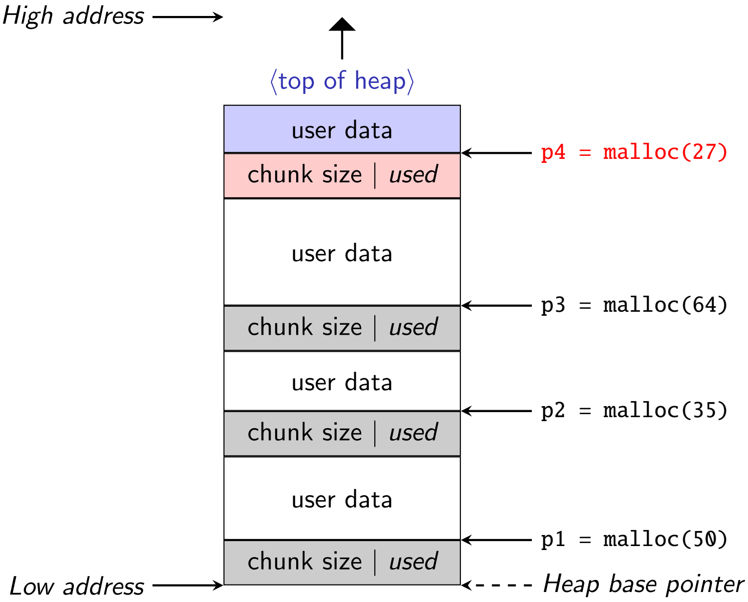
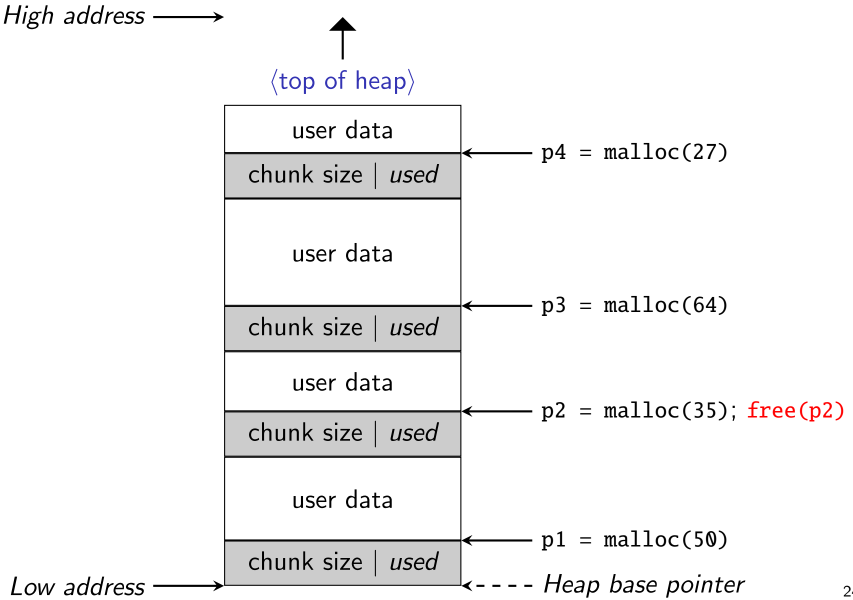


Heap: what happens after `malloc()`?



Heap: what happens after `free()`?



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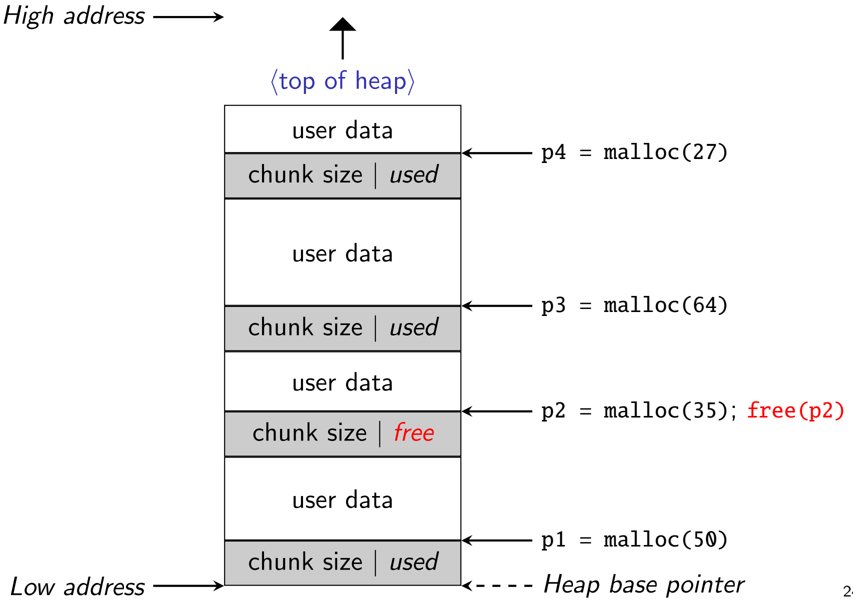

Real-world heap manager

For implementation details of the `glibc`[1] memory allocator, refer to the article from Azeria Labs.

[1] GNU C library

For exploitation of memory errors

Smashing The Stack For Fun And Profit

How2Heap — Educational Heap Exploitation

Outline

A quick recap

This presentation is about memory corruption, a.k.a.,

- memory errors, or
- violations of memory safety properties, or
- unsafe programs

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- unsafe programs

A program is memory safe if it is free of memory errors.

Definition: safety

Q: What is “safe” in memory safety?

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Observation 4: A memory access is always object-oriented, i.e.

- Memory read: `(object_id, offset, length)`
- Memory write: `(object_id, offset, length, value)`

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Observation 4: A memory access is always object-oriented, i.e.

- Memory read: `(object_id, offset, length)`
- Memory write: `(object_id, offset, length, value)`

Wait..., in C/C++, pointers are just 32/64-bit integers. I can do: `int *p = 0xdeadbeef; int v = *p;` Which object do I refer to here?

Definition: safety

Q: What is "safety" in memory safety?

At any point of time during the program execution,
for any object in memory, we know its
`(object_id, size [int], alive [bool])`

At the same time, for each memory access, we know:

- Memory read: `(object_id, offset [int], length [int])`
- Memory write: `(object_id, offset [int], length [int], _)`

Definition: spatial safety

At any point of time during the program execution,
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- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)

It is a violation of spatial safety if:

- `offset + length >= size` or
- `offset < 0`

Example: spatial safety violations

```
int foo(int x) {
    int arr[16] = {0};
    return arr[x];
}
```

Example: spatial safety violations

```c
int foo(int x) {
    int arr[16] = {0};
    return arr[x];
}
```

```c
long foo() {
    int a = 0;
    return *(long *)(&a);
}
```

Definition: NULL-pointer dereference

```
int foo(int *p) {
    // it is possible that p == NULL
    return *p + 42;
}
```

Definition: NULL-pointer dereference

```c
int foo(int *p) {
    // it is possible that p == NULL
    return *p + 42;
}
```

NULL-pointer dereference is sometimes considered as undefined behavior — meaning, its behavior is not given in the C language specification, although most operating systems chooses to panic the program on such behavior.

Definition: NULL-pointer dereference

At any point of time during the program execution,
for any object in memory, we know its
(**object_id** $\neq$ **0**, size [int], alive [bool])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)

Definition: NULL-pointer dereference

At any point of time during the program execution,
for any object in memory, we know its
(**object_id** ≠ 0, size [int], alive [bool])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)

It is a NULL-pointer dereference if

- `object_id == 0`

Definition: temporal safety

At any point of time during the program execution,
for any object in memory, we know its
`(object_id, size [int], alive [bool])`

At the same time, for each memory access, we know:

- Memory read: `(object_id, offset [int], length [int])`
- Memory write: `(object_id, offset [int], length [int], _)`
- Memory free: `(object_id)`

Definition: temporal safety

At any point of time during the program execution,
for any object in memory, we know its
(**object_id**, size [int], alive [bool])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

It is a violation of temporal safety if:

- !alive

Example: temporal safety violations

```
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    return *p;
}
```

Example: temporal safety violations

```c
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    return *p;
}
```

```c
int *ptr;

void foo() {
    int p = 100;
    ptr = &p;
}
int bar() {
    return *ptr;
}
```

Example: temporal safety violations

```c
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    return *p;
}
```

```c
int *ptr;

void foo() {
    int p = 100;
    ptr = &p;
}
int bar() {
    return *ptr;
}
```

```c
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    free(p);
    return *p;
}
```

Definition: temporal safety (revisited)

At any point of time during the program execution,
for any object in memory, we know its
(**object_id**, size [int], status [alloc|init|dead])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

Definition: temporal safety (revisited)

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- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

It is a violation of temporal safety if:

- Read: status != init
- Write: status == dead
- Free: status == dead

Example: temporal safety violations

```
int foo() {
    int p;
    return p;
    // what is the value returned?
}
```

Example: temporal safety violations

```
int foo() {
    int p;
    return p;
    // what is the value returned?
}
```

```
int foo() {
    int *p = malloc(sizeof(int));
    return *p;
    // what is the value returned?
}
```

Definition: memory leak

At any point of time during the program execution,
for any object in memory, we know its
(**object_id**, size [int], status [alloc|init|dead])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

Definition: memory leak

At any point of time during the program execution,
for any object in memory, we know its
(**object_id**, size [int], status [alloc|init|dead])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

It is a memory leak if exists one **object_id** whose:

- status != dead

Example: memory leak

```
int foo() {
    int *p = malloc(sizeof(int));
    int *q = malloc(sizeof(int));
    *p = 42;
    free(q);
    return *p;
}
```

Outline

Heartbleed vulnerability I

```c
int dtls1_process_heartbeat(SSL *s) {
  unsigned char *p = &s->s3->rrec.data[0], *pl;
  unsigned short hbtype;
  unsigned int payload;
  unsigned int padding = 16; /* Use minimum padding */

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

  /* ... redacted ... */

  if (hbtype == TLS1_HB_REQUEST) {
    unsigned char *buffer, *bp;

    /* Allocate memory for the response */
    buffer = OPENSSL_malloc(1 + 2 + payload + padding);
    bp = buffer;

    /* Enter response type, length and copy payload */
    *bp++ = TLS1_HB_RESPONSE;
```

Heartbleed vulnerability II

```
        s2n(payload, bp);
        memcpy(bp, pl, payload);

        /* Random padding */
        RAND_pseudo_bytes(bp, padding);

        /* Send out the response */
        r = dtls1_write_bytes(
            s, TLS1_RT_HEARTBEAT, buffer, 3 + payload + padding
        );

        /* ... redacted ... */

        /* Clean-up used resources */
        OPENSSL_free(buffer);
        return r;
    }

  else { /* ... redacted ... */ }
}
```

Patch for the Heartbleed vulnerability I

```
diff --git a/ssl/d1_both.c b/ssl/d1_both.c
index 7a5596a6b3..2e8cf681ed 100644
@@ -1459,26 +1459,36 @@ dtls1_process_heartbeat(SSL *s)
     unsigned int payload;
     unsigned int padding = 16; /* Use minimum padding */

-    /* Read type and payload length first */
-    hbtype = *p++;
-    n2s(p, payload);
-    pl = p;
-
     if (s->msg_callback)
         s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
             &s->s3->rrec.data[0], s->s3->rrec.length,
             s, s->msg_callback_arg);

+    /* Read type and payload length first */
+    if (1 + 2 + 16 > s->s3->rrec.length)
+        return 0; /* silently discard */
+    hbtype = *p++;
+    n2s(p, payload);
+
```

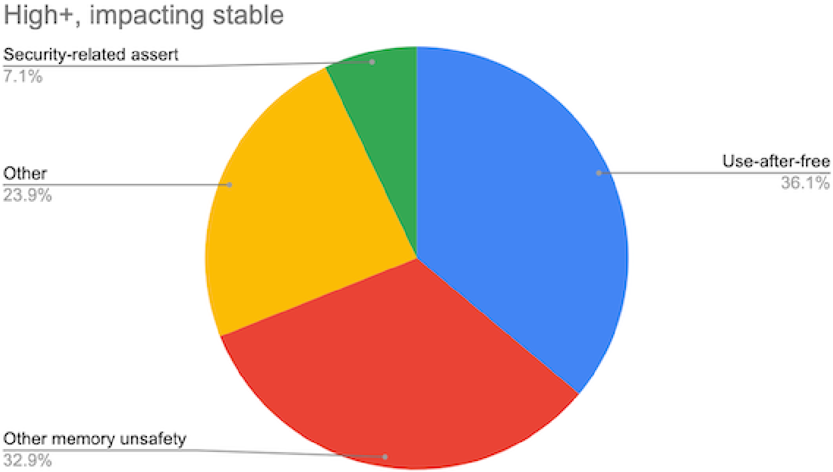
Patch for the Heartbleed vulnerability II

```
+   if (1 + 2 + payload + 16 > s->s3->rrec.length)
+       return 0; /* silently discard per RFC 6520 sec. 4 */
+   pl = p;
+
    if (hbtype == TLS1_HB_REQUEST)
        {
        unsigned char *buffer, *bp;
+       unsigned int write_length = 1 /* heartbeat type */ +
+                           2 /* heartbeat length */ + payload + padding;
        int r;

+       if (write_length > SSL3_RT_MAX_PLAIN_LENGTH)
+           return 0;
+
        /* Allocate memory for the response, size is 1 byte
         * message type, plus 2 bytes payload length, plus
         * payload, plus padding
         */
-       buffer = OPENSSL_malloc(1 + 2 + payload + padding);
+       buffer = OPENSSL_malloc(write_length);
        bp = buffer;
```

Outline

Memory errors are prevalent



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  - Once you find a memory error, you do not need to diligently argue that this is a bug and not a feature

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  - Once you find a memory error, you do not need to diligently argue that this is a bug and not a feature
- Memory errors often lead to a set of known consequences that are generally considered severe (e.g., data leak or denial-of-service)
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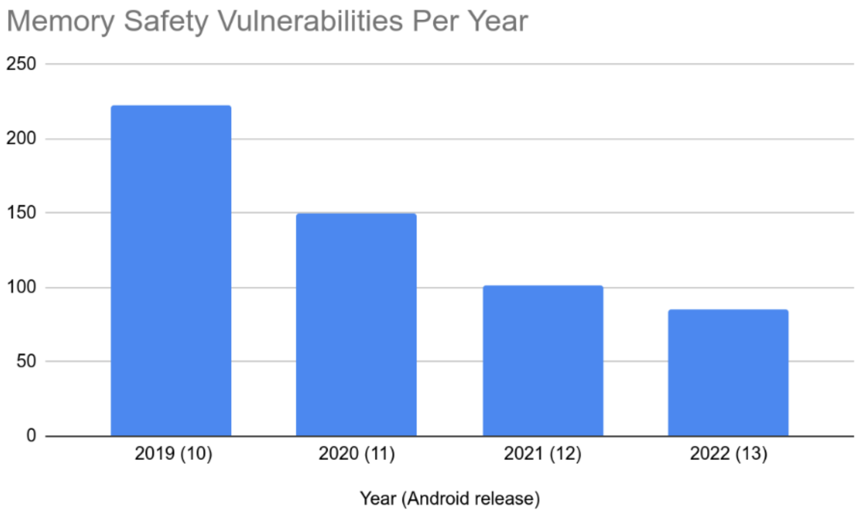
In fact, very few types of vulnerabilities meet these requirements.

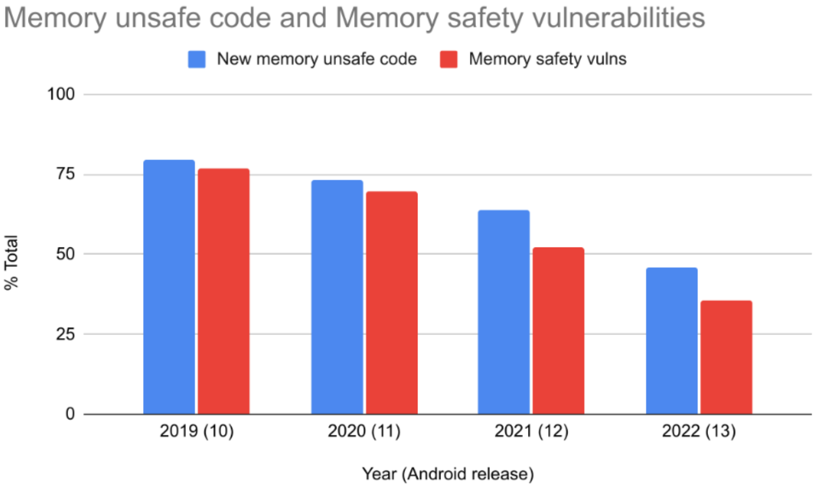
Gradual adoption of memory-safe languages



Source: Blog post Memory Safe Languages in Android 13 from Google.

Number of memory safety vulnerabilities starts to decrease with the adoption of memory-safe languages

Gradual adoption of memory-safe languages



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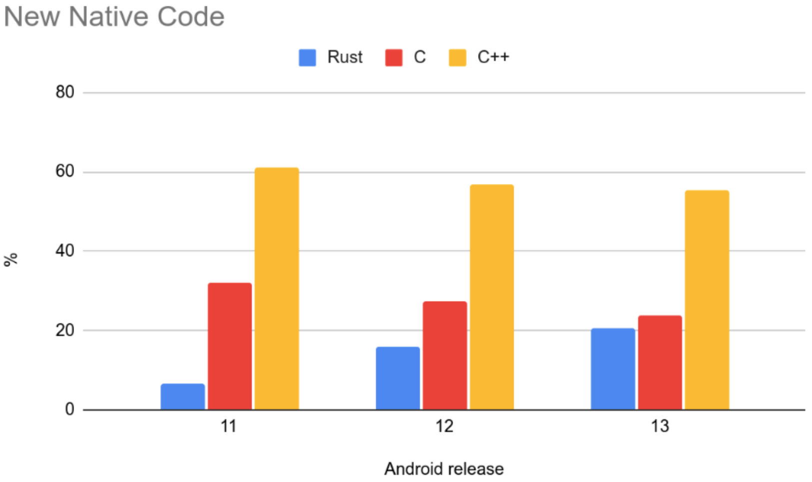
Number of memory safety vulnerabilities correlates to the portion of unsafe code

Gradual adoption of memory-safe languages



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Rust on the rise in Android native implementations

Looking into the future

White House Press Release: Future Software Should Be Memory Safe on February 26, 2024.

ONCD Technical Report: Back to the Building Blocks: A Path Toward Secure and Measurable Software published in February 2024.

$\langle$ **End** $\rangle$