Secure Software Development

Memory Corruption II & Environment

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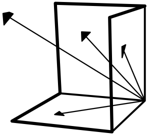
PREVIOUSLY ON

SSD

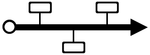
Memory Safety Violation

We can distinguish between two types of memory safety violation



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

- buffer overflow
- out-of-bounds reads
- null pointer dereference



Temporal violation: memory access refers to an invalid object

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

Memory Safety Violation Overview

Overflow (last lecture)

- Stack overflow
- Heap overflow
- Integer overflow

Invalid Memory (this lecture)

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

OVERFLOW

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)

INVALID MEMORY

Use-after-free

Use-after-free

- Referencing a resource after it was freed

Use-after-free

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- C/C++ does not invalidate pointer when freeing its memory

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- Such pointers are called dangling pointers

Use-after-free

- Referencing a resource after it was freed
- C/C++ does not invalidate pointer when freeing its memory
- Such pointers are called dangling pointers
- Also possible without dynamic memory (destroyed scope)

Use-after-free

Context 1 :

```
p = malloc(size) ;
// ...
free( p );
// ...
p = 0;
```

Use-after-free

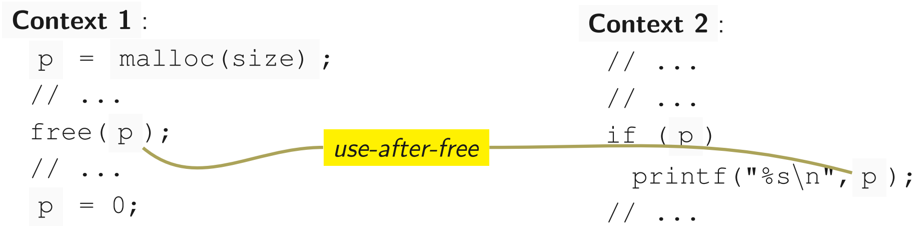
Context 1 :

```
p = malloc(size) ;
// ...
free( p );
// ...
p = 0;
```

Context 2 :

```
// ...
// ...
if ( p )
  printf("%s\n", p );
// ...
```

Use-after-free



Context 1 :

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use-after-free

Context 2 :

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// ...
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if ( p )
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Use-after-free

Resource

Context 1 :

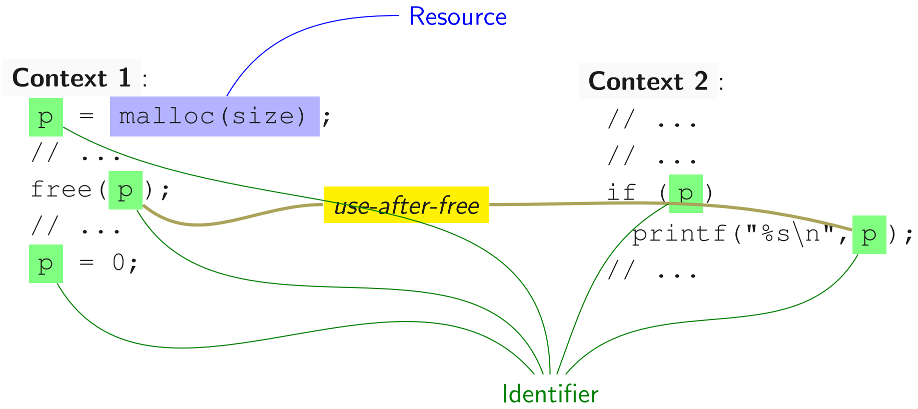
```
p = malloc(size);
// ...
free(p);
// ...
p = 0;
```

use-after-free

Context 2 :

```
// ...
// ...
if (p)
  printf("%s\n", p);
// ...
```

Use-after-free



Resource

Context 1:

```
p = malloc(size);
// ...
free(p);
// ...
p = 0;
```

use-after-free

Context 2:

```
// ...
// ...
if (p)
  printf("%s\n", p);
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```
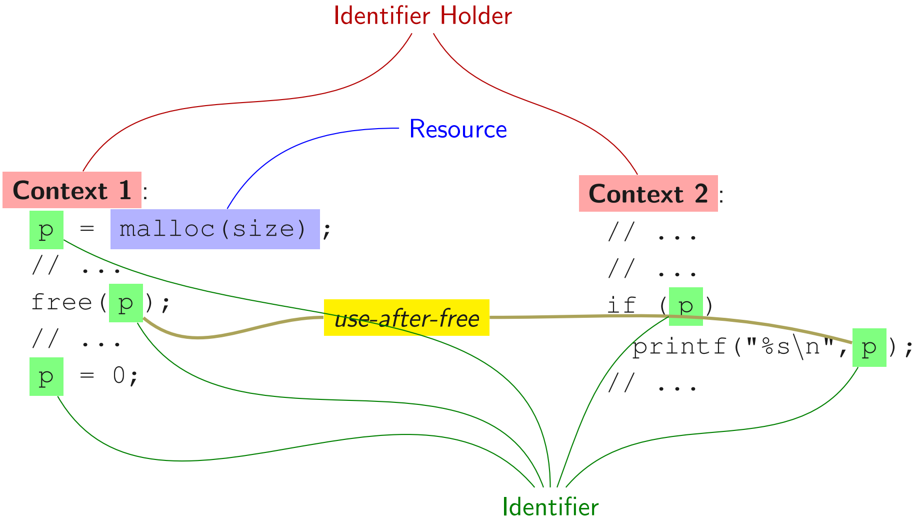

Identifier

Use-after-free



Identifier Holder

Resource

Context 1:

```
p = malloc(size);
// ...
free(p);
// ...
p = 0;
```

use-after-free

Context 2:

```
// ...
// ...
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```

Identifier

Minimal Abstraction

A system **can be** vulnerable to Use-after-free **iff** the system has the concept of:

Minimal Abstraction

A system **can be** vulnerable to Use-after-free **iff** the system has the concept of:

1. resources,
2. resource identifiers,
3. and identifier holders.

Use-After-Free Vulnerable

A system **is** vulnerable to Use-after-free **iff**
the system allows to **silently exchange** resources.

Practical Example: Use-after-free

Use-after-free

```c
#include <stdio.h>

int *get_numbers() {
    int x[] = {1, 2, 4, 8, 16, 32, 64};
    int *y = x;
    return y;
}

void secret() {
    int pins[] = {1337, 1589, 1346, 1470, 8846, 3478, 3669};
}

int main() {
    int *c = get_numbers();
    printf("%d %d %d %d %d %d %d\n", c[0], c[1], c[2], c[3], c[4], c[5], c[6]);
    secret();
    printf("%d %d %d %d %d %d %d\n", c[0], c[1], c[2], c[3], c[4], c[5], c[6]);
    return 0;
}
```

Use-after-free

```
% ./uaf-scope
1 2 4 8 16 32 64
1337 1589 1346 1470 8846 3478 3669
```

Practical Example Analysis: Use-after-free

Use-after-free

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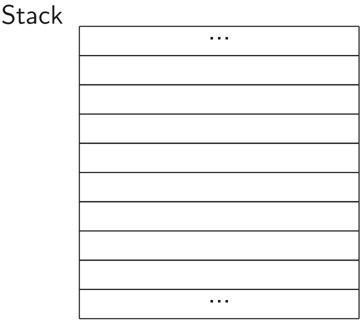

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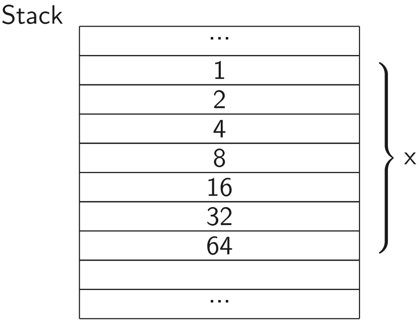
Stack

...

1

2

4

8

16

32

64

...

Use-after-free

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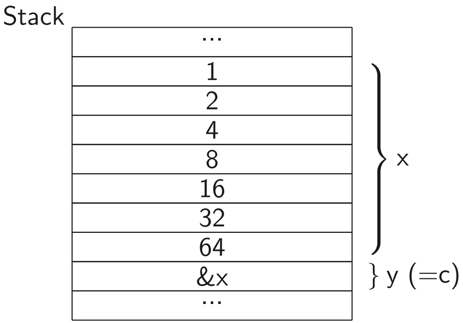

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&x

...

x

y (=c)

Use-after-free

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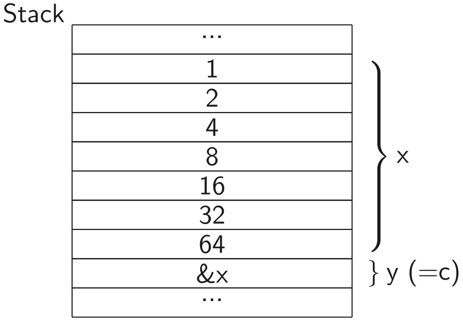

Stack

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2
4
8
16
32
64
&x
...

} x

} y (=c)

Use-after-free

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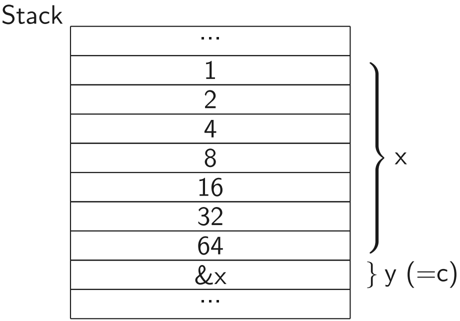

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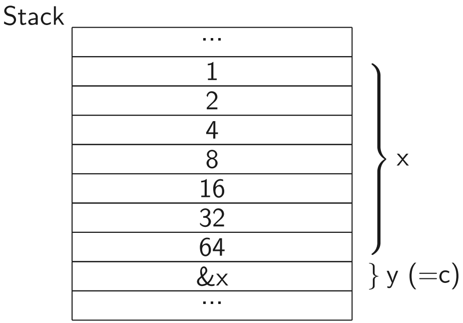

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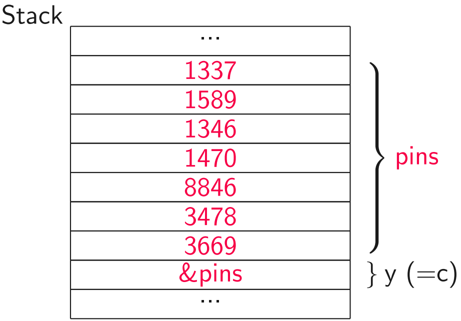

Stack

...

1337

1589

1346

1470

8846

3478

3669

&pins

...

pins

} y (=c)

Use-after-free

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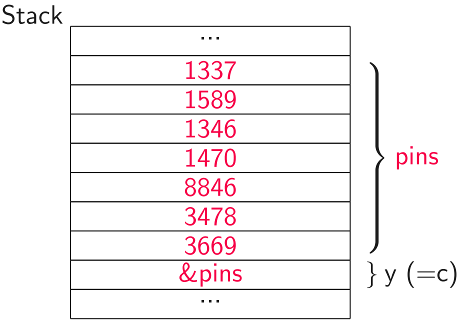

Stack

...
1337
1589
1346
1470
8846
3478
3669
&pins
...

Practical Example Impact: Use-after-free

Use-after-free

- Stack frames are automatically destroyed

Use-after-free

- Stack frames are automatically destroyed
- However, references can still point to the stack frame

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- Not easy to spot

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- Sometimes causes compiler warning, but not in this case

Use-after-free

- Stack frames are automatically destroyed
- However, references can still point to the stack frame
- Not easy to spot
- Sometimes causes compiler warning, but not in this case
- Attacker has access to confidential data of new stack frame

Fun Example: Use-after-free with Threads

Use-after-free Threads

```c
pthread_t tid;
void* thread(void* arg) {  printf("%s\n", (char*)arg); }

void start_thread() {
    char argument[64];
    strcpy(argument, "I’m a thread\n");
    pthread_create(&tid, NULL, thread, (void*)&argument);
}
void do_something() {
    char msg[64];
    strcpy(msg, "I’m NOT a thread\n");
}
int main() {
    start_thread();
    do_something();
    pthread_join(tid, NULL);
    return 0;
}
```

Use-after-free Threads

```
% ./uaf-thread
����
```

Use-after-free Threads

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pthread_t tid;
void* thread(void* arg) {  printf("%s\n", (char*)arg); }

void start_thread() {
    char argument[64];
    strcpy(argument, "I'm a thread\n");
    pthread_create(&tid, NULL, thread, (void*)&argument);
}
void do_something() {
    char msg[64];
    sleep(1);
    strcpy(msg, "I'm NOT a thread\n");
    sleep(1);
}
int main() {
    start_thread();
    do_something();
    pthread_join(tid, NULL);
    return 0;
}
```

Use-after-free Threads

```
% ./uaf-thread
I'm a thread
```

Use-after-free Threads

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    sleep(1);
}
int main() {
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    do_something();
    pthread_join(tid, NULL);
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```

Use-after-free Threads

```
% ./uaf-thread
I'm NOT a thread
```

Practical Example: Use-after-free

Use-after-free

```c
typedef struct {
    void (*print)(char*);
} operation;

int main(int argc, char* argv[]) {
    operation* io = (operation*)malloc(sizeof(operation));
    io->print = puts;
    io->print("Hallo ");
    free(io);

    if(argc > 1) {
        char* buffer = (char*)malloc(8);
        strncpy(buffer, argv[1], 7);
        io->print(buffer);
        free(buffer);
    }
    return 0;
}
```

Use-after-free

```
% gdb --args ./hello
(gdb) r
Starting program: /home/hello
Hallo
[Inferior 1 (process 7378) exited normally]
```

Use-after-free

```
% gdb --args ./hello
(gdb) r
Starting program: /home/hello
Hallo
[Inferior 1 (process 7378) exited normally]
```

```
% gdb --args ./hello ABCD
(gdb) r
Starting program: /home/hello ABCD
Hallo

Program received signal SIGSEGV, Segmentation fault.
0x0000000044434241 in ?? ()
```

Practical Example Analysis: Use-after-free

Use-after-free

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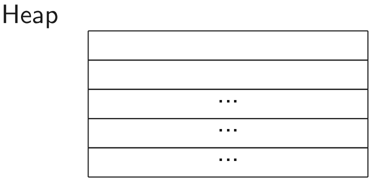
Heap

...

...

...

Use-after-free

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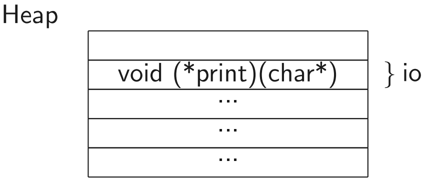

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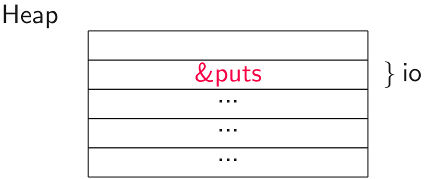

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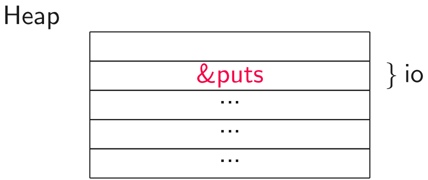

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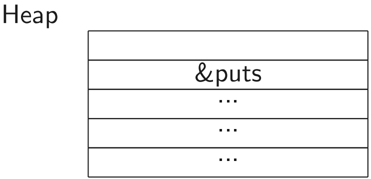

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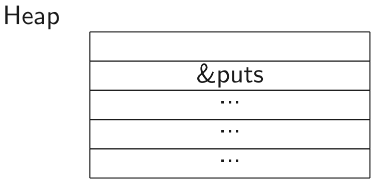

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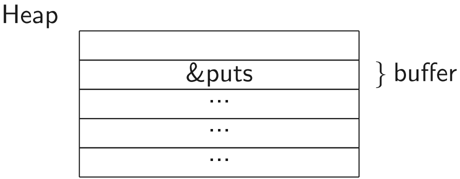

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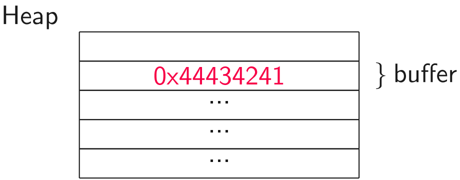
}
```

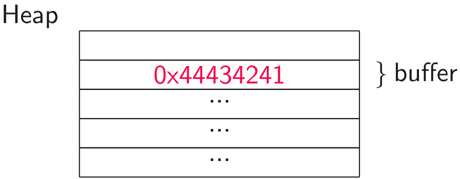


Use-after-free

```c
typedef struct {
    void (*print)(char*);
} operation;

int main(int argc, char* argv[]) {
  operation* io = (operation*)malloc(
      sizeof(operation));
  io->print = puts;
  io->print("Hallo ");
  free(io);

  if(argc > 1) {
    char* buffer = (char*)malloc(8);
    strncpy(buffer, argv[1], 7);
    io->print(buffer);
    free(buffer);
  }
  return 0;
}
```



Practical Example Impact: Use-after-free

Use-after-free

- Reference can point to different memory block or inside a memory block

Use-after-free

- Reference can point to different memory block or inside a memory block
- Using the reference corrupts valid memory

Use-after-free

- Reference can point to different memory block or inside a memory block
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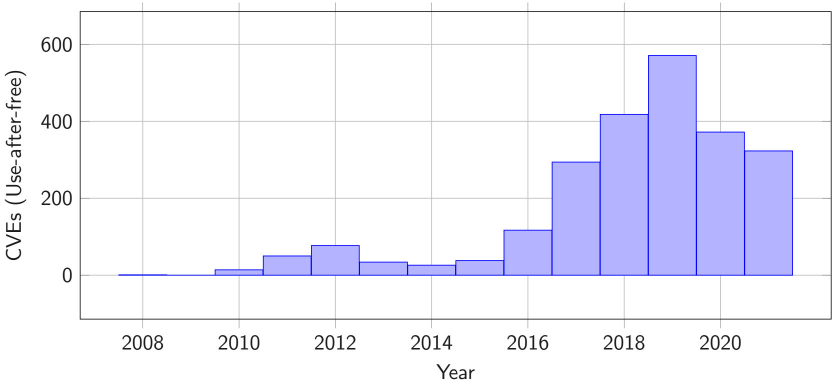
- Allows to read possibly confidential data or overwrite data

Use-after-free

- Reference can point to different memory block or inside a memory block
- Using the reference corrupts valid memory
- Allows to read possibly confidential data or overwrite data
- Overwriting C++ object vtables allows to execute arbitrary code

Use-after-free - CVEs per year



Use-after-free Vulnerable Systems

Resource (R)	Resource Identifier (I_R)	Identifier Holder (H_I)
Memory buffer	Pointer / Address	Variables

Use-after-free Vulnerable Systems

Resource (R)	Resource Identifier (I_R)	Identifier Holder (H_I)
Memory buffer	Pointer / Address	Variables
Server	DNS entry / Domain	Links, databases, human memory

Use-after-free Vulnerable Systems

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Memory buffer	Pointer / Address	Variables
Server	DNS entry / Domain	Links, databases, human memory
Email account	Email address	Links, third-party websites, databases, address books, human memory

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Personal Phone	Phone Number	Personal and business address books, third-party websites, human memory

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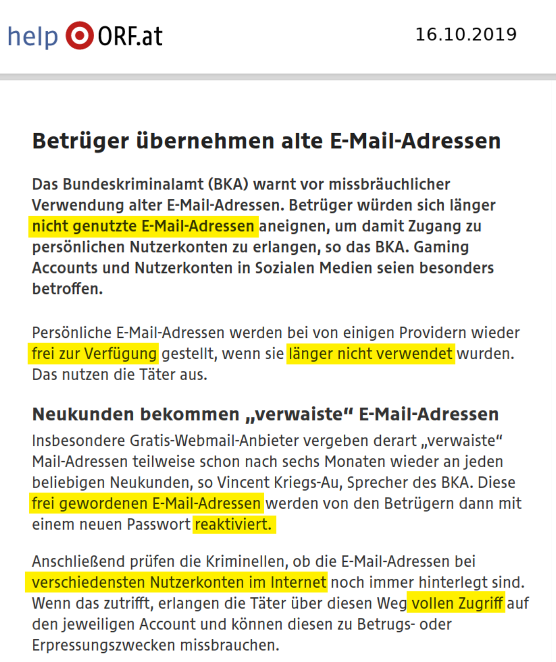
Email account	Email address	Links, third-party websites, databases, address books, human memory
Twitter account	Twitter handle	Links, third-party websites, databases, human memory
Personal Phone	Phone Number	Personal and business address books, third-party websites, human memory
Mailbox	Address	Personal and business address books, human memory

Use-after-free Vulnerable Systems

Resource (R)	Resource Identifier (I_R)	Identifier Holder (H_I)
Memory buffer	Pointer / Address	Variables
Server	DNS entry / Domain	Links, databases, human memory
Email account	Email address	Links, third-party websites, databases, address books, human memory
Twitter account	Twitter handle	Links, third-party websites, databases, human memory
Personal Phone	Phone Number	Personal and business address books, third-party websites, human memory
Mailbox	Address	Personal and business address books, human memory
Employee	Office number	Human memory, business cards



help ORF.at 16.10.2019

Betrüger übernehmen alte E-Mail-Adressen

Das Bundeskriminalamt (BKA) warnt vor missbräuchlicher Verwendung alter E-Mail-Adressen. Betrüger würden sich länger nicht genutzte E-Mail-Adressen aneignen, um damit Zugang zu persönlichen Nutzerkonten zu erlangen, so das BKA. Gaming Accounts und Nutzerkonten in Sozialen Medien seien besonders betroffen.

Persönliche E-Mail-Adressen werden bei von einigen Providern wieder frei zur Verfügung gestellt, wenn sie länger nicht verwendet wurden. Das nutzen die Täter aus.

Neukunden bekommen „verwaiste“ E-Mail-Adressen

Insbesondere Gratis-Webmail-Anbieter vergeben derart „verwaiste“ Mail-Adressen teilweise schon nach sechs Monaten wieder an jeden beliebigen Neukunden, so Vincent Kriegs-Au, Sprecher des BKA. Diese frei gewordenen E-Mail-Adressen werden von den Betrügern dann mit einem neuen Passwort reaktiviert.

Anschließend prüfen die Kriminellen, ob die E-Mail-Adressen bei verschiedensten Nutzerkonten im Internet noch immer hinterlegt sind. Wenn das zutrifft, erlangen die Täter über diesen Weg vollen Zugriff auf den jeweiligen Account und können diesen zu Betrugs- oder Erpressungszwecken missbrauchen.

Double free

- Double free is similar to use-after-free

Double free

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- Instead of referencing the memory after freeing, it is again freed

Double free

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- Instead of referencing the memory after freeing, it is again freed
- Corrupts the internal memory management structures

Double free

- Double free is similar to use-after-free
- Instead of referencing the memory after freeing, it is again freed
- Corrupts the internal memory management structures
- Either crashes, corrupts memory, or returns same pointers for subsequent mallocs

Practical Example: Double free

Double free

```c
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
    char* b2 = malloc(16);
    char* b3 = malloc(16);
    free(b1);
    free(b2);
    free(b1);

    char* secret = malloc(16);
    strcpy(secret, "secret");
    char* dummy = malloc(16);

    char* buffer = malloc(16);
    printf("Should be empty (or garbage): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n", secret, buffer);
}
```

Double free

```
% ./doublefree
Double free demo
Should be empty (or garbage): "secret"
&secret: 0x2090420, &buffer: 0x2090420
```

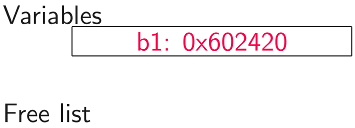
Practical Example Analysis: Double free

Double free

```
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
    char* b2 = malloc(16);
    char* b3 = malloc(16);
    free(b1);
    free(b2);
    free(b1);

    char* secret = malloc(16);
    strcpy(secret, "secret");
    char* dummy = malloc(16);

    char* buffer = malloc(16);
    printf("Should be empty (or garbage
        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```



Variables

b1: 0x602420

Free list

Double free

```c
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
    char* b2 = malloc(16);
    char* b3 = malloc(16);
    free(b1);
    free(b2);
    free(b1);

    char* secret = malloc(16);
    strcpy(secret, "secret");
    char* dummy = malloc(16);

    char* buffer = malloc(16);
    printf("Should be empty (or garbage
        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440

Free list

Double free

```c
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
    char* b2 = malloc(16);
    char* b3 = malloc(16);
    free(b1);
    free(b2);
    free(b1);

    char* secret = malloc(16);
    strcpy(secret, "secret");
    char* dummy = malloc(16);

    char* buffer = malloc(16);
    printf("Should be empty (or garbage
        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440
b3: 0x602460

Free list

Double free

```c
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
    char* b2 = malloc(16);
    char* b3 = malloc(16);
    free(b1);
    free(b2);
    free(b1);

    char* secret = malloc(16);
    strcpy(secret, "secret");
    char* dummy = malloc(16);

    char* buffer = malloc(16);
    printf("Should be empty (or garbage
        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420

b2: 0x602440

b3: 0x602460

Free list

0x602420 (b1)

Double free

```c
int main() {
    printf("Double free demo\n");
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    free(b1);
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    strcpy(secret, "secret");
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    char* buffer = malloc(16);
    printf("Should be empty (or garbage
        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440
b3: 0x602460

Free list

0x602420 (b1)
0x602440 (b2)

Double free

```
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
    char* b2 = malloc(16);
    char* b3 = malloc(16);
    free(b1);
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    free(b1);

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    char* dummy = malloc(16);

    char* buffer = malloc(16);
    printf("Should be empty (or garbage
        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440
b3: 0x602460

Free list

0x602420 (b1)
0x602440 (b2)
0x602420 (b1)

Double free

```c
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
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    char* b3 = malloc(16);
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        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440
b3: 0x602460
secret: 0x602420 (b1)

Free list

0x602440 (b2)
0x602420 (b1)

Double free

```c
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
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    strcpy(secret, "secret");
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        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440
b3: 0x602460
secret: 0x602420 (b1)

Free list

0x602440 (b2)
0x602420 (b1)

Double free

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int main() {
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        ): \"%s\"\n", buffer);
    printf("&secret: %p, &buffer: %p\n"
        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440
b3: 0x602460
secret: 0x602420 (b1)
dummy: 0x602440 (b2)

Free list

0x602420 (b1)

Double free

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        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440
b3: 0x602460
secret: 0x602420 (b1)
dummy: 0x602440 (b2)
buffer: 0x602420 (b1)

Free list

Practical Example Impact: Double free

Double free

- Similar as use-after-free: two (different) references to the same memory location

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- Attacker can read confidential data

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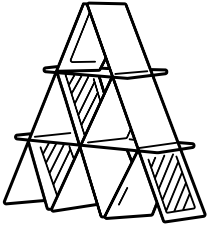
- Memory can be corrupted

Double free

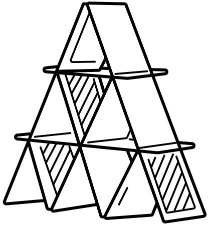
- Similar as use-after-free: two (different) references to the same memory location
- Attacker can read confidential data
- Memory can be corrupted
- If C++ object vtable in memory region, attacker gets arbitrary code execution

Exploitation Techniques



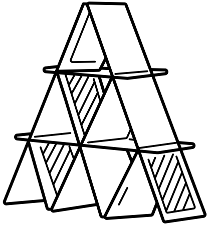
- Goals

Exploitation Techniques



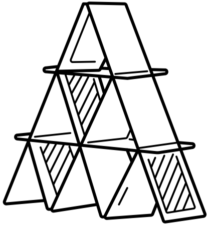
- Goals
  - Create overlapping chunks

Exploitation Techniques



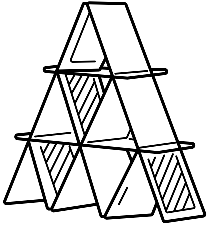
- Goals
  - Create overlapping chunks
  - Let malloc return arbitrary pointers

Exploitation Techniques



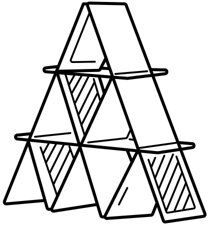
- Goals
  - Create overlapping chunks
  - Let malloc return arbitrary pointers
  - Use malloc to write to arbitrary addresses

Exploitation Techniques



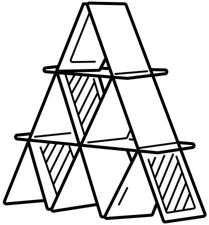
- Goals
  - Create overlapping chunks
  - Let malloc return arbitrary pointers
  - Use malloc to write to arbitrary addresses
- Common Techniques

Exploitation Techniques



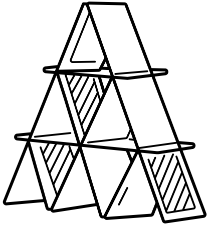
- Goals
  - Create overlapping chunks
  - Let malloc return arbitrary pointers
  - Use malloc to write to arbitrary addresses
- Common Techniques
  - Append fake chunks to free list

Exploitation Techniques



- Goals
  - Create overlapping chunks
  - Let malloc return arbitrary pointers
  - Use malloc to write to arbitrary addresses
- Common Techniques
  - Append fake chunks to free list
  - Overwrite metadata in free'd chunk (size/next pointer)

Exploitation Techniques



- Goals
  - Create overlapping chunks
  - Let malloc return arbitrary pointers
  - Use malloc to write to arbitrary addresses
- Common Techniques
  - Append fake chunks to free list
  - Overwrite metadata in free'd chunk (size/next pointer)
  - many many more (see Further Reading)

Format Strings

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- C uses format strings to construct strings containing variables

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- Well known from `printf` or `fprintf`

```
printf("%d (dec) = 0x%x (hex)\n", 18, 18);
```

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```
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- Format string parameters (`%d`, `%s`, ...) convert function parameters to strings

Format Strings

- C uses format strings to construct strings containing variables
- Well known from `printf` or `fprintf`

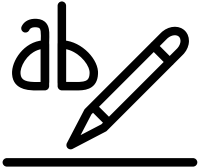
```
printf("%d (dec) = 0x%x (hex)\n", 18, 18);
```

- Format string parameters (`%d`, `%s`, ...) convert function parameters to strings
- Parameters are fetched from registers, and then from the stack (⇒ calling convention)

Format Strings

- What if the number of function parameters and format string parameters mismatch?

Format Strings



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- `printf` trusts the format string (and the developer)
- `printf` is a variadic function, compiler does not care how many parameters
- If format string is constant, compiler could check it by understanding format strings
  - See `__attribute__((format(printf, ...)))`

Format Strings

- What if the number of function parameters and format string parameters mismatch?
- `printf` trusts the format string (and the developer)
- `printf` is a variadic function, compiler does not care how many parameters
- If format string is constant, compiler could check it by understanding format strings
  - See `__attribute__((format(printf, ...)))`
- In reality: no checks are performed (gcc only issues a warning)

Format Strings

- Usually no mismatch if developer writes the format string...

Format Strings

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- ...but if the attacker controls it:

```
printf(user_input);
```

Format Strings

- Usually no mismatch if developer writes the format string...
- ...but if the attacker controls it:

```
printf(user_input);
```

- If the user enters format string parameters, `printf` parses them although there are no function parameters

Practical Example: Format String

Format Strings

```c
#include <stdio.h>

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

Format Strings

```
% ./echo "Test"
Test
% ./echo "Hello World"
Hello World
```

Format Strings

```
% ./echo "Test"
Test
% ./echo "Hello World"
Hello World
```

```
% ./echo "%p %p %p %p %p %p %p %p %p"
0x1 0x7fc3a4008780 0x7ffffff5 (nil) 0xb 0x7ffcb1b66db8
0x200400430 0x7ffcb1b66db0  0xdeadbeef00000000
```

Practical Example Analysis: Format String

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI (0x1)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI (0x1)

RDX (0x7fc3a4008780)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI (0x1)

RDX (0x7fc3a4008780)

RCX (0x7ffffff5)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI (0x1)

RDX (0x7fc3a4008780)

RCX (0x7ffffff5)

R8 (nil)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI	(0x1)
RDX	(0x7fc3a4008780)
RCX	(0x7ffffff5)
R8	(nil)
R9	(0xb)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI	(0x1)
RDX	(0x7fc3a4008780)
RCX	(0x7ffffff5)
R8	(nil)
R9	(0xb)
[RSP]	(0x7ffcb1b66db8)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI	(0x1)
RDX	(0x7fc3a4008780)
RCX	(0x7ffffff5)
R8	(nil)
R9	(0xb)
[RSP]	(0x7ffcb1b66db8)
[RSP + 0x8]	(0x200400430)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

RSI	(0x1)
RDX	(0x7fc3a4008780)
RCX	(0x7ffffff5)
R8	(nil)
R9	(0xb)
[RSP]	(0x7ffcb1b66db8)
[RSP + 0x8]	(0x200400430)
[RSP + 0x10]	(0x7ffcb1b66db0)

Format Strings

```
printf("%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p "
"%p ");
```

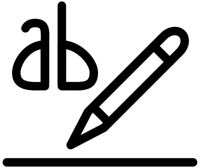
RSI	(0x1)
RDX	(0x7fc3a4008780)
RCX	(0x7ffffff5)
R8	(nil)
R9	(0xb)
[RSP]	(0x7ffcb1b66db8)
[RSP + 0x8]	(0x200400430)
[RSP + 0x10]	(0x7ffcb1b66db0)
[RSP + 0x18]	(0xdeadbeef00000000)

Practical Example Impact: Format String

Format Strings

- A format string attack is possible if the user defines the format string

Format Strings



- A format string attack is possible if the user defines the format string
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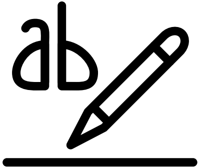
Format Strings



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- Attacker might be able to read confidential data

Format Strings

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- Attacker might be able to read confidential data
- Attacker can crash the program with enough `%s`

Format String - Short History

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2000 Exploits for many applications, including wu-ftpd (FTP), Qualcomm Popper (mail), Apache (webserver), OpenBSD, ...

Format Strings - Data Disclosure

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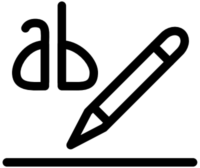
- Thus, arbitrary addresses (both on stack and heap) can be disclosed
- What about manipulating data?

Format Strings - Data Manipulation

- A little-known format string parameter: `%n`

Format Strings - Data Manipulation



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man 3 printf

n The number of characters written so far is stored into the integer pointed to by the corresponding argument. That argument shall be an int *, or variant whose size matches the (optionally) supplied integer length modifier.

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int count;
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- Example:

```
int count;
printf("Some string %n\n", &count);
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Prints `Wrote 12 characters`

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printf("%1337s%n\n", "", &count);
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```

Prints `Wrote 1337 characters`

- The format string itself is also on the stack, so we can inject arbitrary addresses into the stack

Fun Example: Format String Address Injection

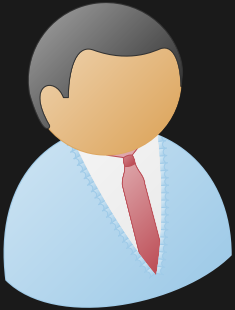
Format String - Address Injection

```c
#include <stdio.h>

int main(int argc, char* argv[]) {
    char buffer[64];
    strcpy(buffer, argv[1]);
    printf(buffer);
}
```

Format String - Address Injection

```
% valgrind ./format "ABCDABCD %p %p %p %p %p %p %p %n"
[...]
==17472== Invalid write of size 4
==17472==    at 0x4E89533: vfprintf (vfprintf.c:1631)
==17472==    by 0x4E8F898: printf (printf.c:33)
==17472==    by 0x40061E: main (printf.c:6)
==17472==  Address 0x4443424144434241 is not stack'd, malloc'd
           or (recently) free'd
==17472==
==17472==
==17472== Process terminating with default action of signal 11
          (SIGSEGV)
```



Real-world Example: Format String BMW 330i (CVE-2017-9212)

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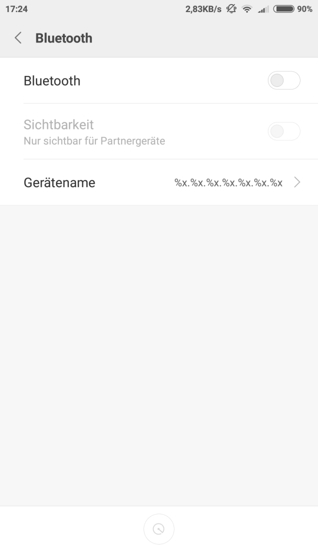


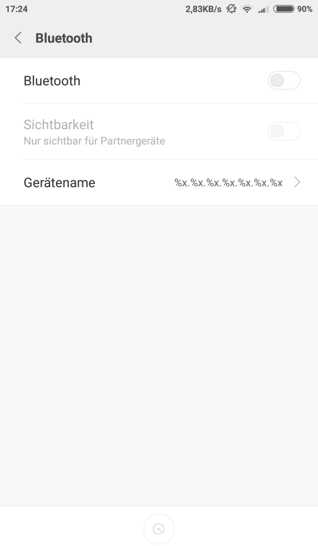
Bluetooth

Bluetooth

Sichtbarkeit
Nur sichtbar für Partnergeräte

Gerätename %x.%x.%x.%x.%x.%x.%x

Format String BMW 330i (CVE-2017-9212)



17:24 2,83KB/s 90%

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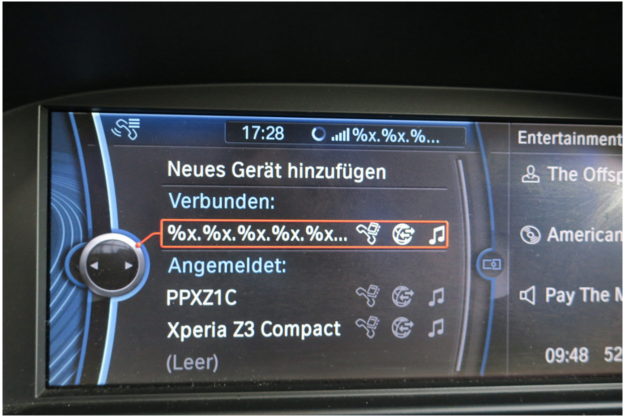

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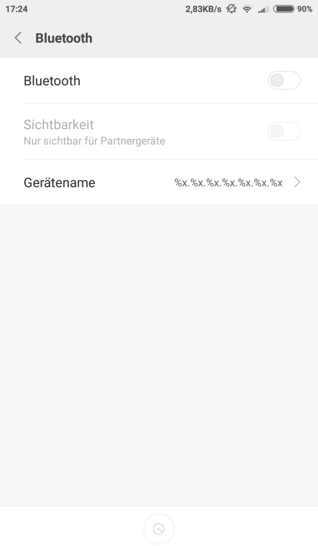

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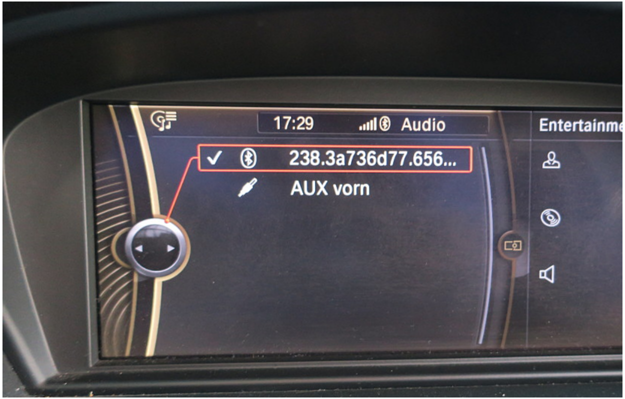
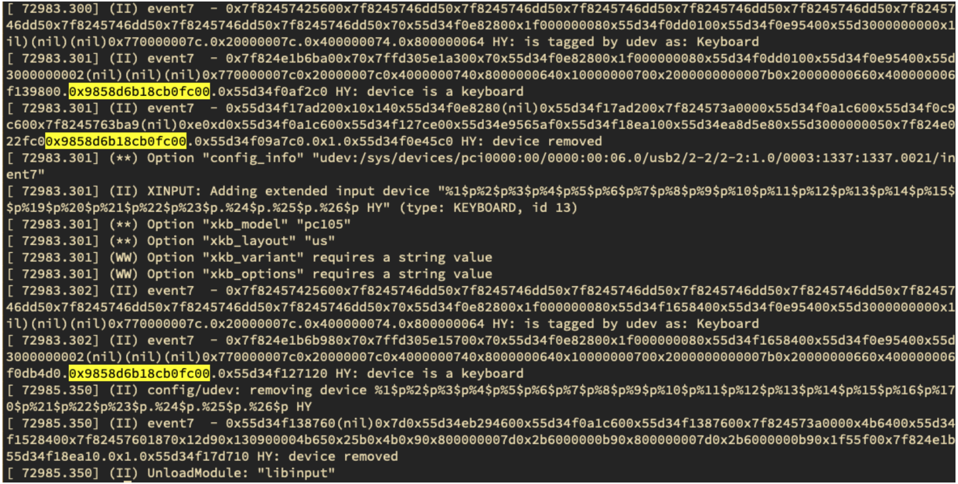


Format string vulnerability in evdev device handling (CVE-2022-1215)



```
[ 72983.300] (II) event7  - 0x7f82457425600x7f8245746dd50x7f8245746dd50x7f8245746dd50x7f8245746dd50x7f8245746dd50x7f82457
46dd50x7f8245746dd50x7f8245746dd50x7f8245746dd50x70x55d34f0e82800x1f000000080x55d34f0dd0100x55d34f0e95400x55d3000000000x1
il)(nil)(nil)0x770000007c.0x20000007c.0x400000074.0x800000064 HY: is tagged by udev as: Keyboard
[ 72983.301] (II) event7  - 0x7f824e1b6ba00x70x7ffd305e1a300x70x55d34f0e82800x1f000000080x55d34f0dd0100x55d34f0e95400x55d
3000000002(nil)(nil)(nil)0x770000007c0x20000007c0x4000000740x8000000640x10000000700x2000000000007b0x20000000660x400000006
f139800.0x9858d6b18cb0fc00.0x55d34f0af2c0 HY: device is a keyboard
[ 72983.301] (II) event7  - 0x55d34f17ad200x10x140x55d34f0e8280(nil)0x55d34f17ad200x7f824573a0000x55d34f0a1c600x55d34f0c9
c600x7f8245763ba9(nil)0xe0xd0x55d34f0a1c600x55d34f127ce00x55d34e9565af0x55d34f18ea100x55d34ea8d5e80x55d3000000050x7f824e0
22fc00x9858d6b18cb0fc00.0x55d34f09a7c0.0x1.0x55d34f0e45c0 HY: device removed
[ 72983.301] (**) Option "config_info" "udev:/sys/devices/pci0000:00/0000:00:06.0/usb2/2-2/2-2:1.0/0003:1337:1337.0021/in
ent7"
[ 72983.301] (II) XINPUT: Adding extended input device "%1$p%2$p%3$p%4$p%5$p%6$p%7$p%8$p%9$p%10$p%11$p%12$p%13$p%14$p%15$
$p%19$p%20$p%21$p%22$p%23$p.%24$p.%25$p.%26$p HY" (type: KEYBOARD, id 13)
[ 72983.301] (**) Option "xkb_model" "pc105"
[ 72983.301] (**) Option "xkb_layout" "us"
[ 72983.301] (WW) Option "xkb_variant" requires a string value
[ 72983.301] (WW) Option "xkb_options" requires a string value
[ 72983.302] (II) event7  - 0x7f82457425600x7f8245746dd50x7f8245746dd50x7f8245746dd50x7f8245746dd50x7f8245746dd50x7f82457
46dd50x7f8245746dd50x7f8245746dd50x7f8245746dd50x70x55d34f0e82800x1f000000080x55d34f1658400x55d34f0e95400x55d3000000000x1
il)(nil)(nil)0x770000007c.0x20000007c.0x400000074.0x800000064 HY: is tagged by udev as: Keyboard
[ 72983.302] (II) event7  - 0x7f824e1b6b980x70x7ffd305e15700x70x55d34f0e82800x1f000000080x55d34f1658400x55d34f0e95400x55d
3000000002(nil)(nil)(nil)0x770000007c0x20000007c0x4000000740x8000000640x10000000700x2000000000007b0x20000000660x400000006
f0db4d0.0x9858d6b18cb0fc00.0x55d34f127120 HY: device is a keyboard
[ 72985.350] (II) config/udev: removing device %1$p%2$p%3$p%4$p%5$p%6$p%7$p%8$p%9$p%10$p%11$p%12$p%13$p%14$p%15$p%16$p%17
0$p%21$p%22$p%23$p.%24$p.%25$p.%26$p HY
[ 72985.350] (II) event7  - 0x55d34f138760(nil)0x7d0x55d34eb294600x55d34f0a1c600x55d34f1387600x7f824573a0000x4b6400x55d34
f1528400x7f82457601870x12d90x130900004b650x25b0x4b0x90x800000007d0x2b6000000b90x800000007d0x2b6000000b90x1f55f00x7f824e1b
55d34f18ea10.0x1.0x55d34f17d710 HY: device removed
[ 72985.350] (II) UnloadModule: "libinput"
```

Format Strings Summary

- A format string attack is possible if the user can define the format string
- Not only in `printf`, but in the whole family (`fprintf`, `snprintf`, `vsprintf`, ...)
- It allows to read (or even manipulate)
  - arbitrary memory locations
  - itself (format strings are Turing complete)
- Easily preventable: never let the user control the format string

  -
    ```
    __attribute__((format(printf, 1, 2)))
    extern char *myFormatText2 (const char *, ...);
    ```
  - `gcc -Werror=format ...`

Challenge #3 - Format String

Find a format string to extract the binary's secret

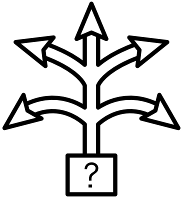
- The binary: `https://sasectf.student.iaik.tugraz.at/`
- Your format string has to extract the secret key (`<THE FLAG!>` in the sample code)
- Submitting the correct format string to the CTF system shows the real flag

Source

```c
char secret[15] __attribute__ ((section (".secret")));
int main(int argc, char* argv[]) {
    char buffer[16];
    printf("What do you want?\n");
    strcpy(secret, "<THE FLAG!>");
    fgets(buffer, 16, stdin);
    printf(buffer);
}
```

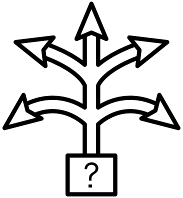
Type Confusion

Type Confusion



- A resource from one type is allocated, but later referenced as a different type

Type Confusion



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- No problem if the types are compatible ($\Rightarrow$ C++ polymorphism)

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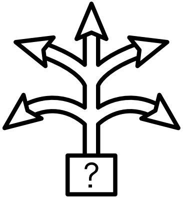

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- C/C++ also allows casts to incompatible types, leading to logic errors

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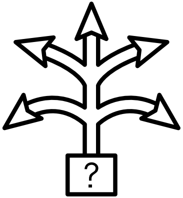
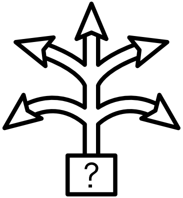


- A resource from one type is allocated, but later referenced as a different type
- No problem if the types are compatible (⇒ C++ polymorphism)
- C/C++ also allows casts to incompatible types, leading to logic errors
- Accesses can be out-of-bounds (⇒ buffer overflow), or leading to different control flow (⇒ vtables)

Type Confusion



- C++ provides different types of casts

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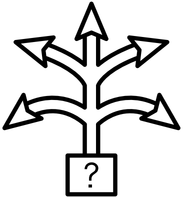

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- dynamic_cast: Explicit type checks at runtime, but slow

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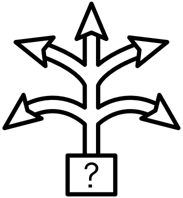

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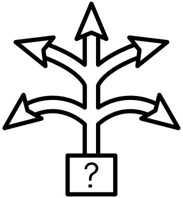

- C++ provides different types of casts
- `dynamic_cast`: Explicit type checks at runtime, but slow
- `static_cast`: Type check only at compile time, type confusion if runtime type is unexpected
- `reinterpret_cast`: Allows to explicitly break type checks

Practical Example: Type Confusion

Type Confusion

```cpp
#include <iostream>

class A {
  public: virtual const char* name() { return "A"; };
};
class B {
  public:  const char* name() { return "B"; };
  private: virtual const char* secret() { return "secret"; };
};

int main() {
  A* a = new A();
  std::cout << a->name() << std::endl;
  B* b = new B();
  std::cout << b->name() << std::endl;

  a = (A*)b;
  std::cout << a->name() << std::endl;
}
```

Type Confusion

```
% ./test
A
B
secret
```

Practical Example Analysis: Type Confusion

Type Confusion

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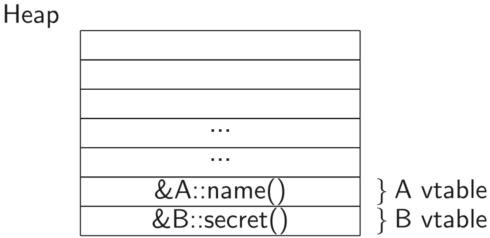

Heap

...

...

&A::name() } A vtable

&B::secret() } B vtable

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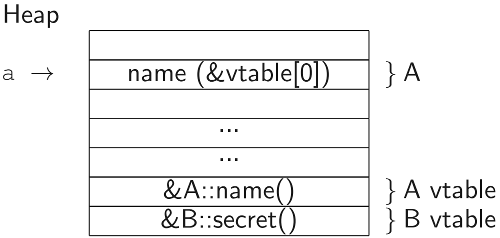

Heap

a →

name (&vtable[0]) } A

...

...

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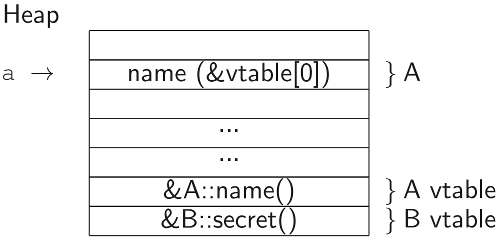

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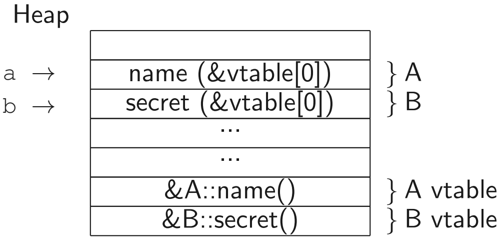

Heap

a →

b →

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...

...

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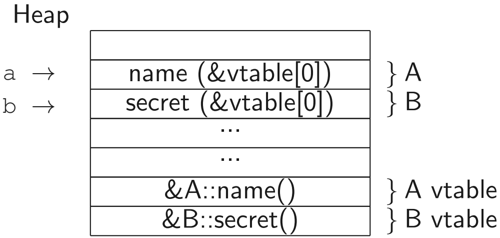

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...

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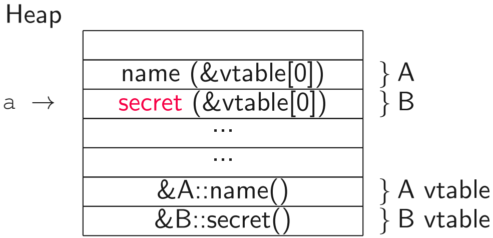
};
class B {
  public:  const char* name()
    { return "B"; };
  private: virtual const char* secret()
    { return "secret"; };
};
int main() {
  A* a = new A();
  std::cout << a->name() << std::endl;
  B* b = new B();
  std::cout << b->name() << std::endl;

  a = (A*)b;
  std::cout << a->name() << std::endl;
}
```



Type Confusion

```
class A {
  public: virtual const char* name()
    { return "A"; };
};
class B {
  public:  const char* name()
    { return "B"; };
  private: virtual const char* secret()
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int main() {
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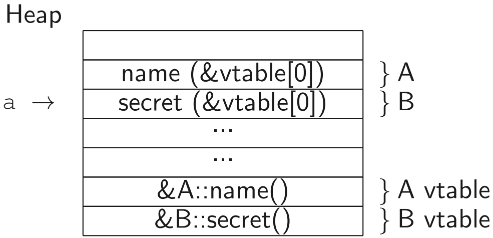


Heap

	name (&vtable[0])	} A
a →	secret (&vtable[0])	} B
	...	
	...	
	&A::name()	} A vtable
	&B::secret()	} B vtable

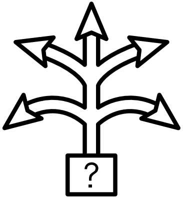
Type Confusion

```
% ./g++ vtables.h -fdump-lang-class && cat vtables.h.001l.class
Vtable for A                       Vtable for B
A::_ZTV1A: 3 entries               B::_ZTV1B: 3 entries
0      (int (*)(...))0             0      (int (*)(...))0
8      (int (*)(...))(& _ZTI1A)    8      (int (*)(...))(& _ZTI1B)
16     (int (*)(...))A::name       16     (int (*)(...))B::secret

Class A                            Class B
   size=8 align=8                  size=8 align=8
   base size=8 base align=8        base size=8 base align=8
A (0x0x7f4964ef0420) 0 nearly-empty B (0x0x7f4964ef04e0) 0 nearly-
    vptr=((& A::_ZTV1A) + 16)      vptr=((& B::_ZTV1B) + 16)
```

Practical Example Impact: Type Confusion

Type Confusion



- A type confusion happens if a pointer (or object) is cast to a wrong object
- It allows to
  - execute (arbitray) code
  - read/write out-of-bounds
  - crash the application
- Relatively new type of memory corruption

Type Confusion

- Type confusion bugs were exploited in many applications
  - Linux kernel (CVE-2022-34918)
  - Acrobat reader (CVE-2021-39841)
  - PHP (CVE-2016-3185)
  - Google Chrome (CVE-2022-2158, CVE-2022-1869,CVE-2022-1486,CVE-2022-1364,. . .)

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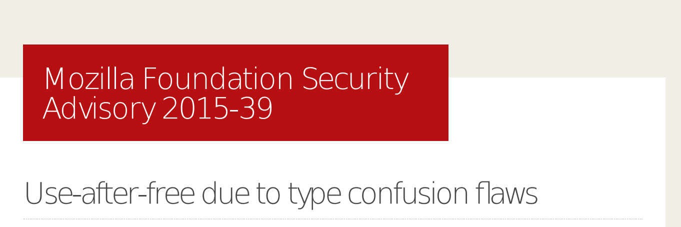

Mozilla Foundation Security Advisory 2015-39

Use-after-free due to type confusion flaws

Invalid Memory Usage Summary

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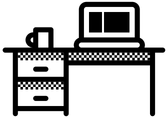
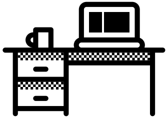
ENVIRONMENT

Environment



- Programs are always executed in some environment

Environment



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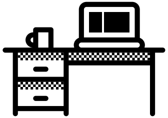

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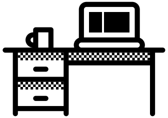
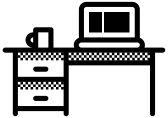


- Programs are always executed in some environment
- The environment is usually not fully known at compile time
- Defined by operating system, user, configurations, ...
- Environment can even change while the program is running

Environment



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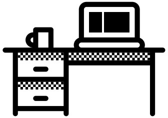

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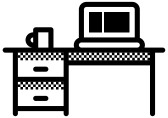

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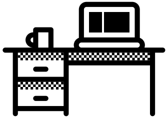

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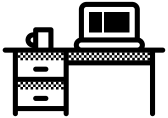

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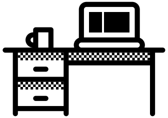

- Some bugs might not be exclusively in the binary
- They appear due to the program's interaction with the environment
  - Environment variables
  - Loader
  - Access control
- These factors have to be considered when writing programs

ENVIRONMENT
VARIABLES

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- Each process has its own set (usually copy of the parent)
- Provided by the envp pointer of `exec`
- Can also be set using `VARIABLE=VALUE` in most shells
- Accessed using `setenv`/`getenv` in C/C++

Environment Variables

Some well-known environment variables

PATH Colon-separated list of folders to search for executables (e.g. `/usr/local/bin:/usr/bin:/bin:`)

HOME Path of user's home directory

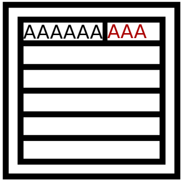
PWD The current directory

DISPLAY Identifier of the default X11 display (e.g. `:0`)

LANG Default locale (e.g. `en_US.UTF-8`)

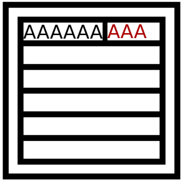
Environment Variables Problems

Buffer Overflow using Environment Variables



- Environment variables are strings ⇒ used with buffers

Buffer Overflow using Environment Variables



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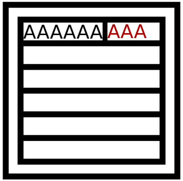

- Environment variables are strings ⇒ used with buffers
- Attacker controls length and content of environment variables
- Just a different form of user input

Practical Example: Buffer Overflow

Buffer Overflow (Environment Variable)

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

void greetings(int hello) {
    char buffer[32];
    if(hello) {
        sprintf(buffer, "Welcome %s", getenv("USER"));
    } else {
        sprintf(buffer, "Goodbye %s", getenv("USER"));
    }
    printf("%s\n", buffer);
}

int main() {
    greetings(1);
}
```

Buffer Overflow (Environment Variable)

```
% gdb ./env
(gdb) r
Starting program: /home/sasd/env
Welcome sasd
[Inferior 1 (process 14974) exited normally]
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Starting program: /home/sasd/env
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```

```
% USER=AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA; gdb ./env
(gdb) r
Starting program: /home/sasd/env
Welcome AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA

Program received signal SIGSEGV, Segmentation fault.
0x000000000040061d in greetings (hello=1) at envovf.c:12
(gdb) bt
#0  0x000000000040061d in greetings (hello=1) at envovf.c:12
#1  0x4141414141414141 in ?? ()
```

Practical Example Analysis: Buffer Overflow

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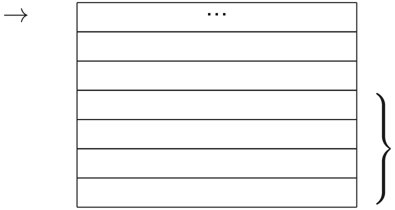

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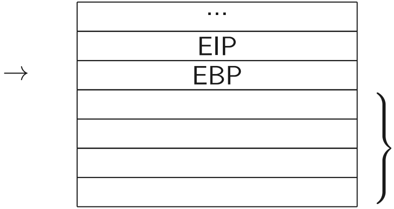

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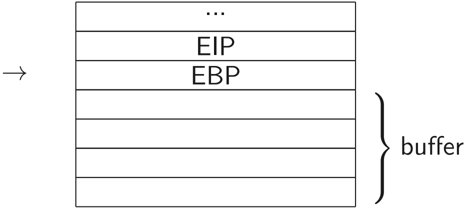

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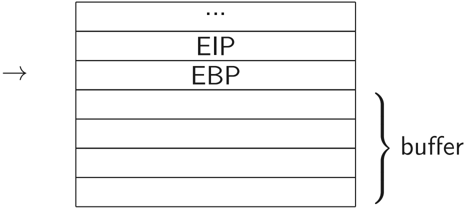

→

...

EIP

EBP

buffer

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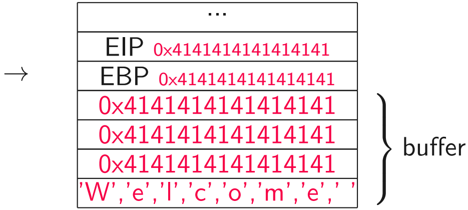

→

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EIP 0x4141414141414141

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0x4141414141414141

0x4141414141414141

0x4141414141414141

'W','e','l','c','o','m','e',' '

Practical Example Impact: Buffer Overflow

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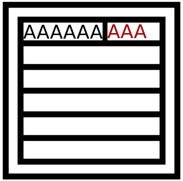

- Same impact as classical stack buffer overflow

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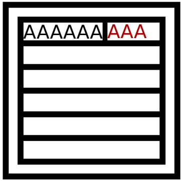

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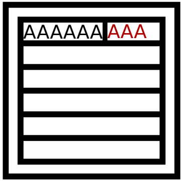

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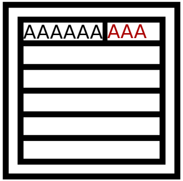
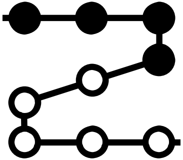


- Same impact as classical stack buffer overflow
- Attacker can jump to arbitrary location in memory
- Every function that is mapped in the address space can be executed
- Attacker has effectively full control over the program

PATH



- If a binary to execute does not have full path (e.g. /bin/ls), folders in PATH variable are searched

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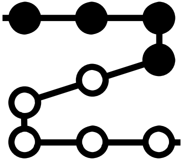

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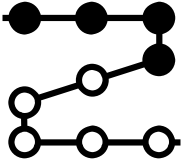

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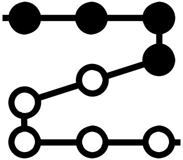

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- As soon as binary is found in one of these folders, it is executed
- Not only shell does that, but also `execlp`, `execvp`, and `system`
- Attacker might prepend folder to PATH variable

Fun Example: PATH manipulation

PATH manipulation

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

int main() {
    printf("Today: ");
    fflush(stdout);
    system("date");
}
```

PATH manipulation

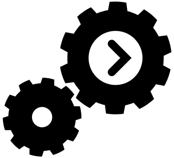
```
% cp /usr/games/fortune ./date
% ./today
Today: Fri Oct 27 13:17:34 CEST 2017
```

PATH manipulation

```
% cp /usr/games/fortune ./date
% ./today
Today: Fri Oct 27 13:17:34 CEST 2017
```

```
% export PATH=.:$PATH
% ./today
Today: It is so very hard to be an
on-your-own-take-care-of-yourself-because-there-is-no-one-else-
to-do-it-for-you grown-up.
```

LD_PRELOAD



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- Object files are loaded before anything else
- Overwrites functions in other shared libraries

Fun Example: LD_PRELOAD

LD_PRELOAD

```c
#include <stdio.h>
#include <string.h>
#include <unistd.h>
#include <sys/types.h>

int main(int argc, char* argv[]) {
    char buffer[32];
    strcpy(buffer, "ultra secret password");
    if(getuid() == 0) {
        printf("Password: %s\n", buffer);
    } else {
        printf("Only root can get the password\n");
    }
}
```

LD_PRELOAD

```
% ./secret
Only root can get the password
```

LD_PRELOAD

```
% ./secret
Only root can get the password
```

```c
#include <sys/types.h>
uid_t getuid(void)
{
  return 0;
}
```

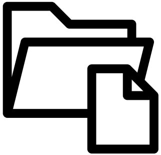
```
gcc -shared -fPIC getuid.c -o getuid.so
LD_PRELOAD=$PWD/getuid.so ./secret
Password: ultra secret password
```

Live Demo

Cheating in Tetris with LD_PRELOAD

FILE SYSTEM

File System



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- Well-known permissions read, write, and execute for owner, group members, and others
- Lesser-known permissions setuid bit, setgid bit, and sticky bit

File System Pitfalls

setuid (SUID)

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- `find / -perm -u=s -type f 2>/dev/null`

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- Files without this bit cannot be executed
- Dynamic linker/loader is obviously executable
- It can be abused as interpreter

Fun Example: Linker as Interpreter

Linker as Interpreter

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% ./hello
Hello World
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% chmod -x ./hello
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bash: ./hello: Permission denied
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% /lib64/ld-linux-x86-64.so.2 ./hello
Hello World
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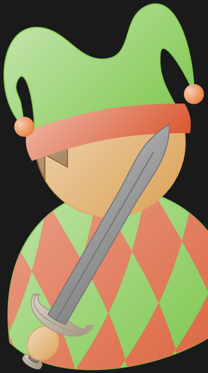
- If file can change between check and usage, this is a time-of-check-to-time-of-use (TOCTTOU) bug
- Problematic in combination with suid binaries
- Program can be tricked to read different file by exchanging it



Fun Example: File TOCTTOU

File TOCTTOU

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

int main(int argc, char* argv[]) {
  char buffer[128];
  if(access(argv[1], R_OK) != 0) {
    printf("Access denied!\n");
    exit(0);
  }
  FILE* f = fopen(argv[1], "r");
  while(fgets(buffer, sizeof(buffer), f)) {
    printf("%s", buffer);
    memset(buffer, 0, sizeof(buffer));
  }
  fclose(f);
  return 0;
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-rwsrwsr-x 1 root root
  8776 Aug 27 21:58 supercat
% ./supercat /etc/shadow
Access denied!
% touch file
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root:!:17287:0:99999:7:::
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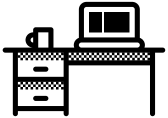
Environment Summary



- User often controls the environment

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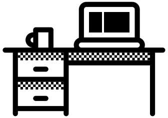

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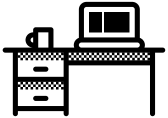

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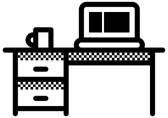

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- Never trust any input
- Consider environment properties as user input
- Environment can change during program execution → race conditions

Questions?

"It's the latest innovation in office safety.
When your computer crashes, an air bag is activated
so you won't bang your head in frustration."

Further Reading i

Jonathan Afek and Adi Sharabani.
Dangling pointer: Smashing the pointer for fun and profit.
Black Hat USA, 2007.

Azeria Labs.
Arm heap exploitation.
`https://azeria-labs.com/heap-exploitation`.

Daniel Gruss, Michael Schwarz, Matthias Wübbeling, Simon Guggi, Timo Malderle, Stefan More, and Moritz Lipp.
Use-after-freemail: Generalizing the use-after-free problem and applying it to email services.
In Proceedings of the 2018 on Asia Conference on Computer and Communications Security, 2018.

Further Reading ii

- Dhaval Kapil.
  Heap exploitation.
  https://heap-exploitation.dhavalkapil.com/attacks.
- Natalie Silvanovich, Dazed, (Type) Confused.
  One perfect bug: Exploiting type confusion in flash.
- scut / team teso.
  Exploiting format string vulnerabilities.
  https://crypto.stanford.edu/cs155/papers/formatstring-1.2.pdf.
- Shellphish.
  how2heap.
  https://github.com/shellphish/how2heap.

Further Reading iii

- Laszlo Szekeres, Mathias Payer, Tao Wei, and Dawn Song.
  Sok: Eternal war in memory.
  In 2013 IEEE Symposium on Security and Privacy, 2013.

- Jinpeng Wei and Calton Pu.
  TOCTTOU vulnerabilities in UNIX-style file systems: An anatomical study.
  2005.