Secure Software Development

Memory Corruption II & Environment

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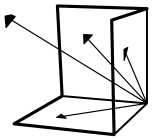
PREVIOUSLY ON

SSD

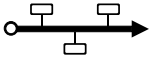
Memory Safety Violation

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)

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INVALID MEMORY

Use-after-free

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

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Use-after-free

Context 1 :

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

Context 2 :

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

Use-after-free

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use-after-free

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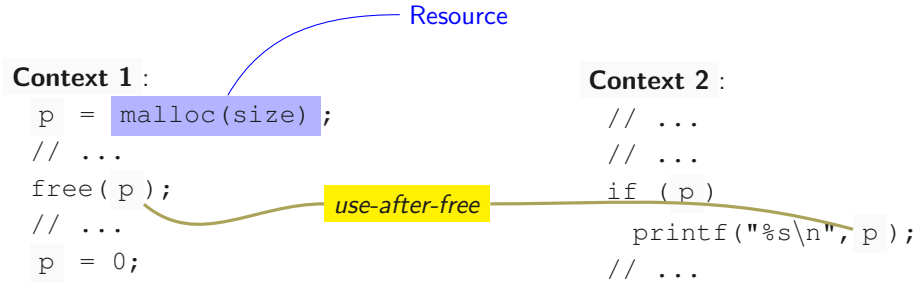

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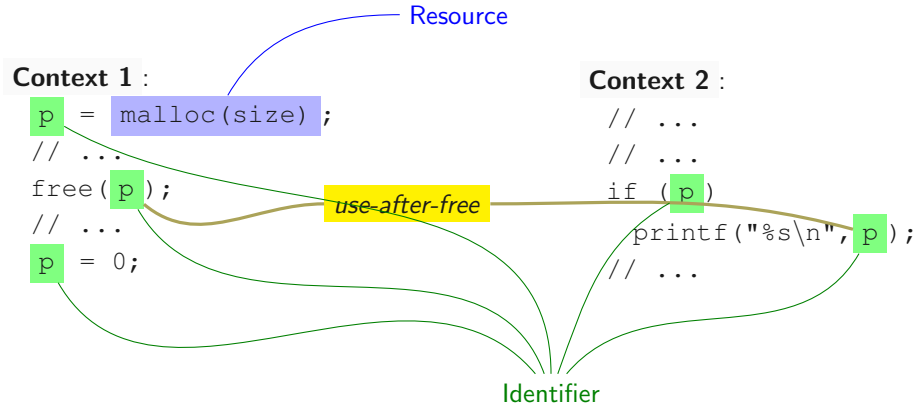

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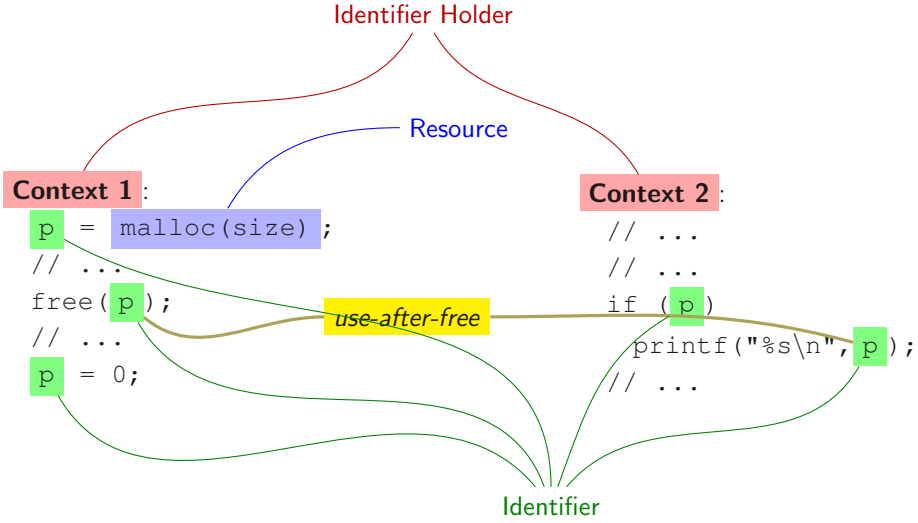

A system **can be** vulnerable to Use-after-free **iff** the system has the concept of:

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

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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]);
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% ./uaf-scope
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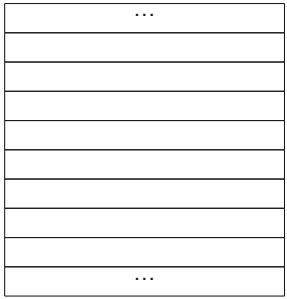
Stack



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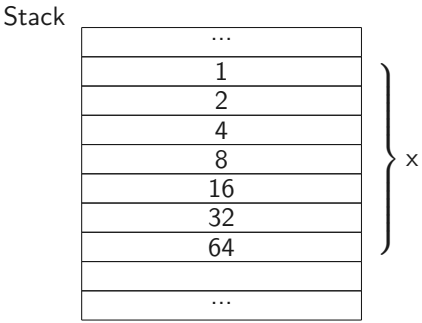

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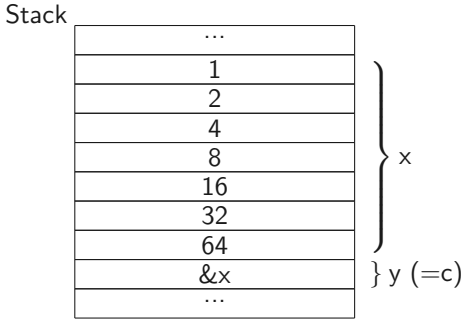

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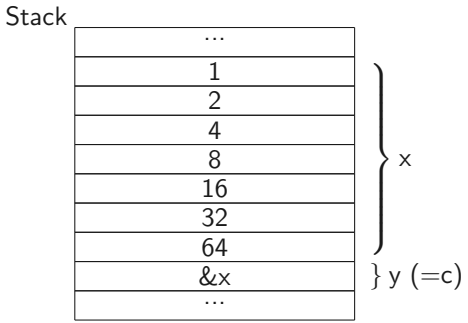

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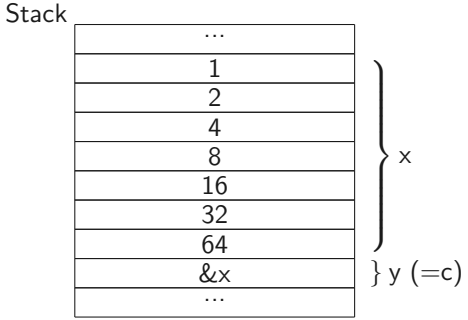

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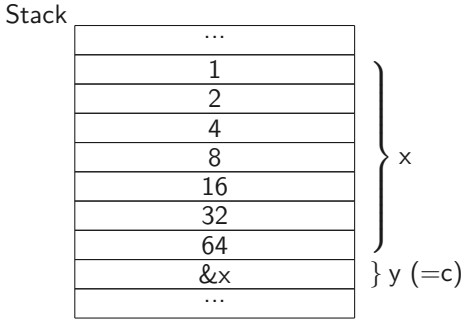

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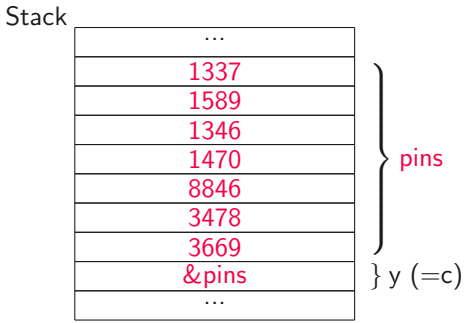

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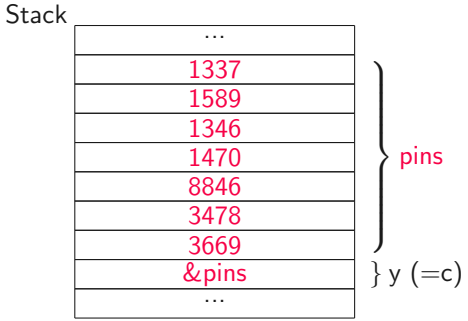

Practical Example Impact: Use-after-free

- 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

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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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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);
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Use-after-free Threads


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

Practical Example: Use-after-free

Use-after-free

```
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;
}
```


```
% 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 ?? ()
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Use-after-free

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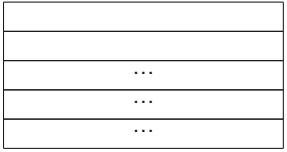

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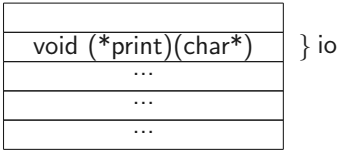

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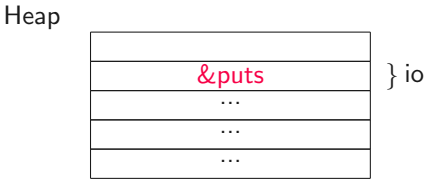

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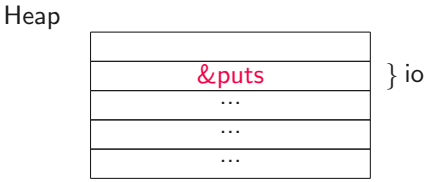


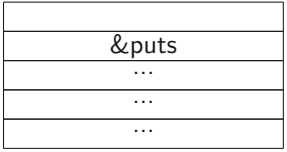
Use-after-free


```
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;
}
```

Heap



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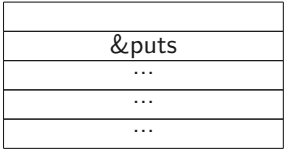

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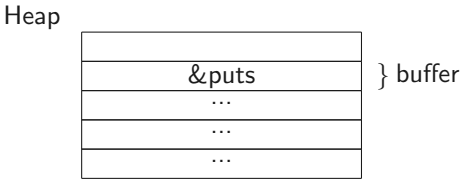

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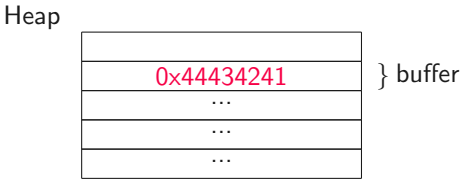

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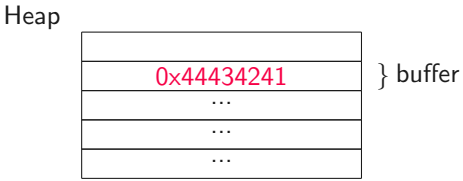

Practical Example Impact: Use-after-free

- 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

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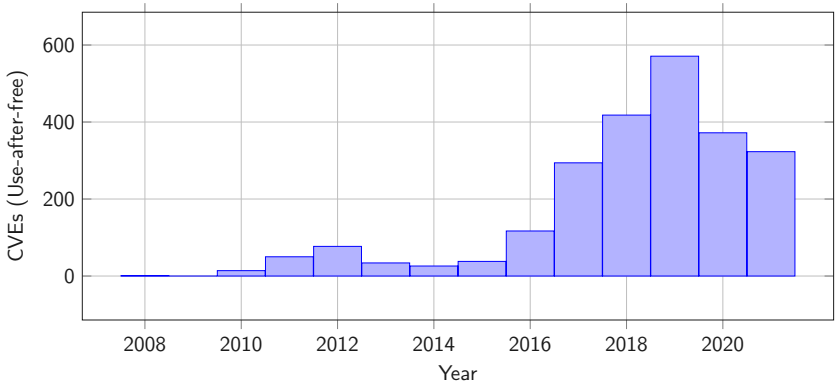
Use-after-free - CVEs per year



Use-after-free Vulnerable Systems

Resource (R)	Resource Identifier (I_R)	Identifier Holder (H_I)

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Twitter account	Twitter handle	Links, third-party websites, databases, human memory
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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

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Memory buffer	Pointer / Address	Variables
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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
- 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

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Practical Example: Double free

Double free

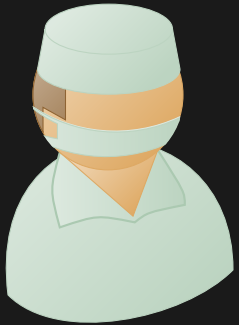

```c
int main() {
    printf("Double free demo\n");
    char* b1 = malloc(16);
    char* b2 = malloc(16);
    char* b3 = malloc(16);
    free(b1);
    free(b2);
    free(b1);

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

Variables

b1: 0x602420

Free list

Double free


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int main() {
    printf("Double free demo\n");
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        , secret, buffer);
}
```

Variables

b1: 0x602420
b2: 0x602440

Free list

Double free


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int main() {
    printf("Double free demo\n");
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        , secret, buffer);
}
```

Variables

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

Free list

Double free


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```

Variables

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

Free list

0x602420 (b1)

Double free


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}
```

Variables

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

Free list

0x602420 (b1)
0x602440 (b2)

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}
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Variables

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

Free list

0x602420 (b1)
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0x602420 (b1)

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Free list

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buffer: 0x602420 (b1)

Free list

Practical Example Impact: Double free

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- 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

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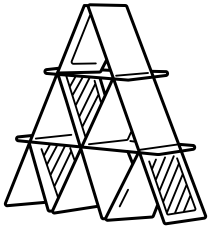

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  - Create overlapping chunks
  - Let malloc return arbitrary pointers
  - Use malloc to write to arbitrary addresses
- Common Techniques
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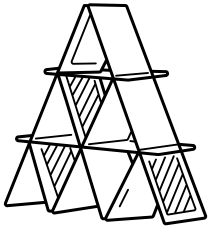
  - Overwrite metadata in free'd chunk (size/next pointer)
  - many many more (see Further Reading)



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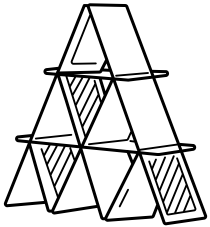

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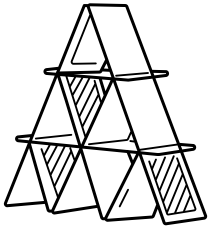

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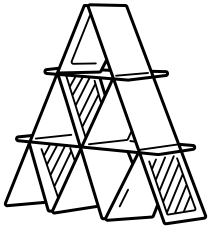

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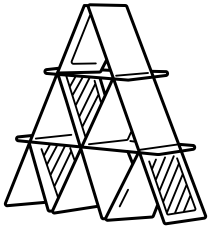

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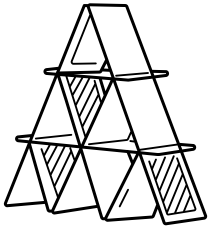

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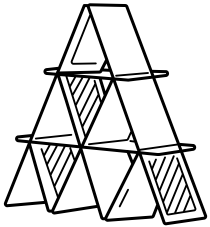

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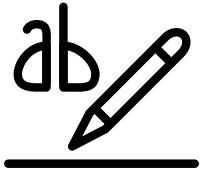
Format Strings



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

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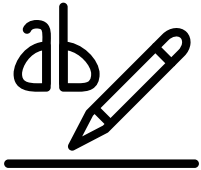

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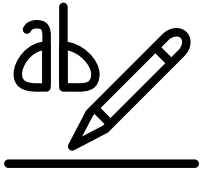

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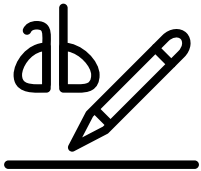

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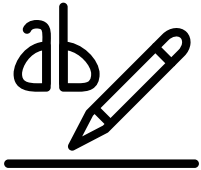

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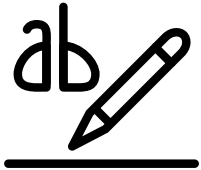

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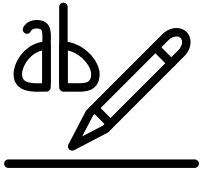

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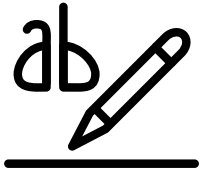

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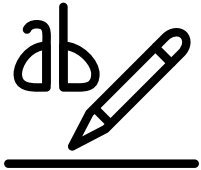

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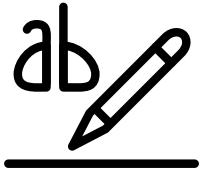

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printf(user_input);
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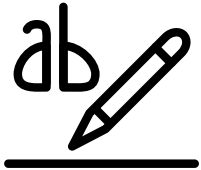

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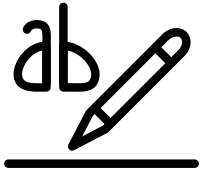

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Practical Example: Format String


```c
#include <stdio.h>

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


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

```
% ./echo "%p %p %p %p %p %p %p %p %p"
0x1 0x7fc3a4008780 0x7ffffff5 (nil) 0xb 0x7ffcb1b66db8
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Practical Example Analysis: Format String


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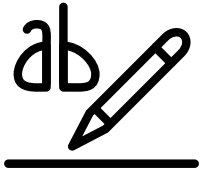

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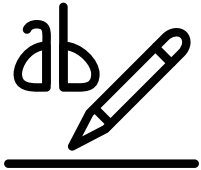

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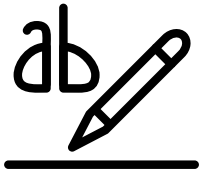

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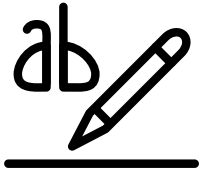

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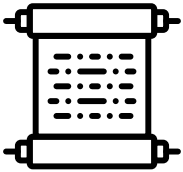

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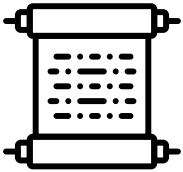

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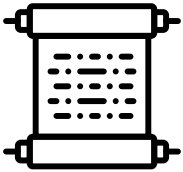

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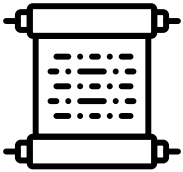

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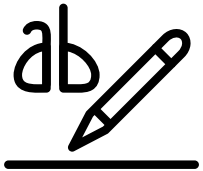

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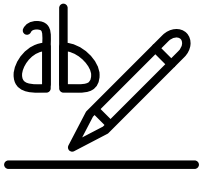

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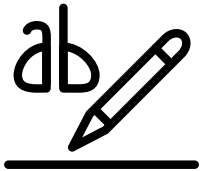

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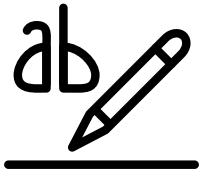

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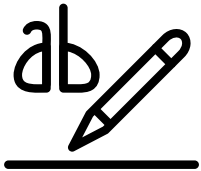

- Format string parameters `%x` and similar (e.g., `%p`, `%d`, `%z`, ...) allow to read stack contents
- `%s` dereferences arbitrary addresses on the stack and outputs contents
- Encoding target address in format string allows to read arbitrary memory location
- Thus, arbitrary addresses (both on stack and heap) can be disclosed
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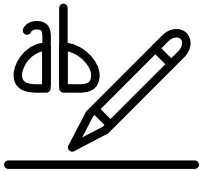

- A little-known format string parameter: `%n`

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.

- Example:

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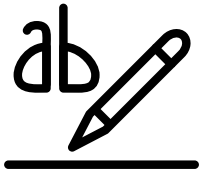
Prints `Wrote 12 characters`



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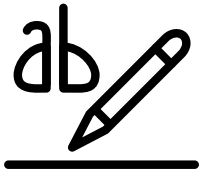

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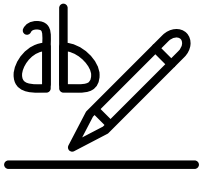

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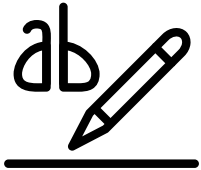

- If there is an address on the stack, we can write to it
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- Example:

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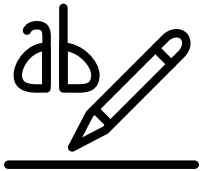
```

  Prints `Wrote 1337 characters`

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



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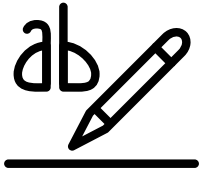

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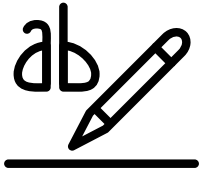

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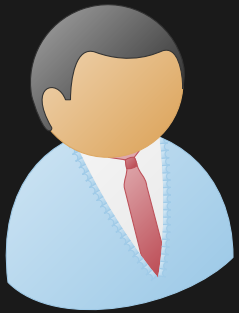
Fun Example: Format String Address Injection

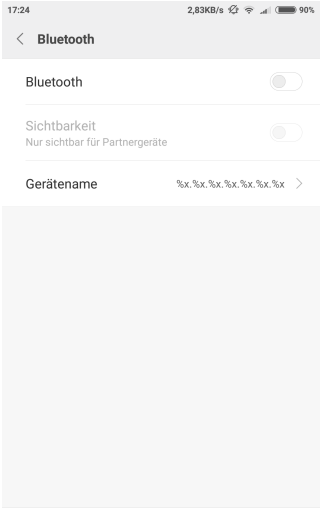

```c
#include <stdio.h>

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


```
% 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)


17:24
2,83KB/s
90%
Bluetooth
Bluetooth
Sichtbarkeit
Nur sichtbar für Partnergeräte
Gerätename
%x.%x.%x.%x.%x.%x.%x

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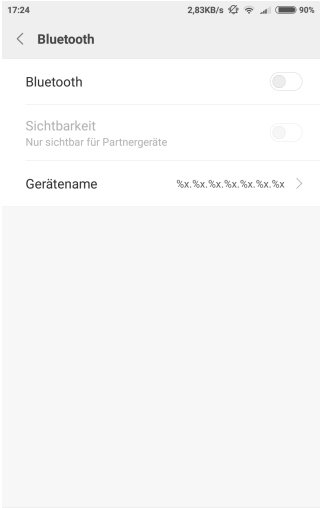

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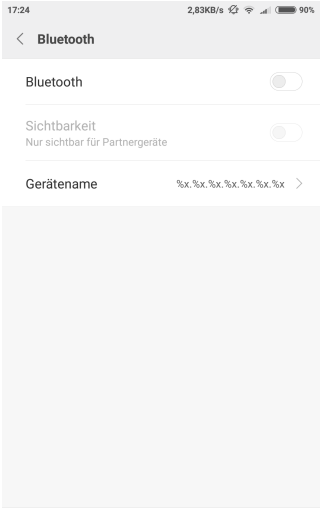


- A format string attack is possible if the user can define the format string
- Not only in `printf`, but in the whole family (`fprintf`, `snprintf`, `vsprintf`, ...)
- It allows to read (or even manipulate)
  - arbitrary memory locations
  - itself (format strings are Turing complete)
- Easily preventable: never let the user control the format string
-
```
__attribute__((format(printf, 1, 2)))
extern char *myFormatText2 (const char *, ...);
```

Find a format string to extract the binary's secret

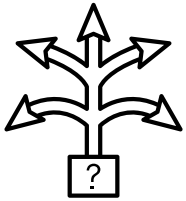
- The binary:
  `https://sasectf.student.iaik.tugraz.at/`
- Your format string has to extract the secret key (`<THE FLAG!>` in the sample code)
- Submitting the correct format string to the CTF system shows the real flag

Source

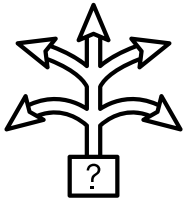
```
char secret[15] __attribute__ ((section (".secret")));
int main(int argc, char* argv[]) {
    char buffer[16];
    printf("What do you want?\n");
    strcpy(secret, "<THE FLAG!>");
    fgets(buffer, 16, stdin);
    printf(buffer);
}
```

Type Confusion

Type Confusion



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



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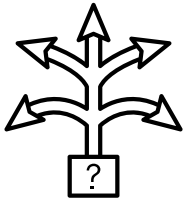

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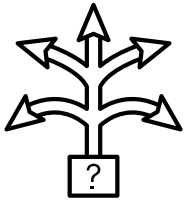

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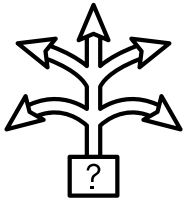

- C++ provides different types of casts
- `dynamic_cast`: Explicit type checks at runtime, but slow
- `static_cast`: Type check only at compile time, type confusion if runtime type is unexpected
- `reinterpret_cast`: Allows to explicitly break type checks

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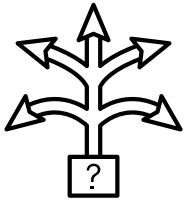

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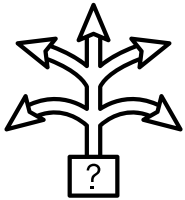

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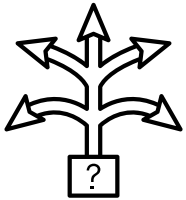

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Practical Example: Type Confusion

Type Confusion


```
#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"; };
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int main() {
  A* a = new A();
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  a = (A*)b;
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```


```
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A
B
secret
```


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Practical Example Analysis: Type Confusion

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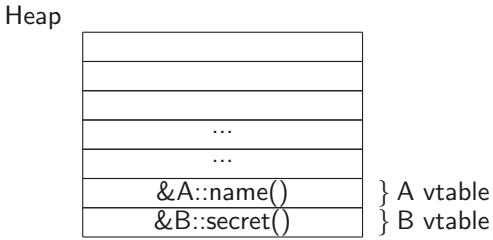

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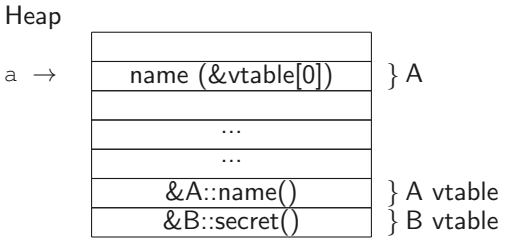

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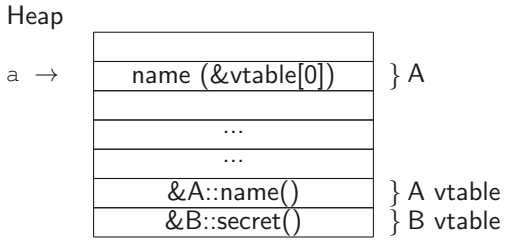

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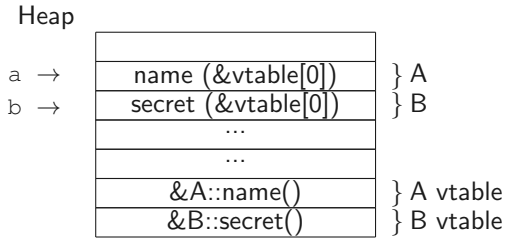

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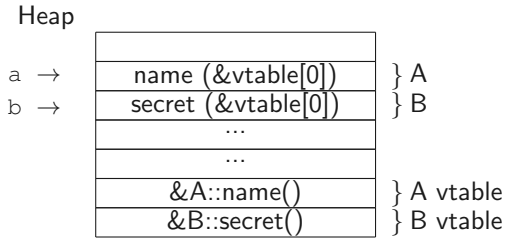

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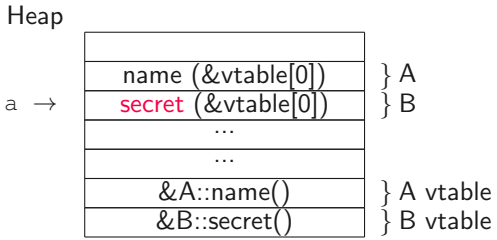

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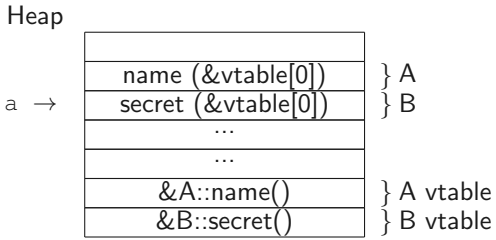
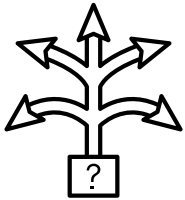



```
% ./g++ vtables.h -fdump-lang-class && cat vtables.h.001l.class
Vtable for A                          Vtable for B
A::_ZTV1A: 3 entries                  B::_ZTV1B: 3 entries
0     (int (*)(...))0                 0     (int (*)(...))0
8     (int (*)(...))(& _ZTI1A)        8     (int (*)(...))(& _ZTI1B)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



- 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
- Impacts not thoroughly studied yet...

- Type confusion bugs were exploited in many applications
  - Adobe Flash (CVE-2015-3077)
  - Microsoft Internet Explorer (CVE-2015-6184)
  - PHP (CVE-2016-3185)
  - Google Chrome (CVE-2013-0912)
- Generally play an important role in browser exploits
- You can also be like Mozilla and combine them with other bugs:

Mozilla Foundation Security Advisory 2015-39

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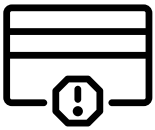

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- allow attacker to get full control over the system (more in the Exploit lecture)
- are often harder to exploit than typical overflow bugs
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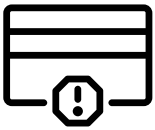

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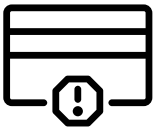

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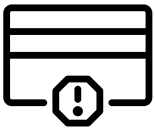

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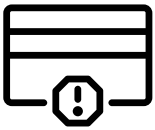

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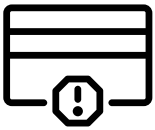

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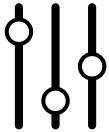
ENVIRONMENT
VARIABLES

Environment Variables



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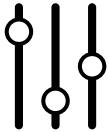

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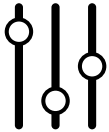

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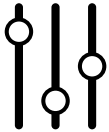

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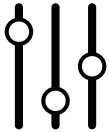

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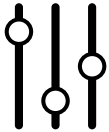

Some well-known environment variables

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

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

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Practical Example: Buffer Overflow


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

void greetings(int hello) {
    char buffer[32];
    if(hello) {
        sprintf(buffer, "Welcome %s", getenv("USER"));
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int main() {
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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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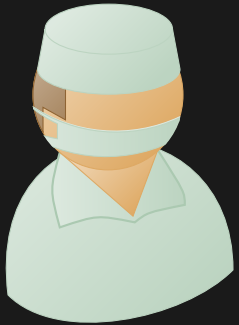

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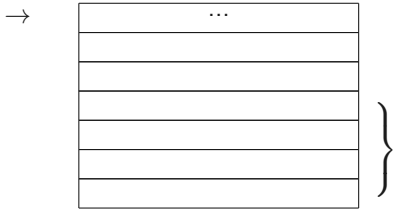


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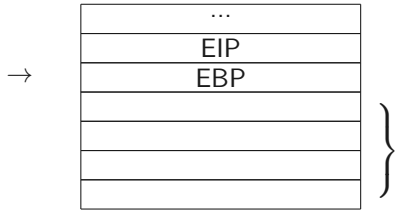

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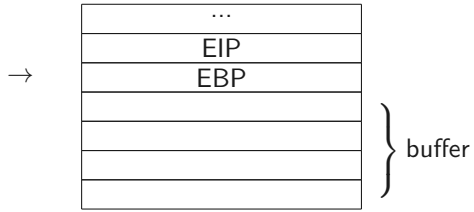

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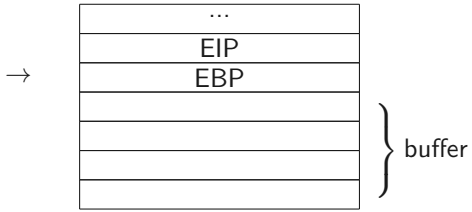

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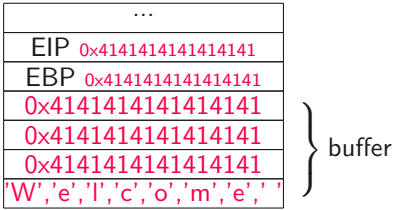

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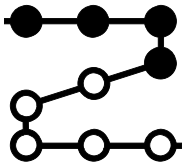

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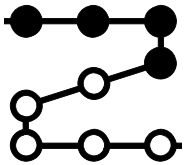

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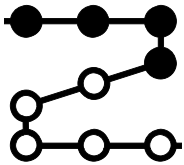

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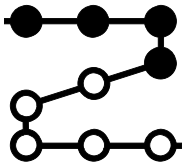

- If a binary to execute does not have full path (e.g. /bin/ls), folders in PATH variable are searched
- As soon as binary is found in one of these folders, it is executed
- Not only shell does that, but also `execlp`, `execvp`, and `system`
- Attacker might prepend folder to PATH variable

Fun Example: PATH manipulation


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

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


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

```
% 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.
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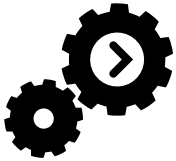
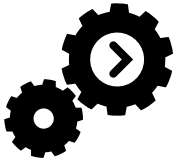


- LD_PRELOAD is used by the dynamic linker/loader
- Contains one or more ELF shared object files
- Object files are loaded before anything else
- Overwrites functions in other shared libraries



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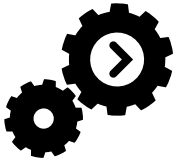

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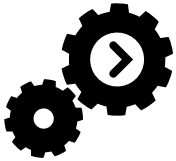

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Fun Example: LD_PRELOAD


```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");
    }
}
```


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

```c
#include <stdio.h>
char *strcpy(char *dest, const char *src) {
    printf("Copy: %s\n", src);
    while((*dest++ = *src++));
}
```

```
% gcc -shared -fPIC strcpy.c -o strcpy.so
% LD_PRELOAD=$PWD/strcpy.so ./secret
Copy: ultra secret password
Only root can get the password
```


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

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#include <stdio.h>
char *strcpy(char *dest, const char *src) {
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Live Demo

Cheating in Tetris with LD_PRELOAD


FILE SYSTEM

- File system does not only store the binaries
- Keeps track of file permissions
- Well-known permissions read, write, and execute for owner, group members, and others
- Lesser-known permissions setuid bit, setgid bit, and sticky bit

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File System Pitfalls

setuid (SUID)

- setuid: short for "set user ID upon execution"
- Runs the program with the rights of the owner (usually root) instead of the current user
- Several standard tools have suid bit set (e.g. ping)
- Exploiting a suid binary gives the attacker root privileges

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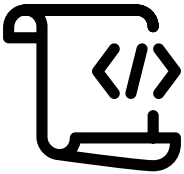
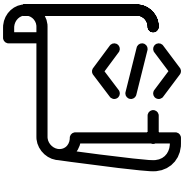
Linker as Interpreter



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



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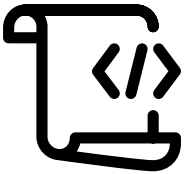

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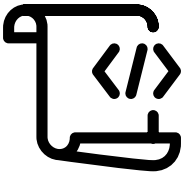

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Fun Example: Linker as Interpreter


```
% ./hello
Hello World
% chmod -x ./hello
% ./hello
bash: ./hello: Permission denied
```

```
% /lib64/ld-linux-x86-64.so.2 ./hello
Hello World
```


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% ./hello
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- File system is asynchronous, files can change
- If file can change between check and usage, this is a time-of-check-to-time-of-use (TOCTTOU) bug
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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;
}
```

```
% ls -l supercat
-rwsrwsr-x 1 root root
  8776 Aug 27 21:58 supercat
% ./supercat /etc/shadow
Access denied!
% touch file
% ./supercat file
% rm file
% ln -s /etc/shadow ./file
root:!:17287:0:99999:7:::
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Questions?


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"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."


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