CS 489 / 698
Software and Systems Security

Module 2
Program Security

Fall 2024

Secure programs

- Why is it so hard to write secure programs?
- A simple answer:
  - Axiom (Murphy):
    Programs have bugs
  - Corollary:
    Security-relevant programs have security bugs

Module outline

1. Flaws, faults, and failures
2. Unintentional security flaws
3. Malicious code: Malware
4. Other malicious code
5. Nonmalicious flaws
6. Controls against security flaws in programs

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Flaws, faults, and failures

- A flaw is a problem with a program
- A security flaw is a problem that affects security in some way
  - Confidentiality, integrity, availability
- Flaws come in two types: faults and failures
- A fault is a mistake "behind the scenes"
  - An error in the code, data, specification, process, etc.
  - A fault is a potential problem

Flaws, faults, and failures

- A failure is when something actually goes wrong
  - You log in to the library's web site, and it shows you someone else's account
  - "Goes wrong" means a deviation from the desired behaviour, not necessarily from the specified behaviour!
    - The specification itself may be wrong
- A fault is the programmer/specifier/inside view
- A failure is the user/outside view

Finding and fixing faults

- How do you find a fault?
  - If a user experiences a failure, you can try to work backwards to uncover the underlying fault
  - What about faults that haven't (yet) led to failures?
  - Intentionally try to cause failures, then proceed as above
    - Remember to think like an attacker!

Finding and fixing faults

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  - What about faults that haven't (yet) led to failures?
  - Intentionally try to cause failures, then proceed as above
    - Remember to think like an attacker!
- Once you find some faults, fix them
  - Usually by making small edits (patches) to the program
  - This is called "penetrate and patch"
  - Microsoft's "Patch Tuesday" is a well-known example

Problems with patching

- Patching sometimes makes things worse!
- Why?

Problems with patching

- Patching sometimes makes things worse!
- Reasons:
  - Pressure to patch a fault is often high, causing a narrow focus on the observed failure, instead of a broad look at what may be a more serious underlying problem
  - The fault may have caused other, unnoticed failures, and a partial fix may cause inconsistencies or other problems
  - The patch for this fault may introduce new faults, here or elsewhere!

- Alternatives to patching?

Unexpected behaviour

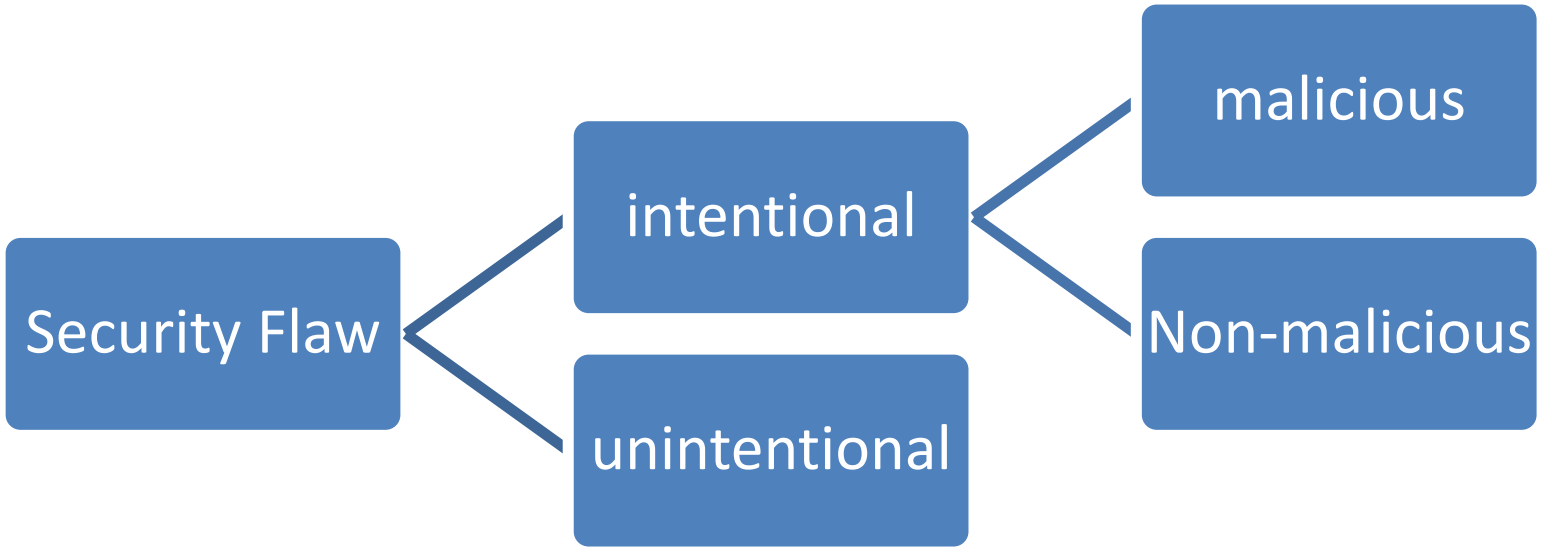
- When a program's behaviour is specified, the spec usually lists the things the program must do
  - The `ls` command must list the names of the files in the directory whose name is given on the command line, if the user has permissions to read that directory
- Most implementors wouldn't care if it did additional things as well
  - Sorting the list of filenames alphabetically before outputting them is fine

Unexpected behaviour

- But from a security / privacy point of view, extra behaviours could be bad!
  - After displaying the filenames, post the list to a public web site
  - After displaying the filenames, delete the files
- When implementing a security or privacy relevant program, you should consider “and nothing else” to be implicitly added to the spec
  - “should do” vs. “shouldn’t do”
  - How would you test for “shouldn’t do”?

Types of security flaws

- One way to divide up security flaws is by genesis (where they came from)



Types of security flaws

- One way to divide up security flaws is by genesis (where they came from)
- Some flaws are intentional/inherent
  - Malicious flaws are intentionally inserted to attack systems, either in general, or certain systems in particular
    - If it's meant to attack some particular system, we call it a targeted malicious flaw
  - Nonmalicious (but intentional or inherent) flaws are often features that are meant to be in the system, and are correctly implemented, but nonetheless can cause a failure when used by an attacker
- Most security flaws are caused by unintentional program errors

Types of security flaws

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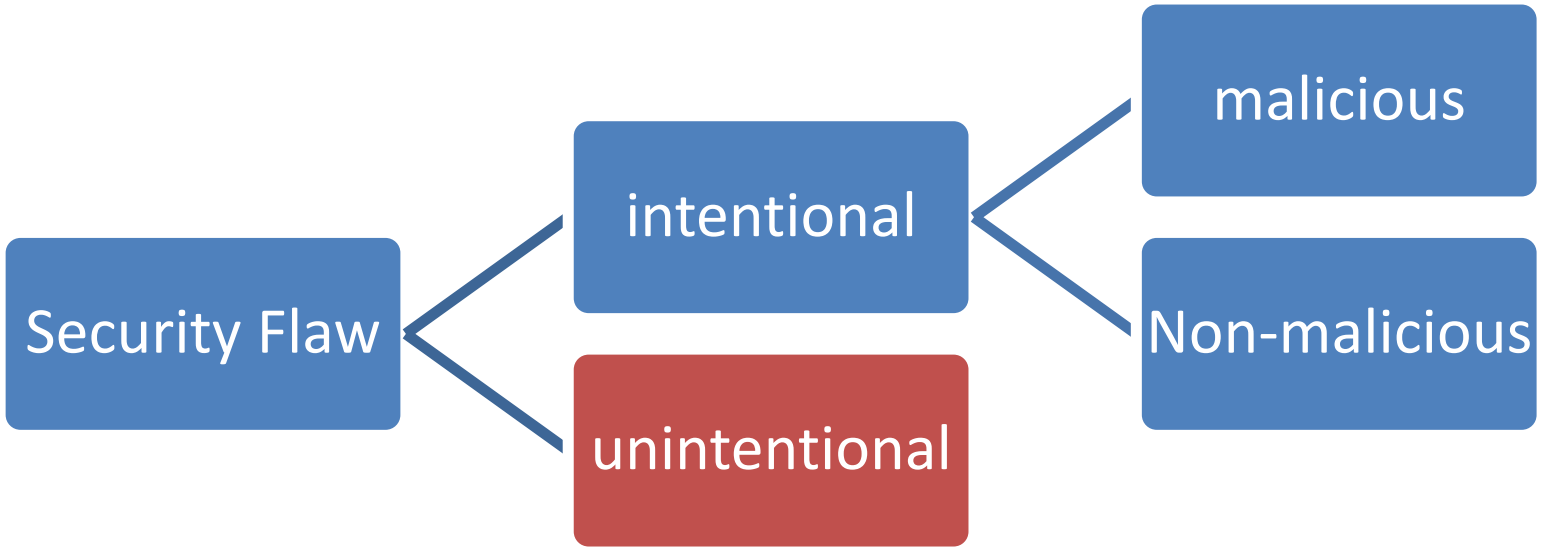

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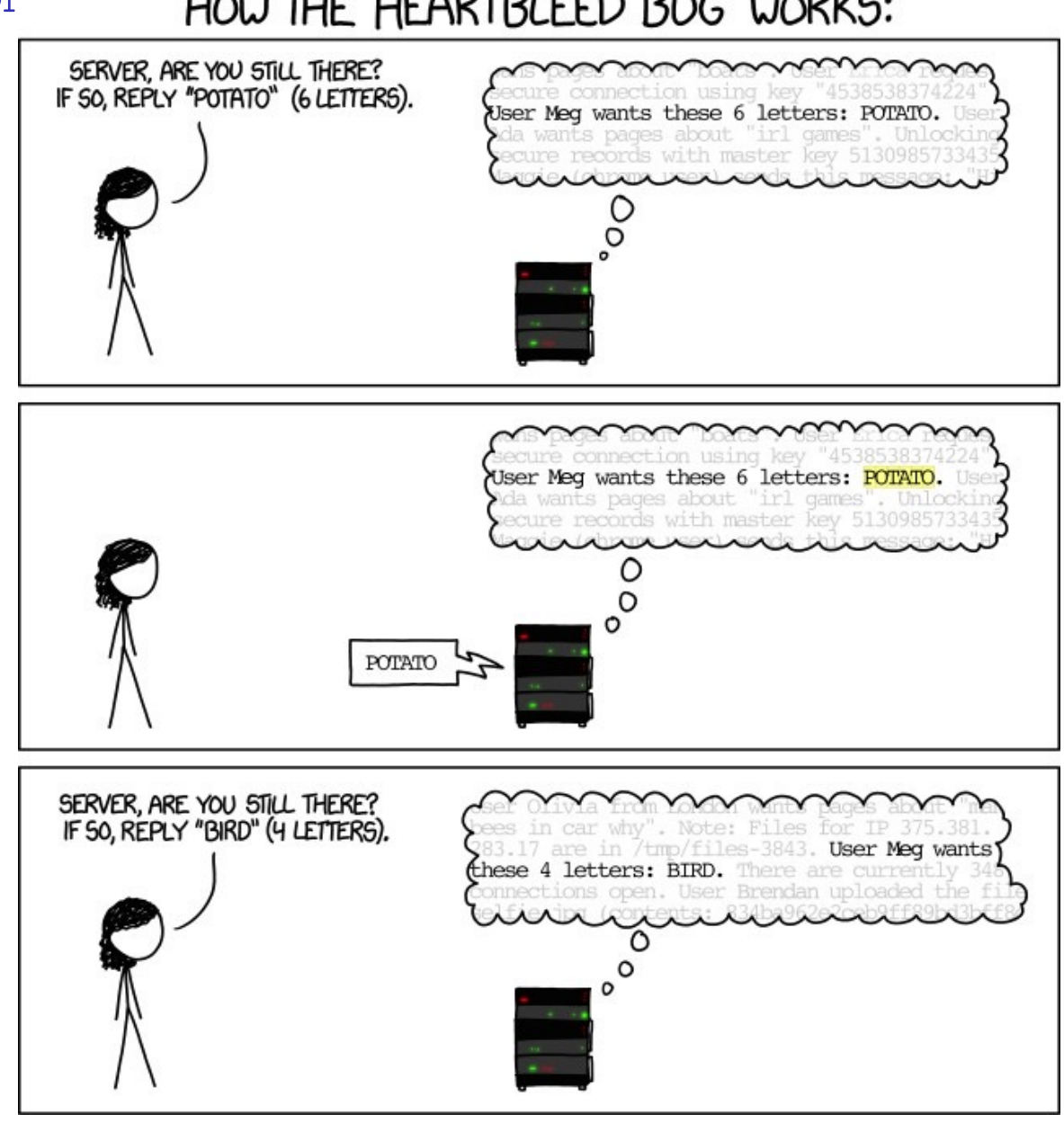
The Heartbleed Bug in OpenSSL (April 2014)

- The TLS Heartbeat mechanism is designed to keep SSL/TLS connections alive even when no data is being transmitted.
- Heartbeat messages sent by one peer contain random data and a payload length.
- The other peer is suppose to respond with a mirror of exactly the same data.

http://imgs.xkcd.com/comics/heartbleed_explanation...



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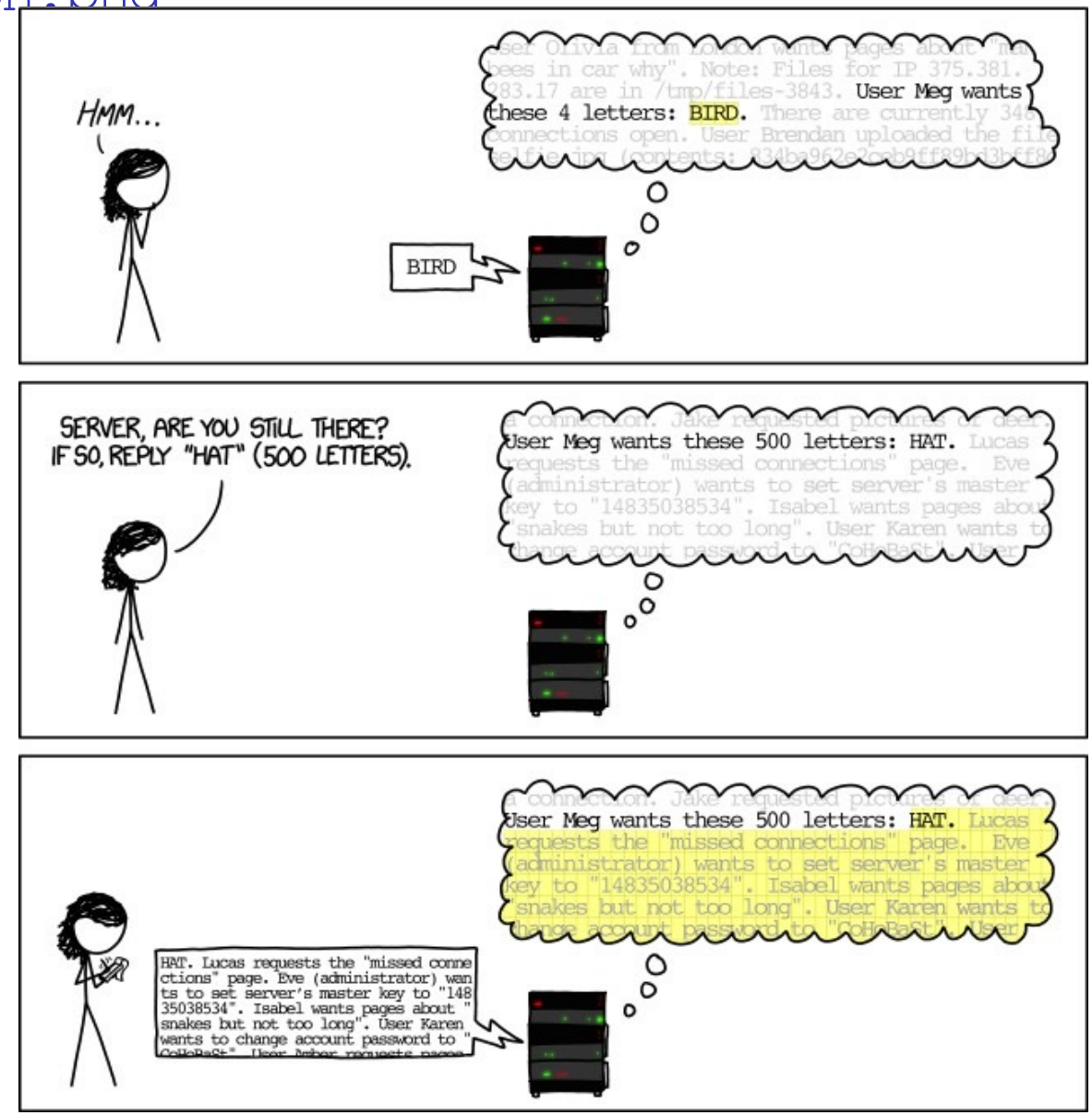


The Heartbleed Bug in OpenSSL (April 2014)

- There was a missing bounds check in the code.
- An attacker can request that a TLS server hand over a relatively large slice (up to 64KB) of its private memory space.
- This is the same memory space where OpenSSL also stores the server's private key material as well as TLS session keys.

Apple's SSL/TLS Bug (February 2014)

- The bug occurs in code that is used to check the validity of the server's signature on a key used in an SSL/TLS connection.
- This bug existed in certain versions of OSX 10.9 and iOS 6.1 and 7.0.
- An active attacker (a "man-in-the-middle") could potentially exploit this flaw to get a user to accept a counterfeit key that was chosen by the attacker.

The Buggy Code

```
static OSStatus
SSLVerifySignedServerKeyExchange(SSLContext *ctx, bool isRsa, SSLBuffer signedParams,
                                 uint8_t *signature, UInt16 signatureLen)
{
        OSStatus        err;
        ...

        if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
                goto fail;
        if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
                goto fail;
                goto fail;
        if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
                goto fail;
        ...

fail:
        SSLFreeBuffer(&signedHashes);
        SSLFreeBuffer(&hashCtx);
        return err;
}
```

What's the Problem?

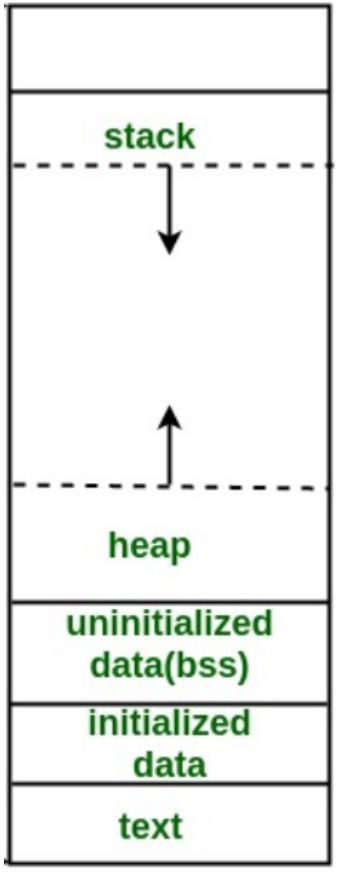
- There are two consecutive `goto fail` statements.
- The second `goto fail` statement is always executed if the first two checks succeed.
- In this case, the third check is bypassed and 0 is returned as the value of `err`.

Types of unintentional flaws

- Buffer overflows
- Integer overflows
- Incomplete mediation
- Format string vulnerabilities
- TOCTTOU errors

What does the memory layout of a process look like?

- Program code (Text)
- Global data (BSS and data segments)
- Dynamically allocated data (Heap)
- Function call data (Stack)



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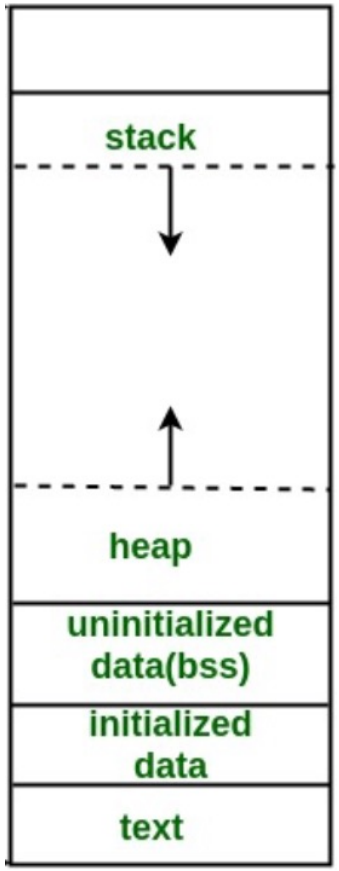
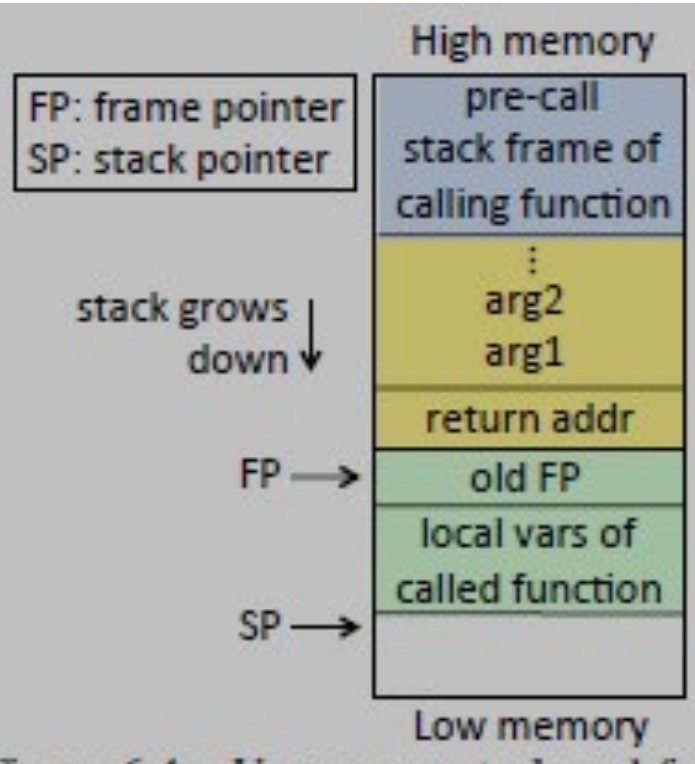



```c
int admin_id = 1000;
int main()
{
        int user_id;
        static int default_id;

        int *pin = (int*) malloc(2*sizeof(int));
        pin[0] = 1;
        pin[1] = 1;
```

What happens in stack during a function call?

Function Calls



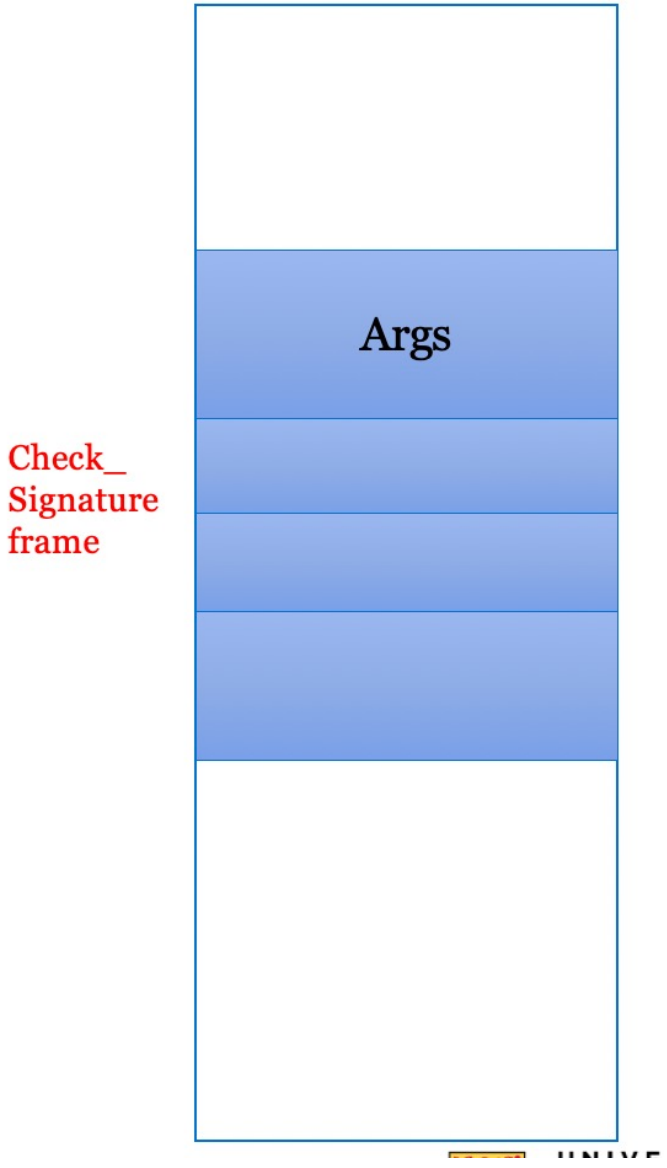
1. calling function pushes args onto stack
2. "call" opcode pushes Instruction Pointer (IP) as return address, then sets IP to begin executing code in called function
3. called function pushes FP for later recovery
4. FP ← SP (so FP points to old FP), now FP+k = args, FP-k = local vars
5. decrement SP, making stack space for local vars
6. called function executes until ready to return
7. called function cleans up stack before return (SP ← FP , FP ← old FP popped from stack)
8. "ret" opcode pops return address into IP, to resume execution back to calling function

Figure 6.4: User-space stack and function call sequence (x86 conventions). FP is also called BP (Base Pointer). Register state may also be saved onto the stack (not shown).

(Source: van Oorschot textbook, Chapter 6, https://people.scs.carleton.ca/~paulv/toolsjewels.html)

Buffer overflows

```
int check_signature(char *str, int j)
{
        int i = 0;
        char user_signature[24];
        strcpy(user_signature, str);
```



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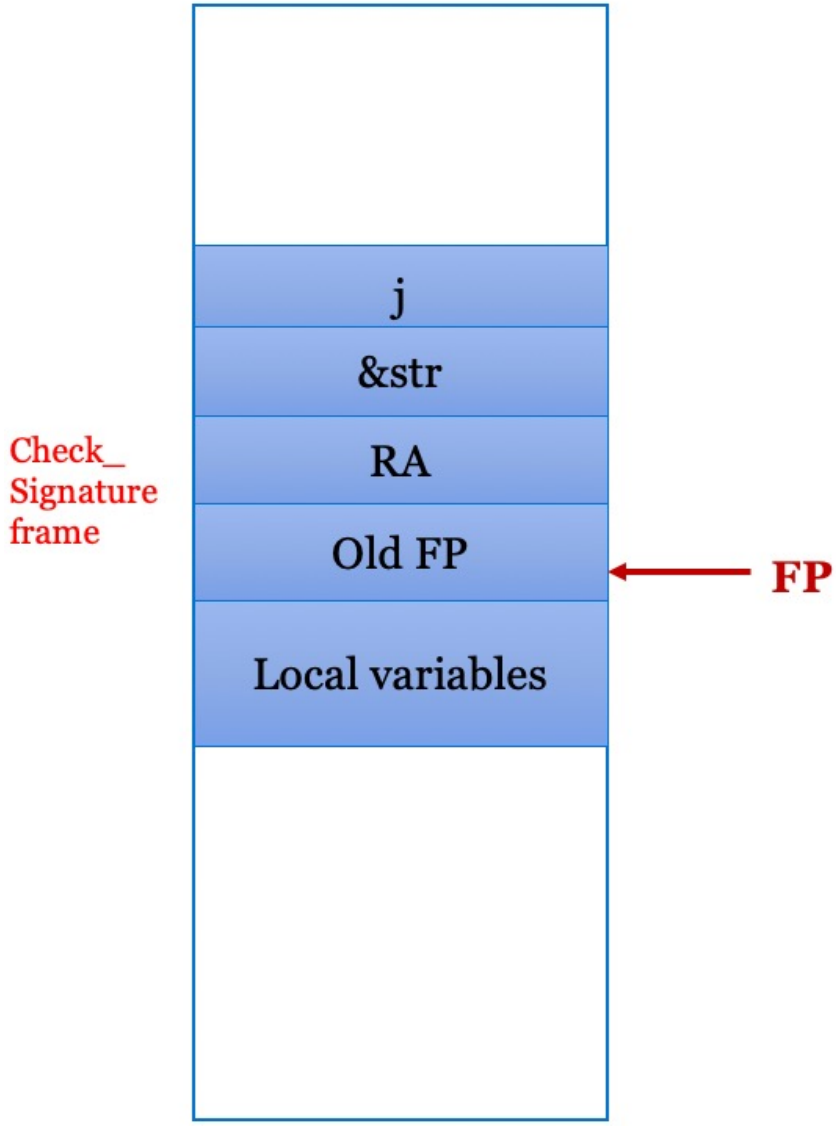

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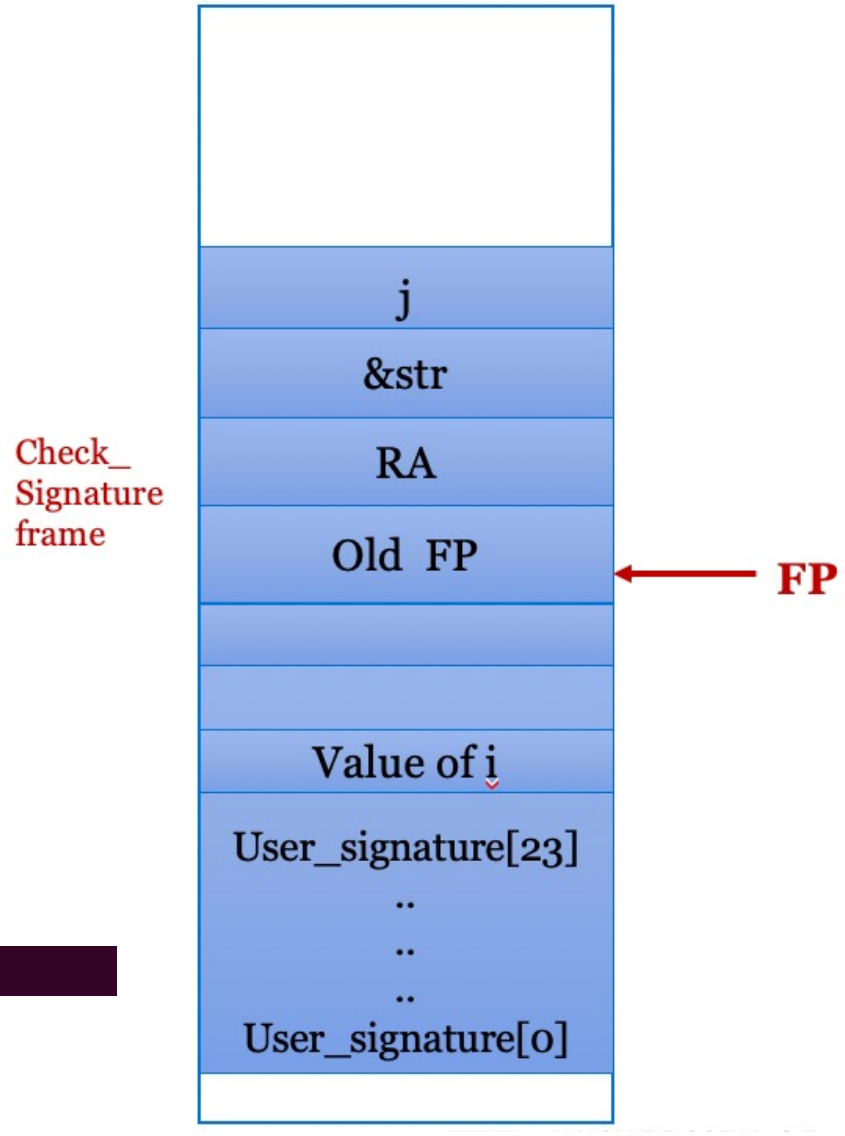
```

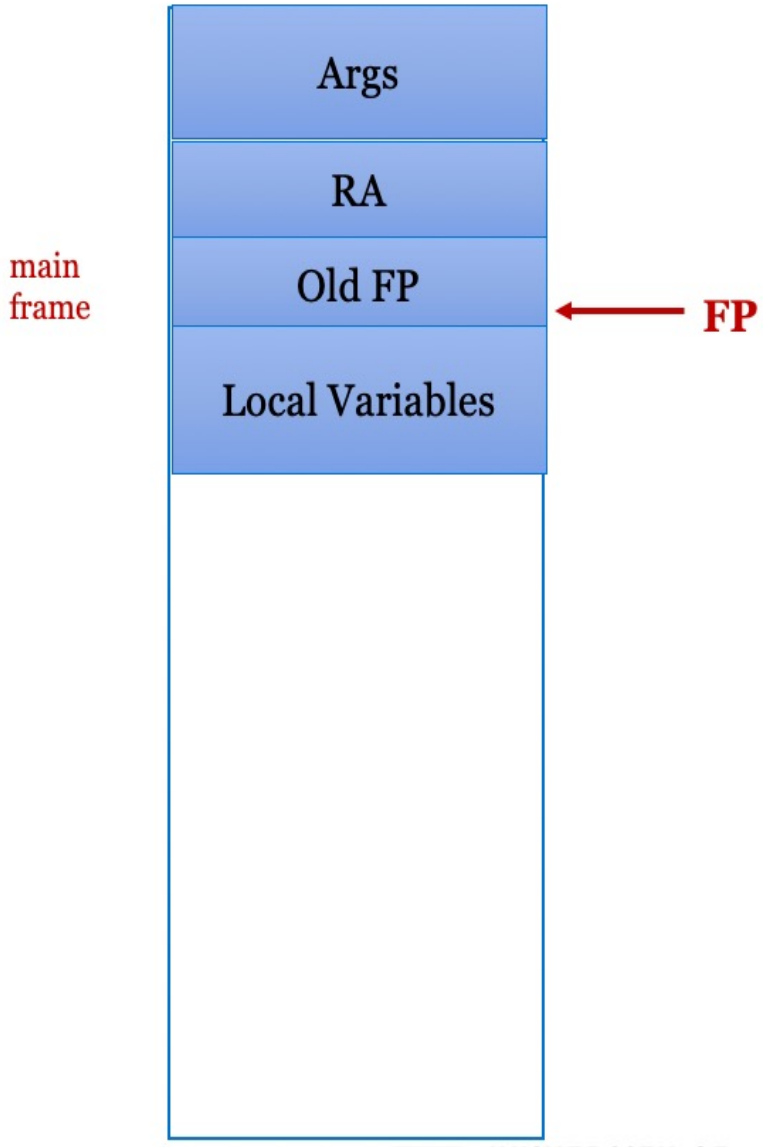
```
0x080484cb <+6>:     movl   $0x0,-0xc(%ebp)
```



Buffer overflows

```c
int check_signature(char *str)
{
        int i = 0;
        char user_signature[24];
        strcpy(user_signature, str);

        if(isValid(user_signature))
                i = 1;
        return i;
}
int main()
{
        char user_signature[240];
        // read user signature
        FILE *signature_file;
        signature_file = fopen("signature", "r");
        fread(user_signature, sizeof(char), 240, signature_file);
        // check if user_signature is equal to the system_signature
        int i  = check_signature(user_signature);
```



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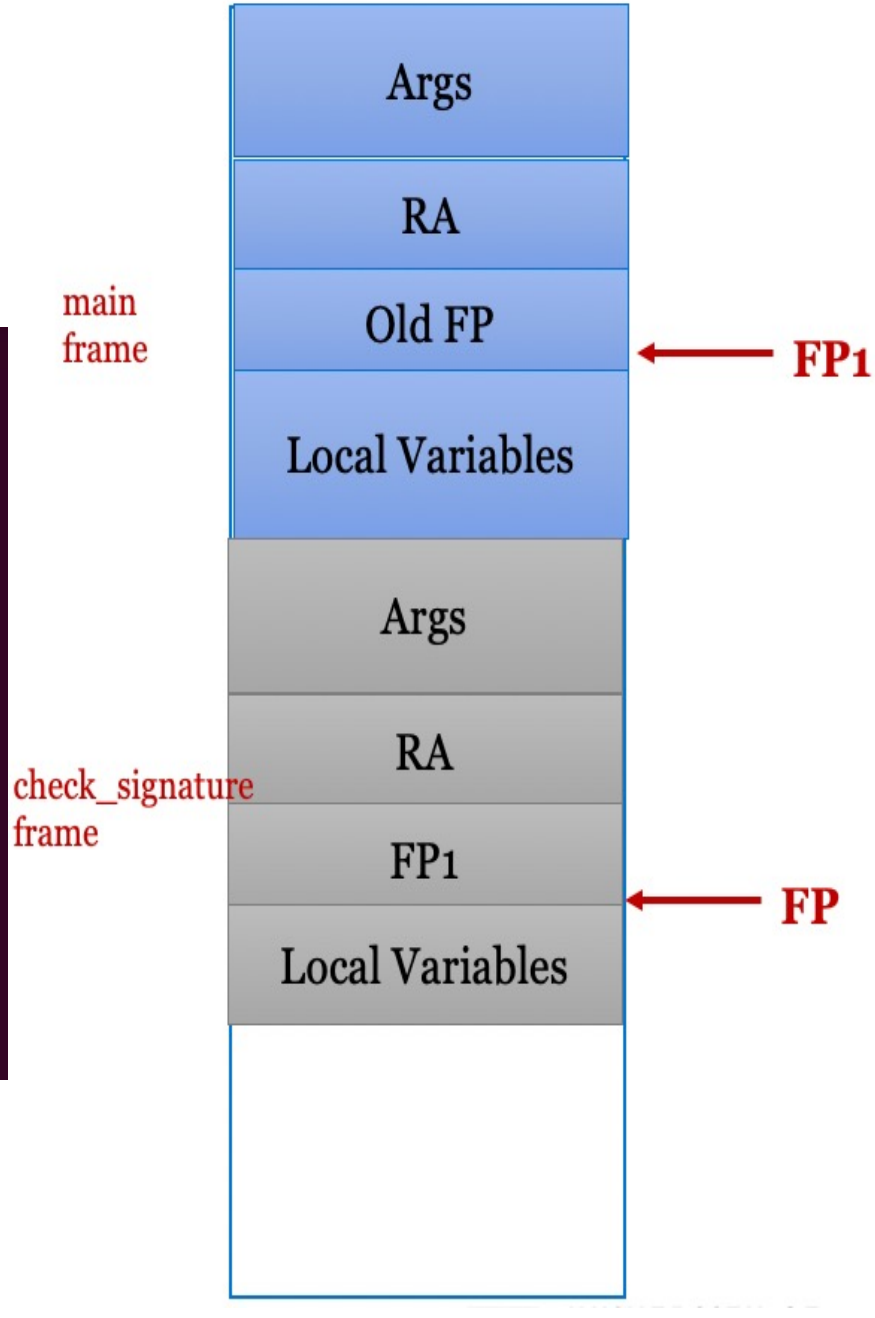

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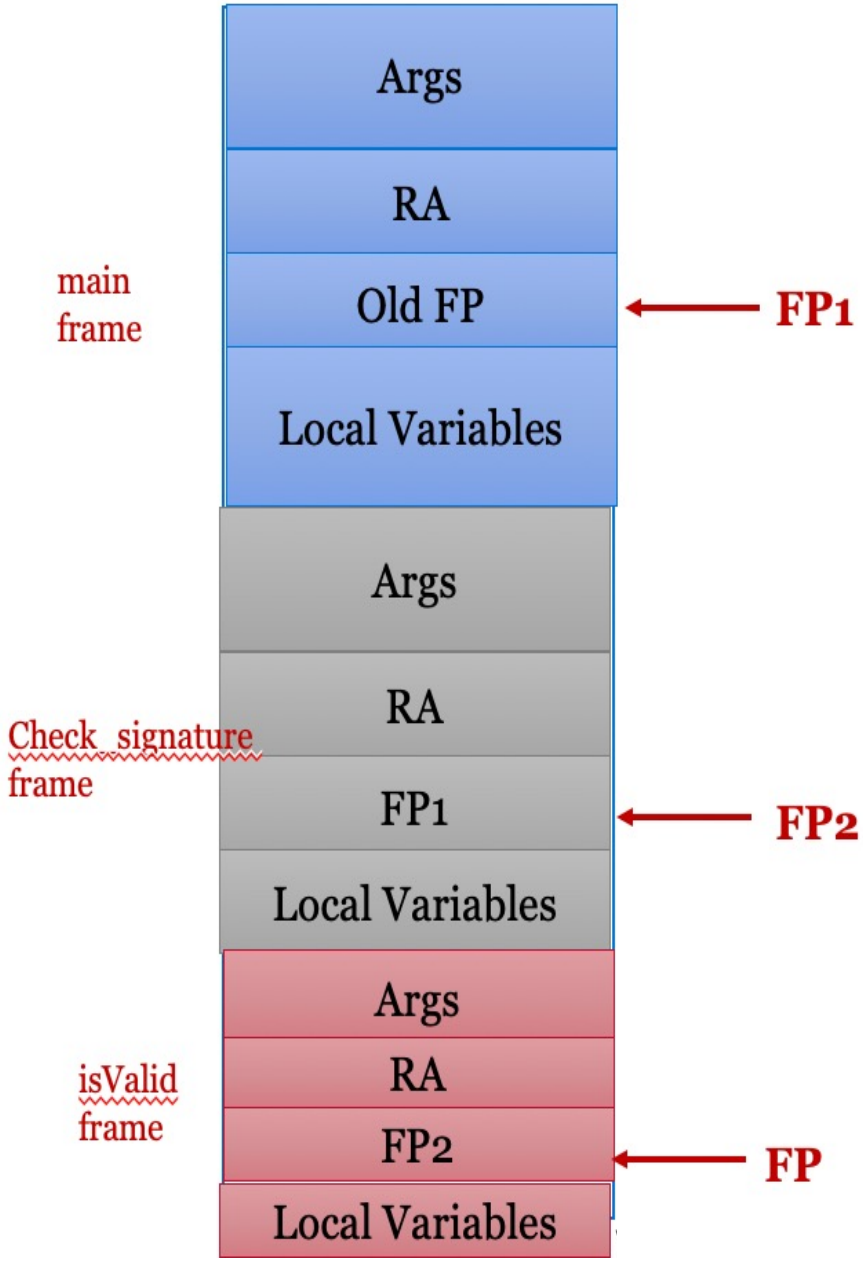

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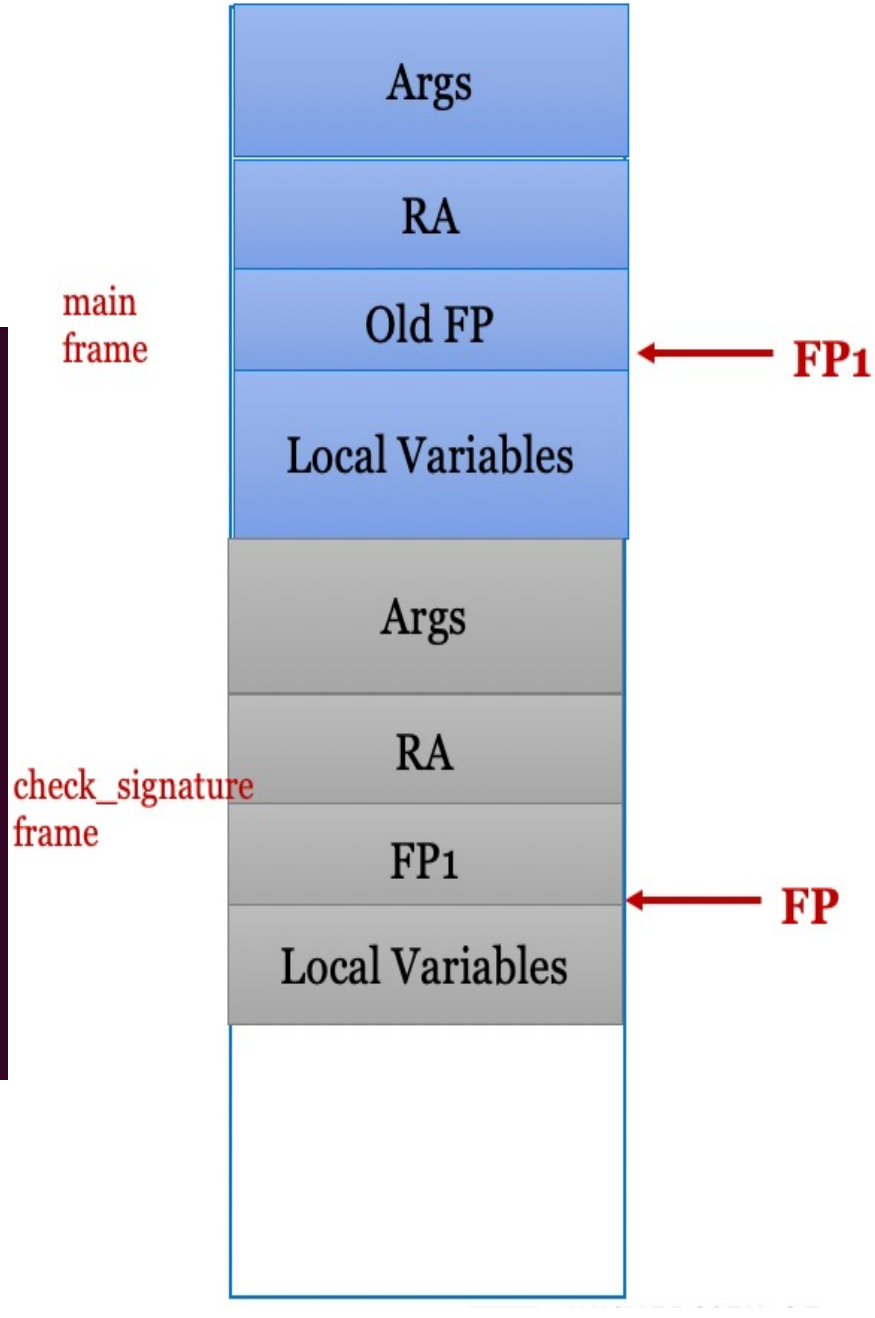


Buffer overflows

- The single most commonly exploited type of security flaw
- Simple example:

```
#define LINELEN 1024

char buffer[LINELEN];

gets(buffer);
```

or

```
strcpy(buffer, argv[1]);
```

What happens when strlen(buffer) < strlen(argv[1])?

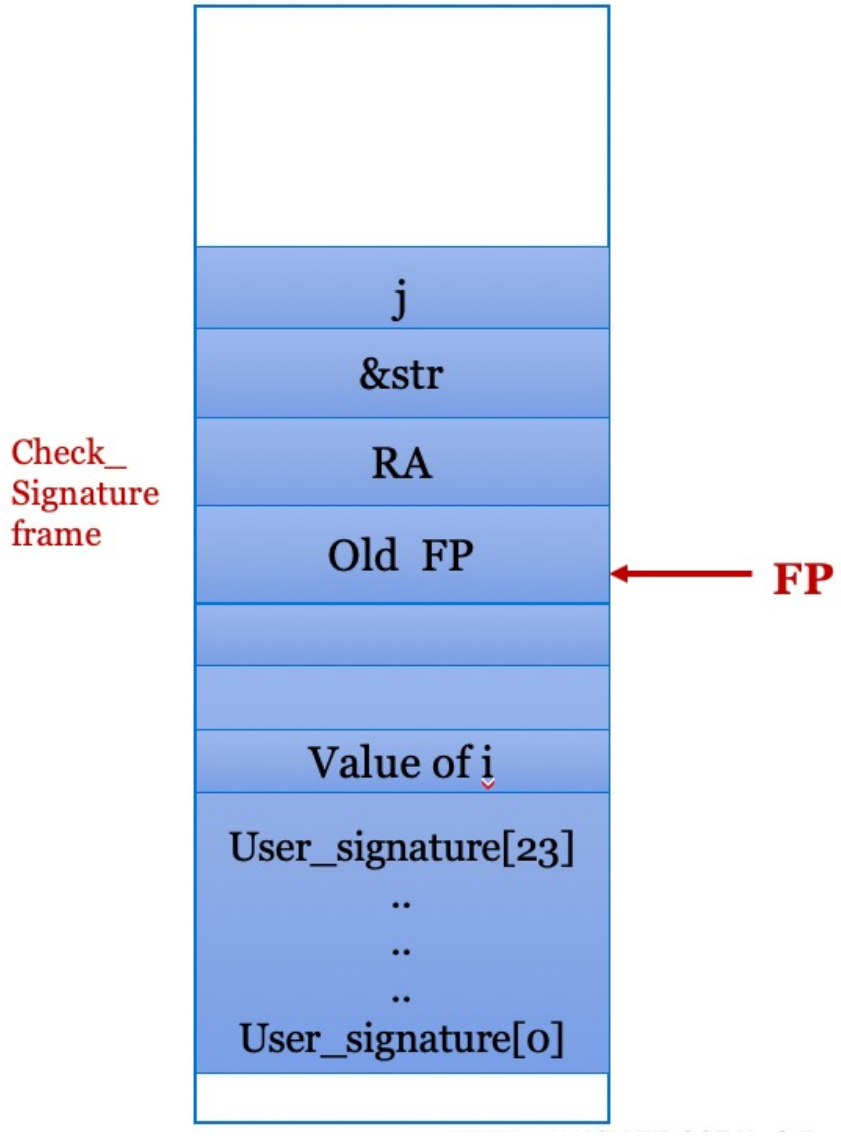
What's the problem?

- The `gets` and `strcpy` functions don't check that the string they're copying into the buffer will fit in the buffer!
- So?
- Some languages would give you some kind of exception here, and crash the program
  - Is this an OK solution?
- Not C (the most commonly used language for systems programming). C doesn't even notice something bad happened, and continues on its merry way

Buffer overflows

```
int check_signature(char *str, int j)
{
        int i = 0;
        char user_signature[24];
        strcpy(user_signature, str);
```

Str = "randomStringLongerthan24bytes ...."";



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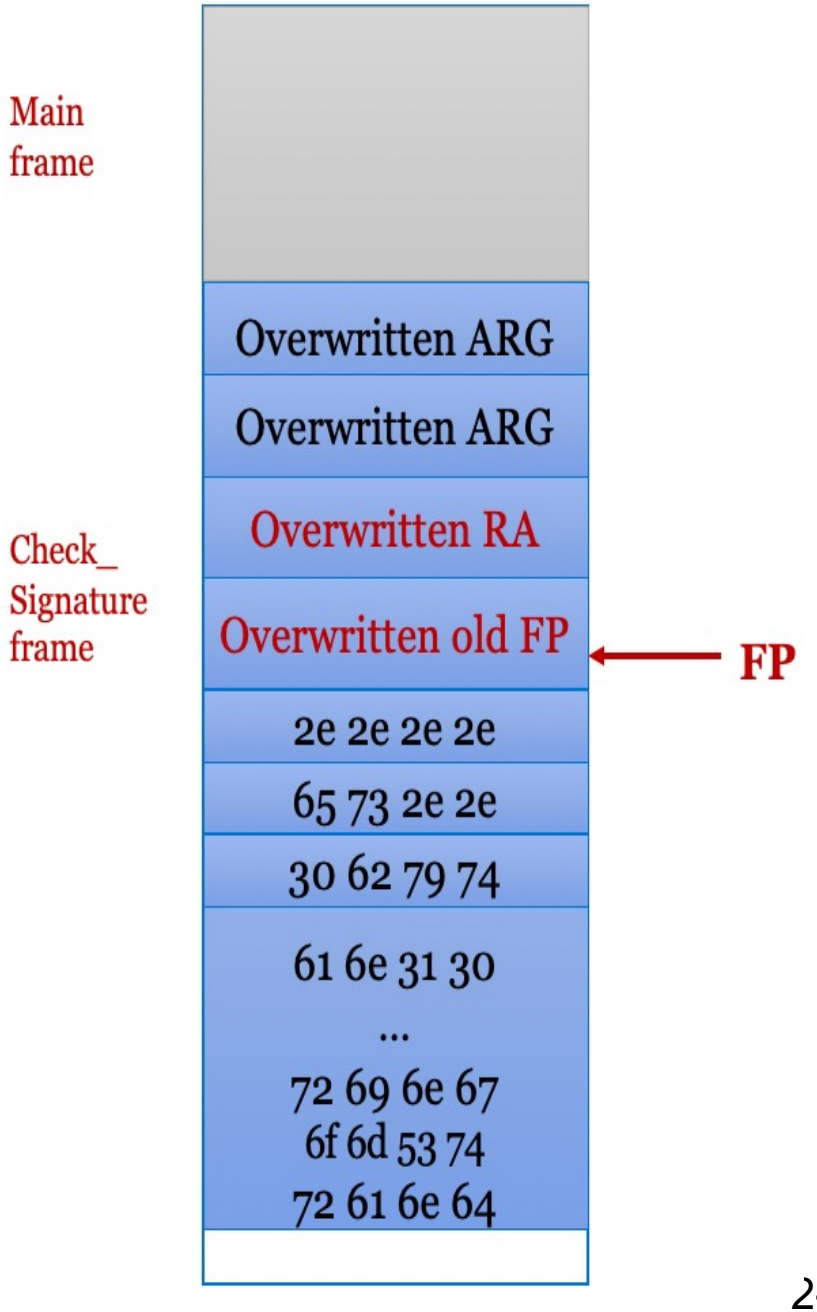

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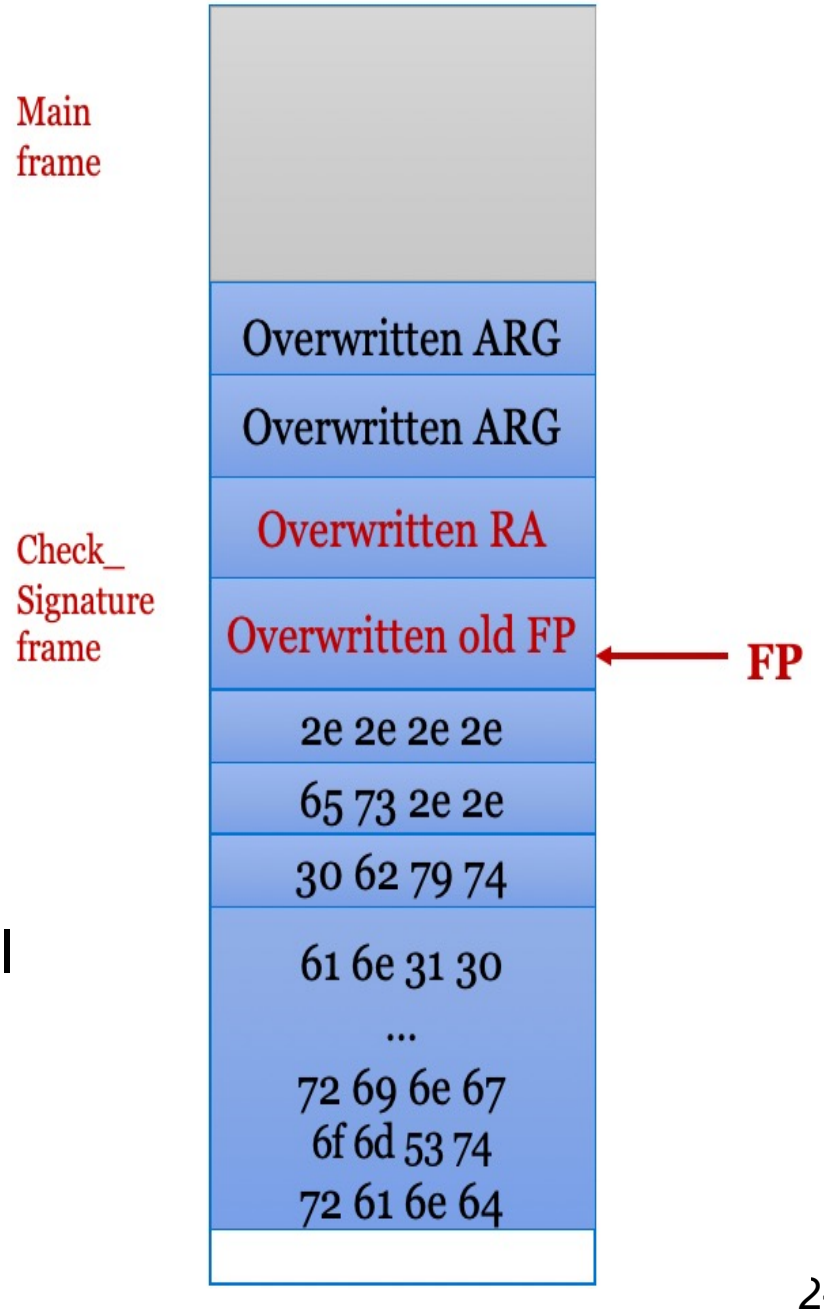

- Segmentation faults or illegal instruction errors

Buffer overflows

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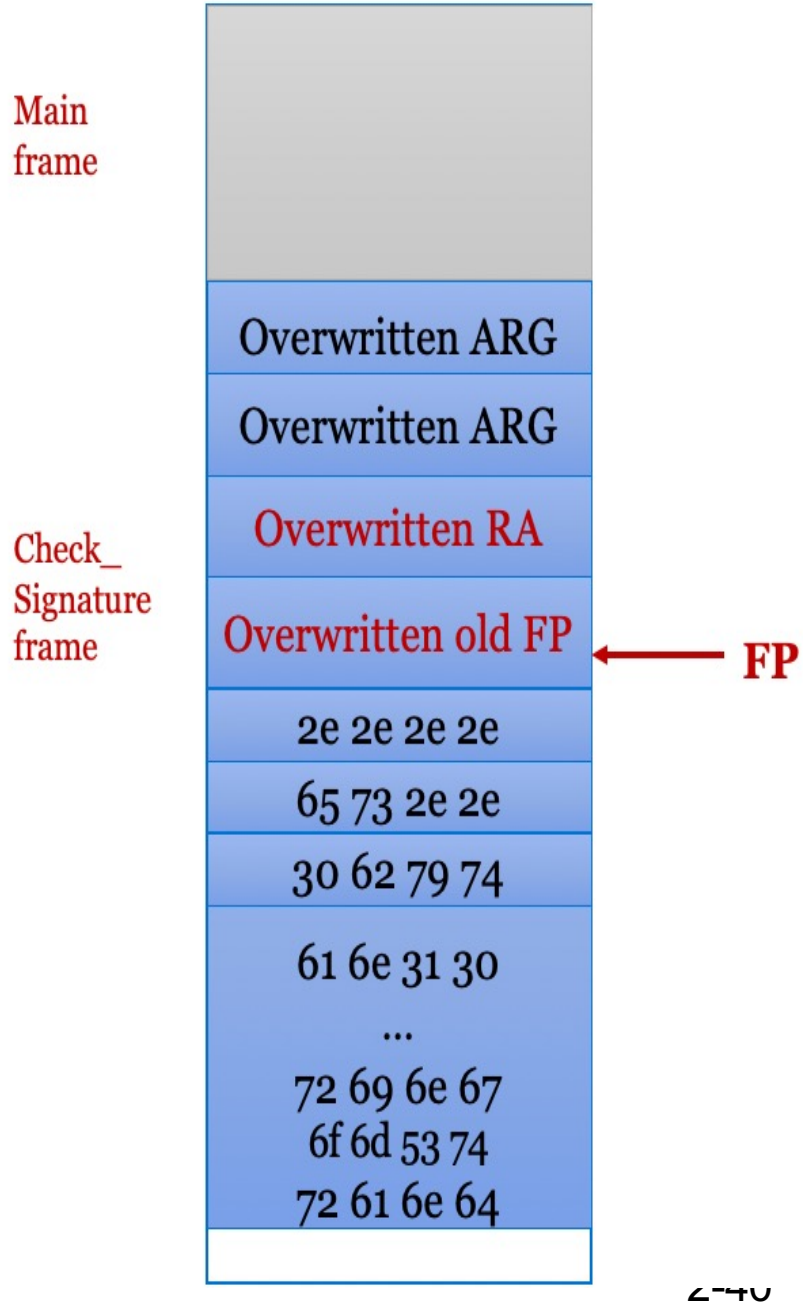
        strcpy(user_signature, str);
```

**Str = "randomStringLongerthan24bytes ...."; **



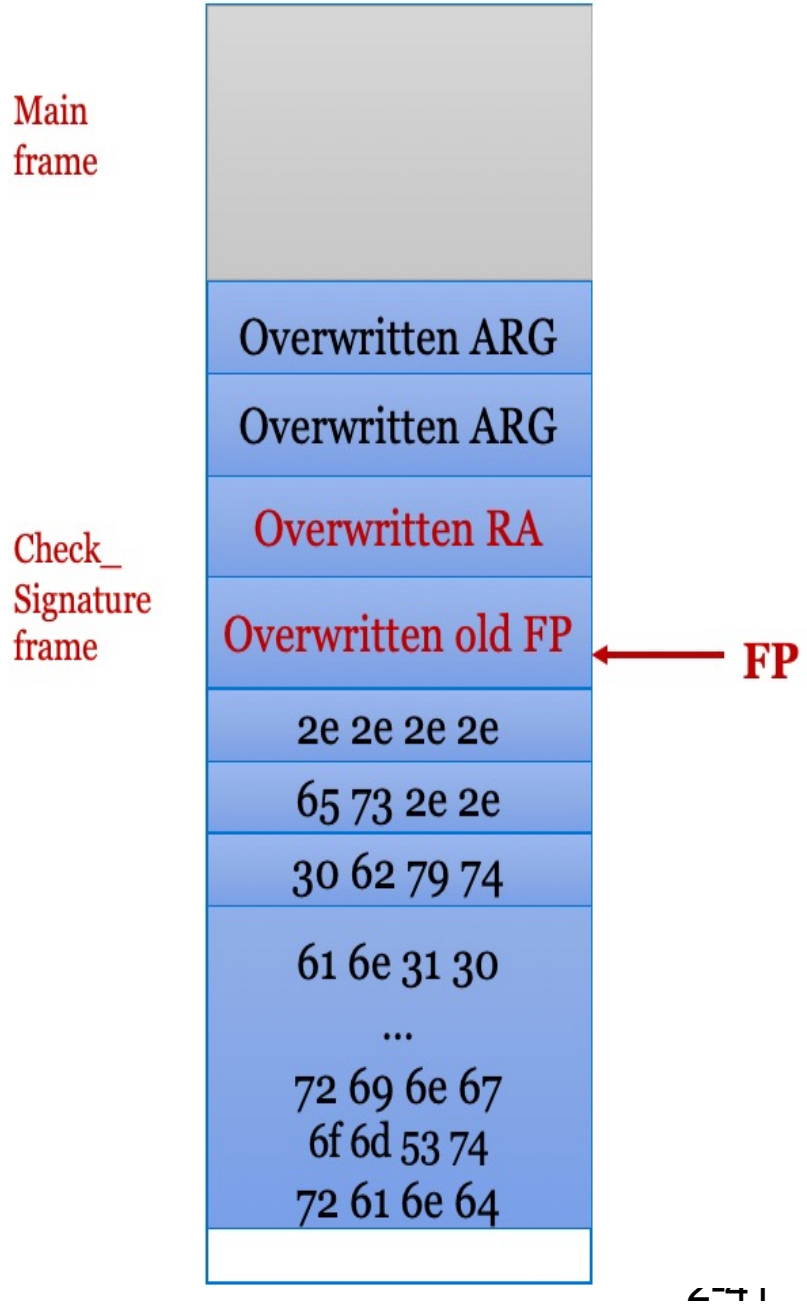
- Crash reasons:

1. Overwritten RA is an Invalid address
2. Unmapped virtual address
3. Address does not point to an instruction
4. Address content is off limit

Buffer overflows

```
int check_signature(char *str, int j)
{
        int i = 0;
        char user_signature[24];
        strcpy(user_signature, str);
```

- *What if there is no crash?*



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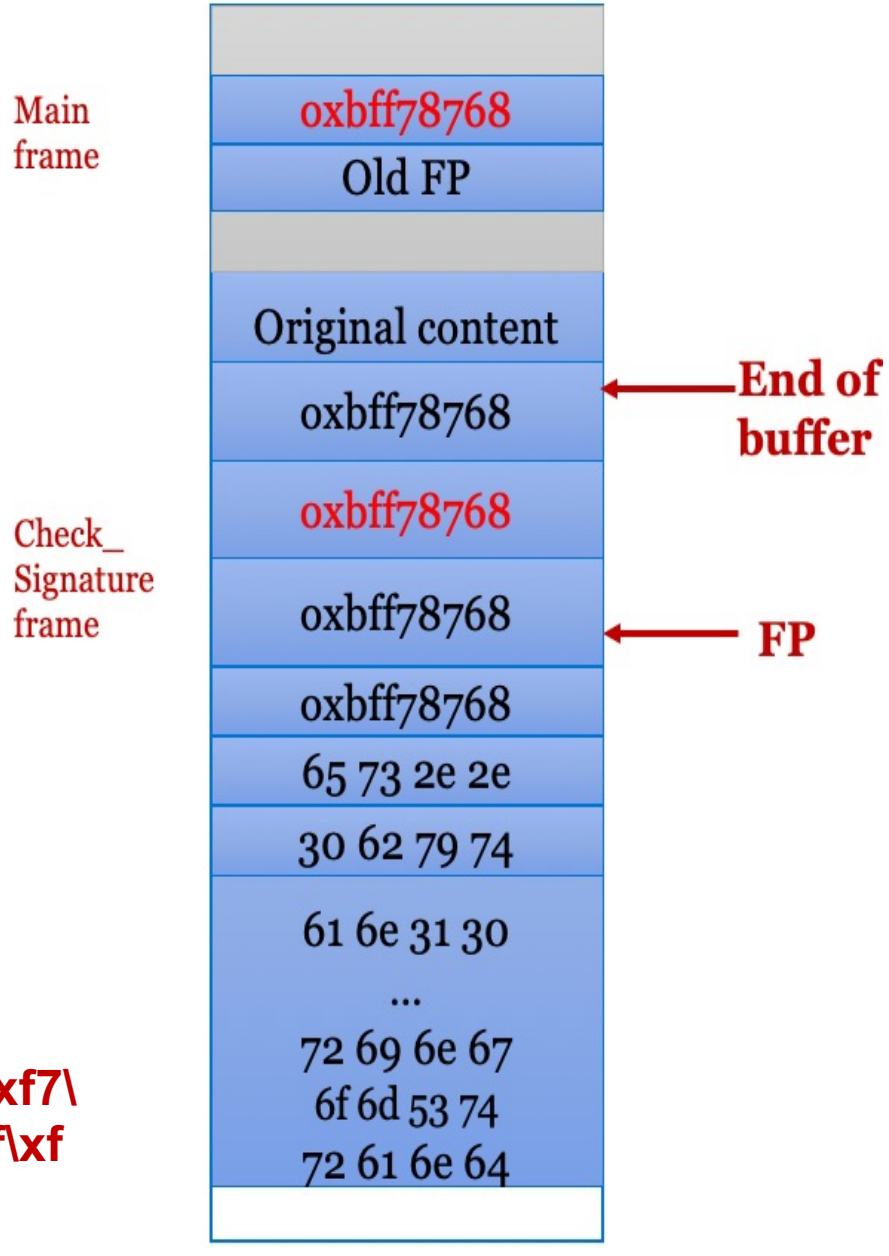

- *What if there is no crash?*

Str = "randomStringLonger\xbf\xf7\x87\x68\xbf\xf7\x87\x68\xbf\xf7\x87\x68\xbf\xf7\x87\x68\xbf\xf7\x87\x68\xbf\xf7\x87\x68\xbf\xf7\x87\x68\xbf\xf7\x87\x68\xbf\xf7\x87\x68";

Buffer overflows

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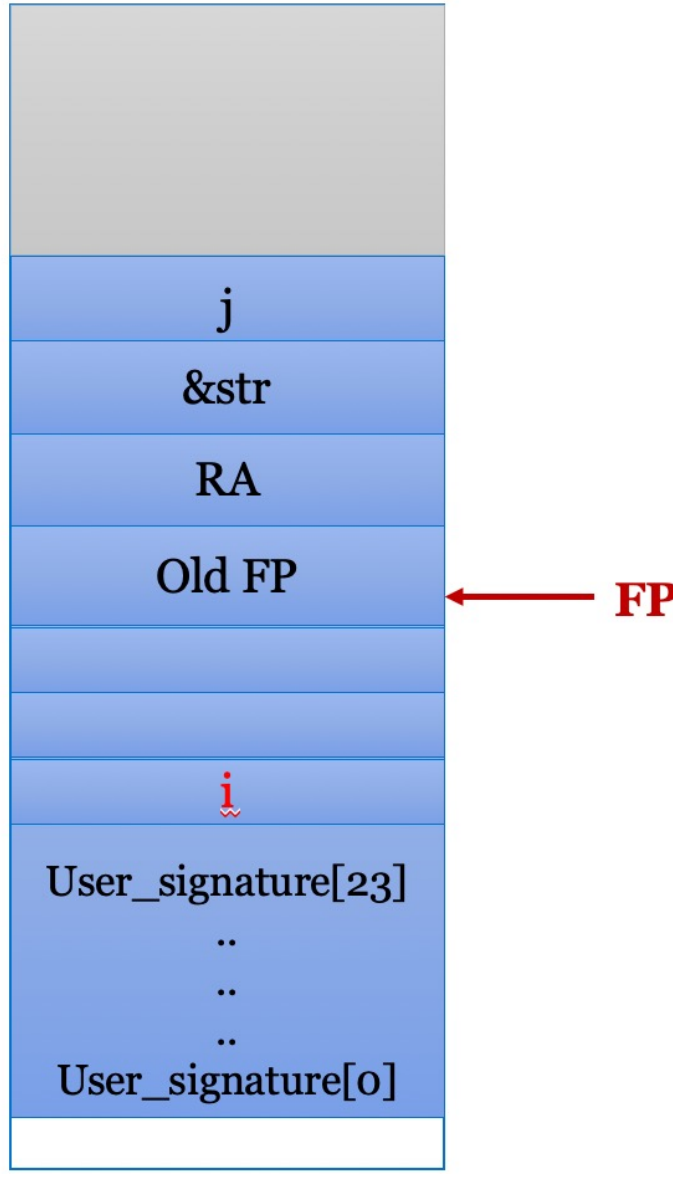
                i = 1;
        return i;
}
```

Main frame

Check_ Signature frame



Str = “?”

Buffer overflows

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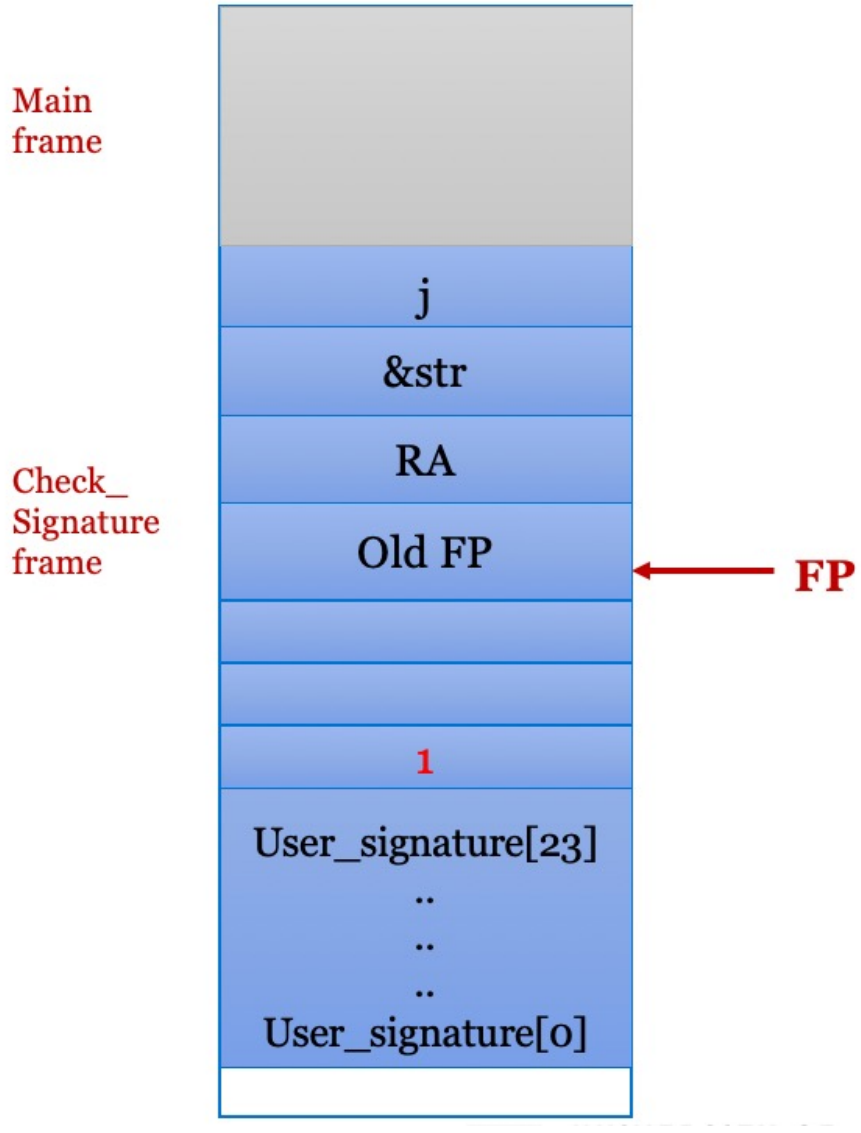

Str = “aaaaaaaaaaaaaaaaaaaaaaaa\x01”

Smashing The Stack For Fun And Profit

- This is a classic (read: somewhat dated) exposition of how buffer overflow attacks work.
- Upshot: if the attacker can write data past the end of an array on the stack, she can usually overwrite things like the saved return address. When the function returns, it will jump to any address of her choosing.
- Targets: programs on a local machine that run with setuid (superuser) privileges, or network daemons on a remote machine

Buffer overflows

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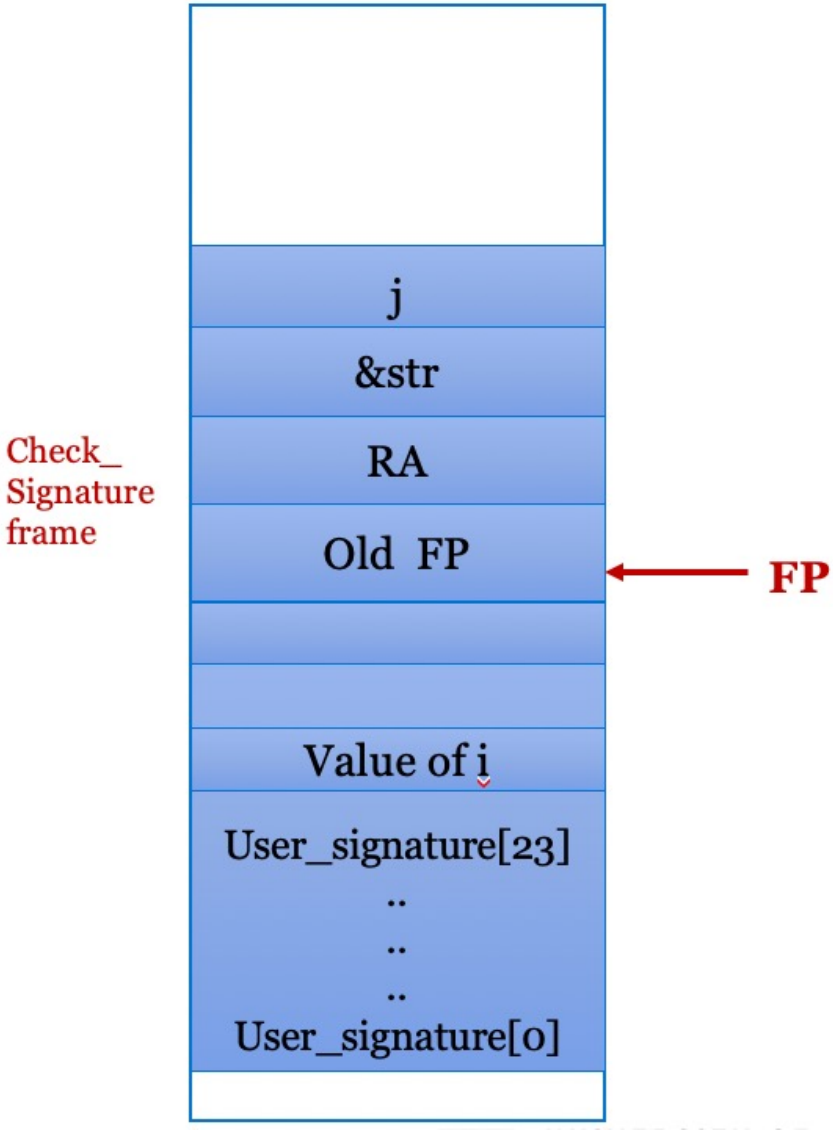

- *Goal of the attacker: exploit a vulnerable privileged program to:*

1. *Inject code into memory*
2. *Execute it under the privilege of the vulnerable program*

Buffer overflows

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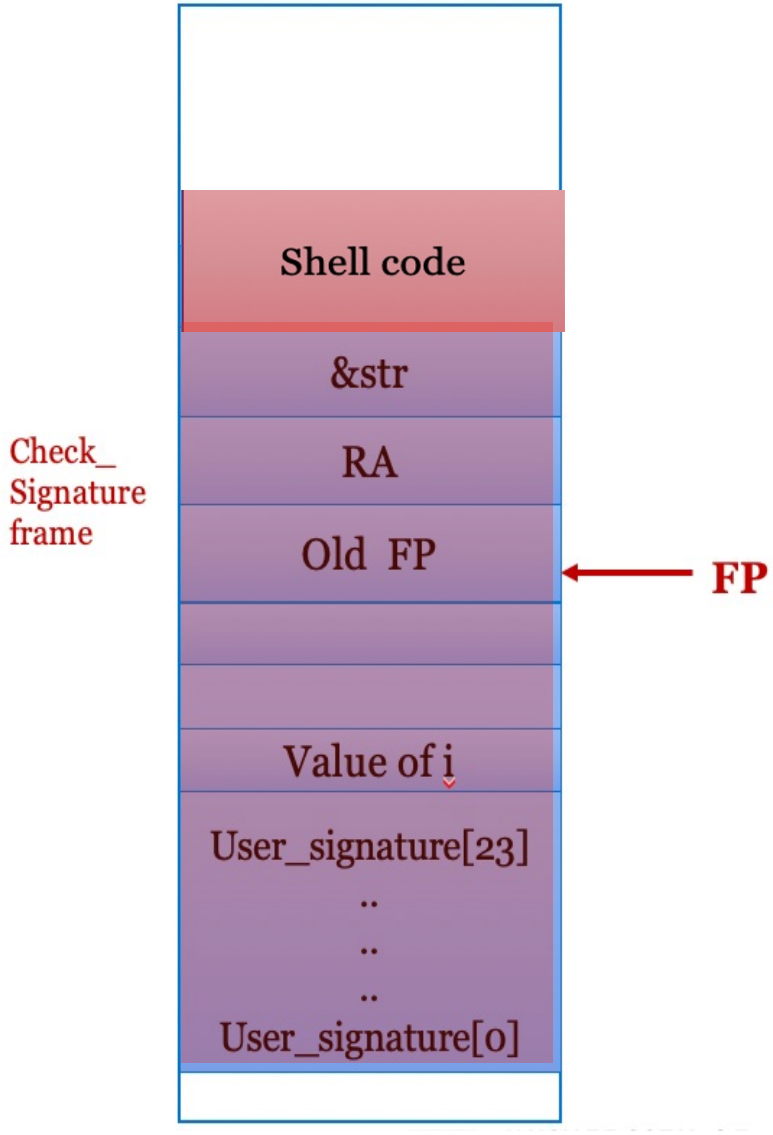

- *Goal of the attacker: exploit a vulnerable privileged program to:*

1. *Inject code into memory:* ***HOW?***
2. *Execute it under the privilege of the vulnerable program*

Buffer overflows

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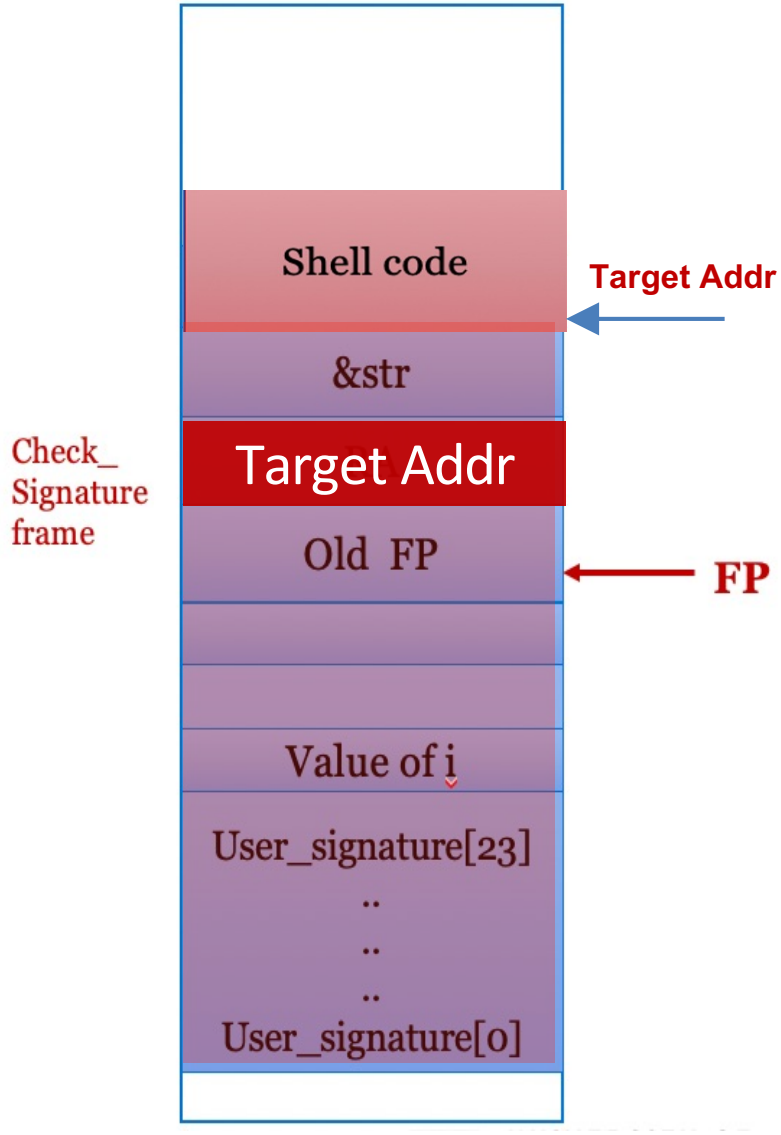

- *Goal of the attacker: exploit a vulnerable privileged program to:*

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Buffer overflows

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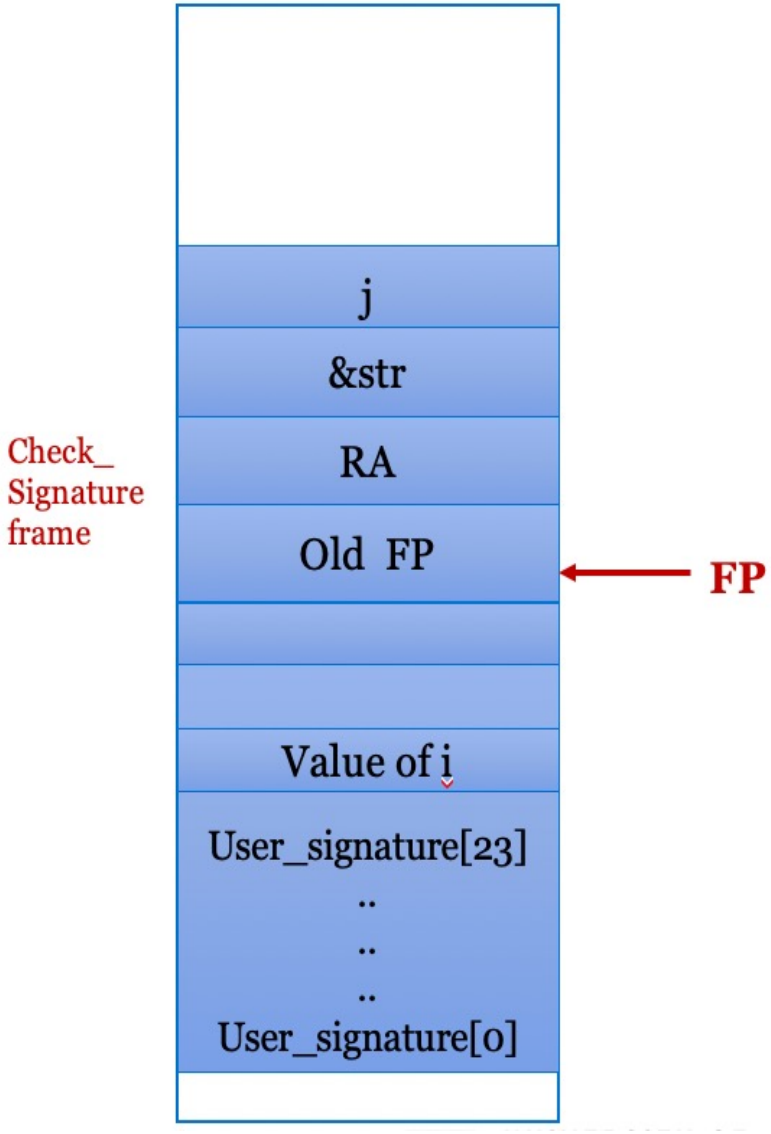
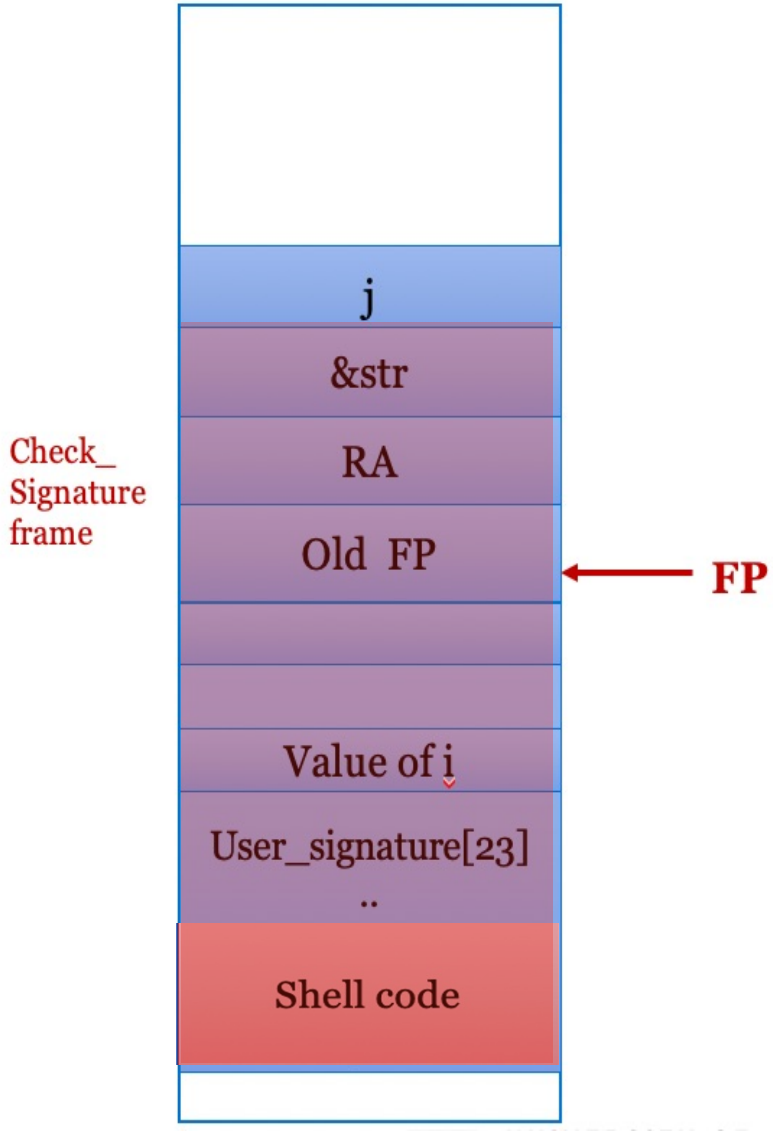


- *Attacker needs to figure out the following:*

1. *Content of injected code:* ***Shell code***

Buffer overflows

```
int check_signature(char *str, int j)
{
        int i = 0;
        char user_signature[24];
        strcpy(user_signature, str);
        if(isValid(user_signature))
                i = 1;
        return i;
}
```



- *Attacker needs to figure out the following:*

1. *Content of injected code:* ***Shell code***
2. *Where to inject the code*

Buffer overflows

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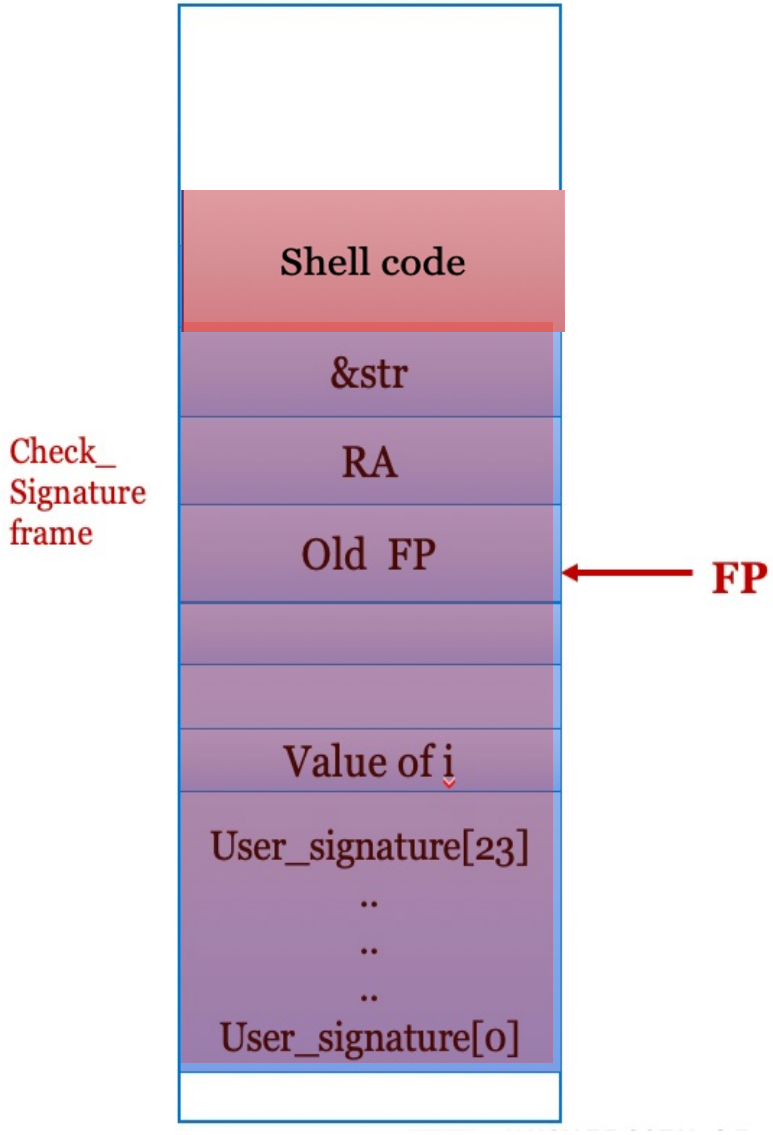

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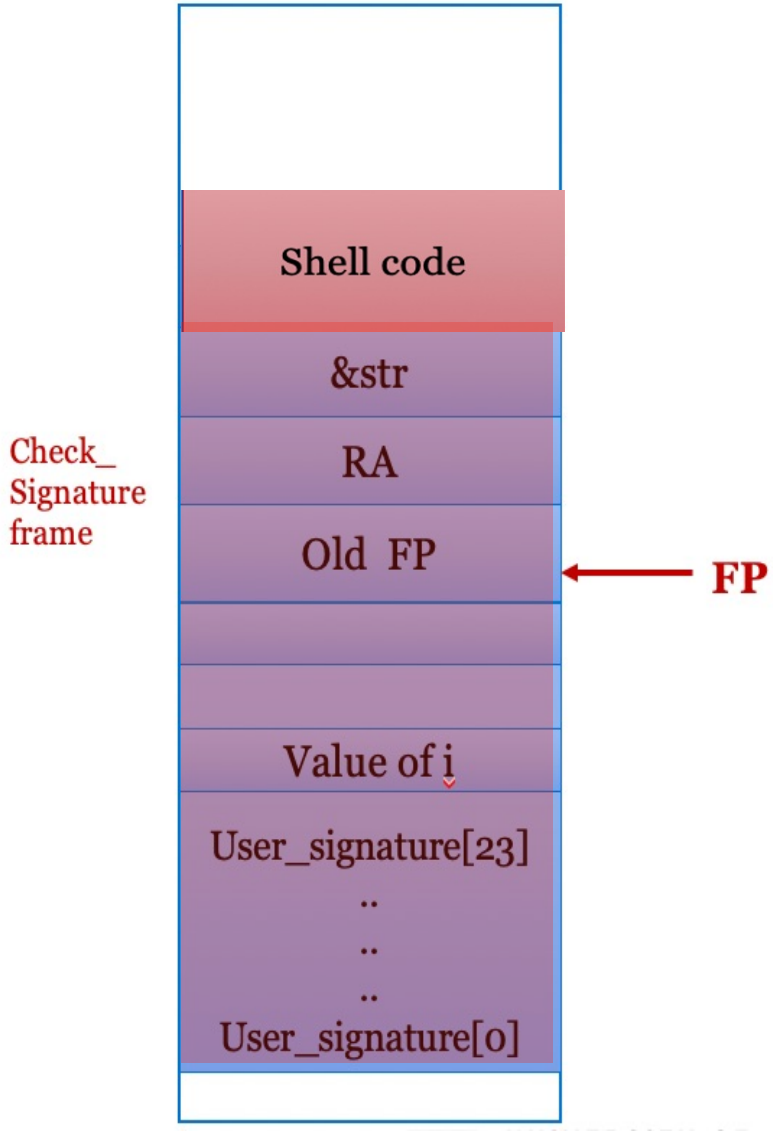

- *Attacker needs to figure out the following:*

1. *Content of injected code*
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3. *Location of RA*

Buffer overflows

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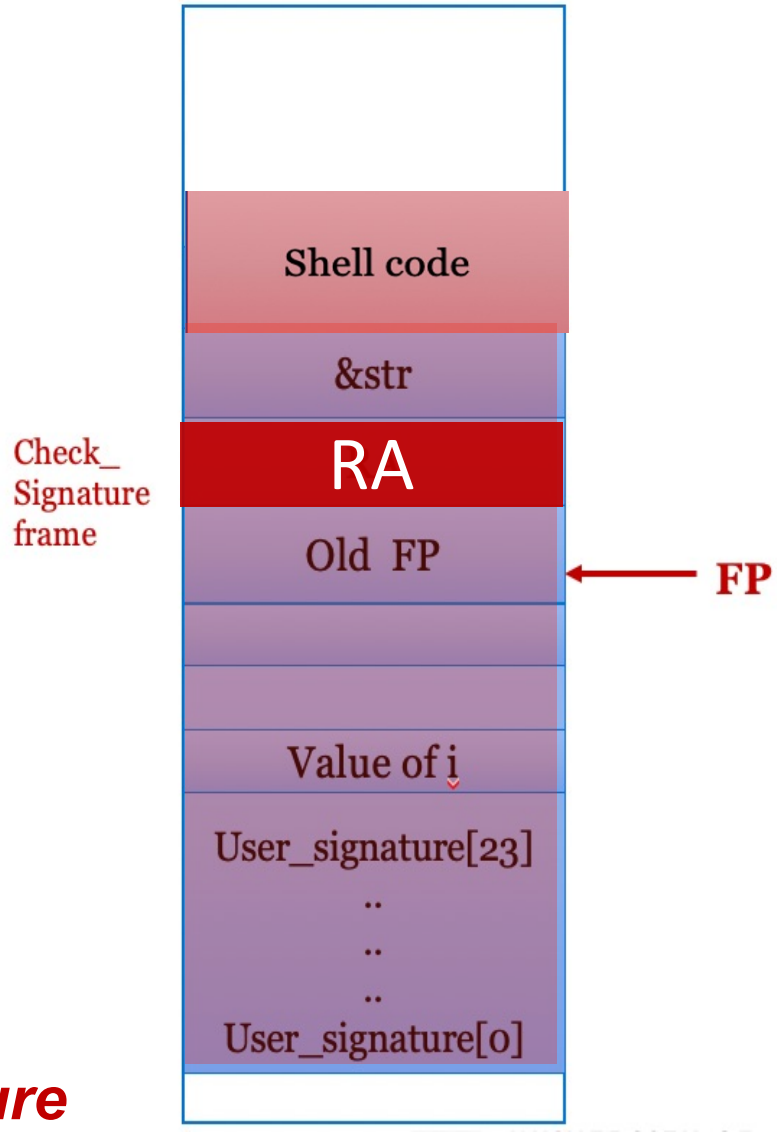

- *Attacker needs to figure out the following:*

1. *Content of injected code*
2. *Where to inject the code*
3. *Location of RA*

If we have the source code, we can figure out the location of RA through debugging

Buffer overflows

```
int check_signature(char *str, int j)
{
        int i = 0;
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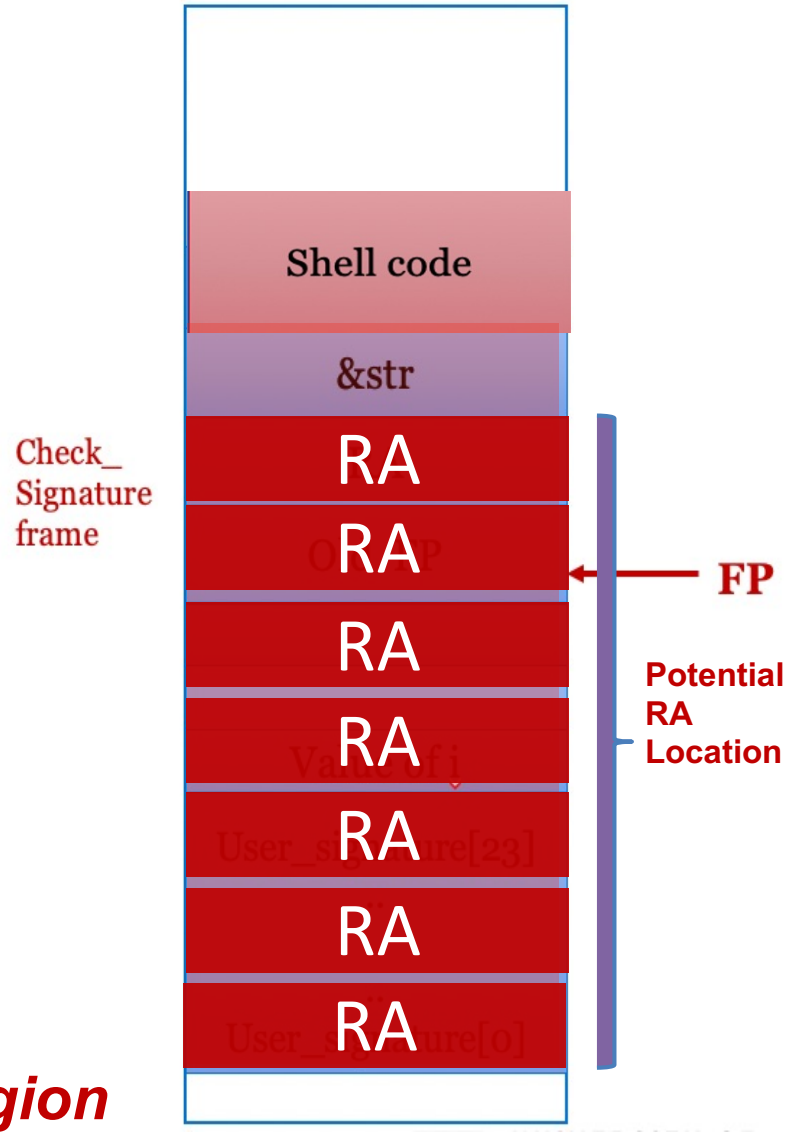

- *Attacker needs to figure out the following:*

1. *Content of injected code*
2. *Where to inject the code*
3. *Location of RA*

If not, select a whole (large enough) region as potential location for the RA

Buffer overflows

```
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        int i = 0;
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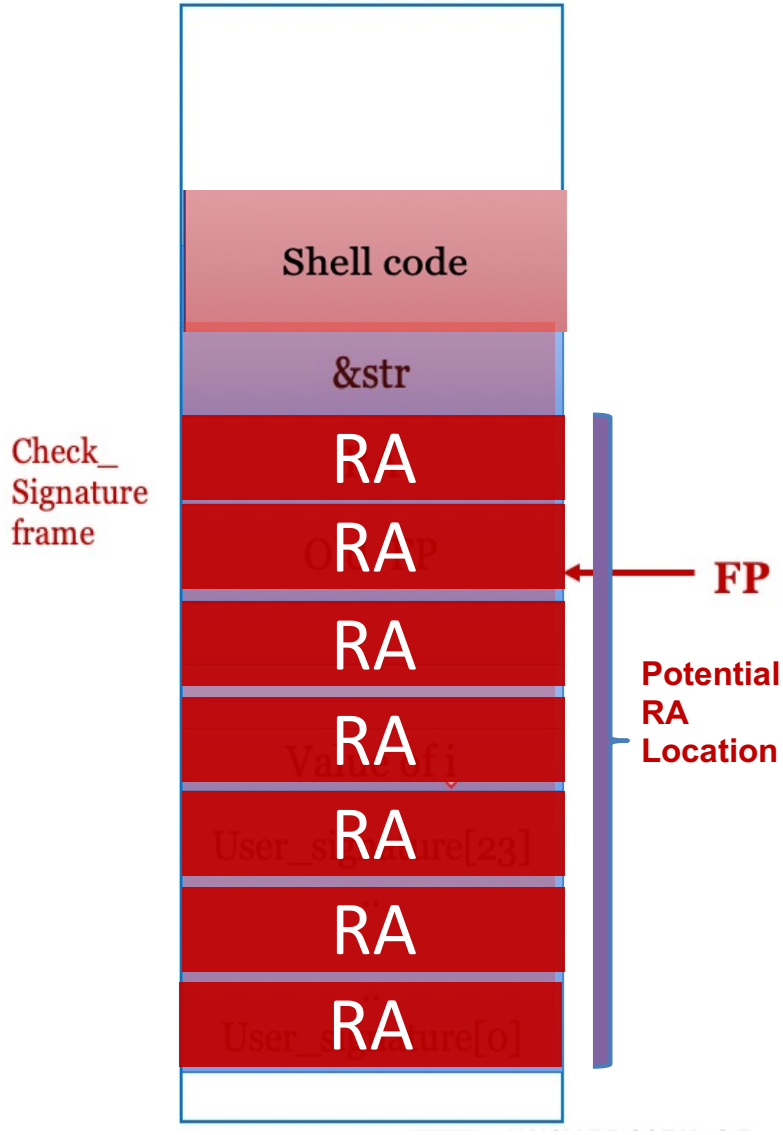

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4. ***Fill RA***

Buffer overflows

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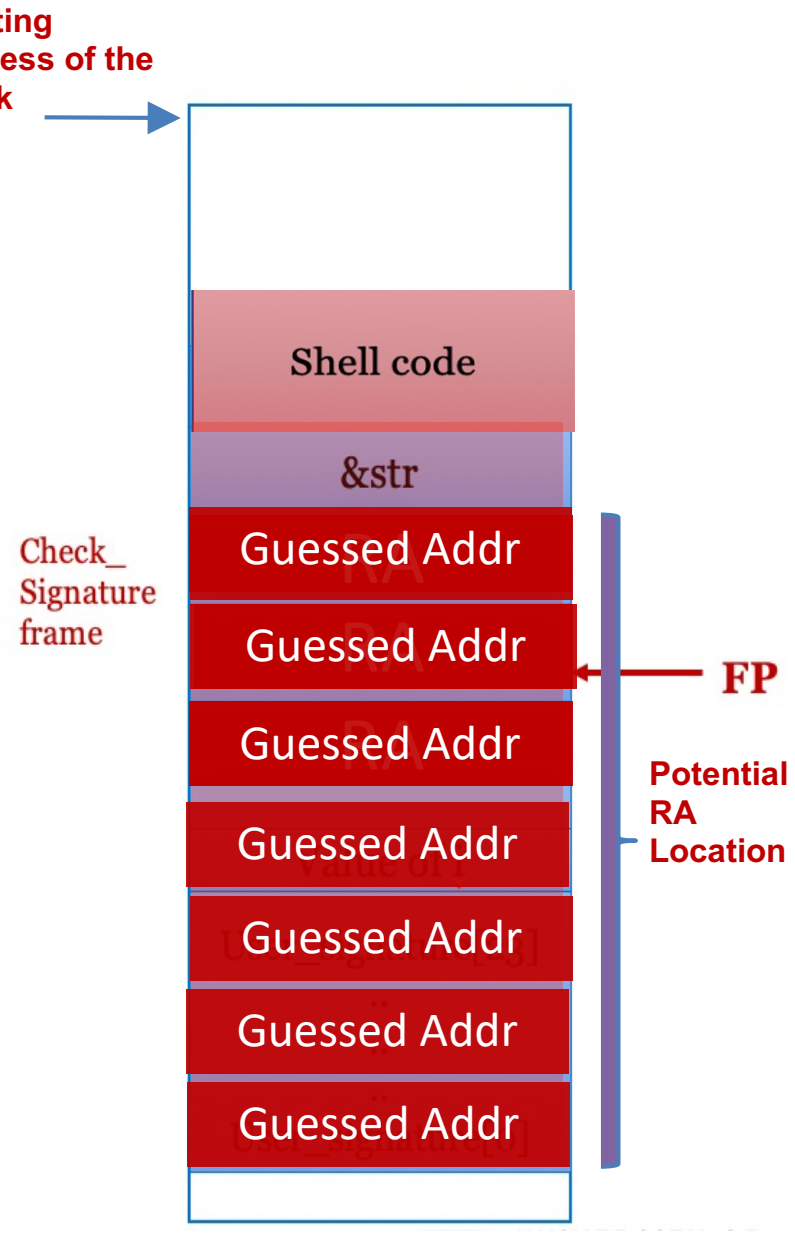
}
```



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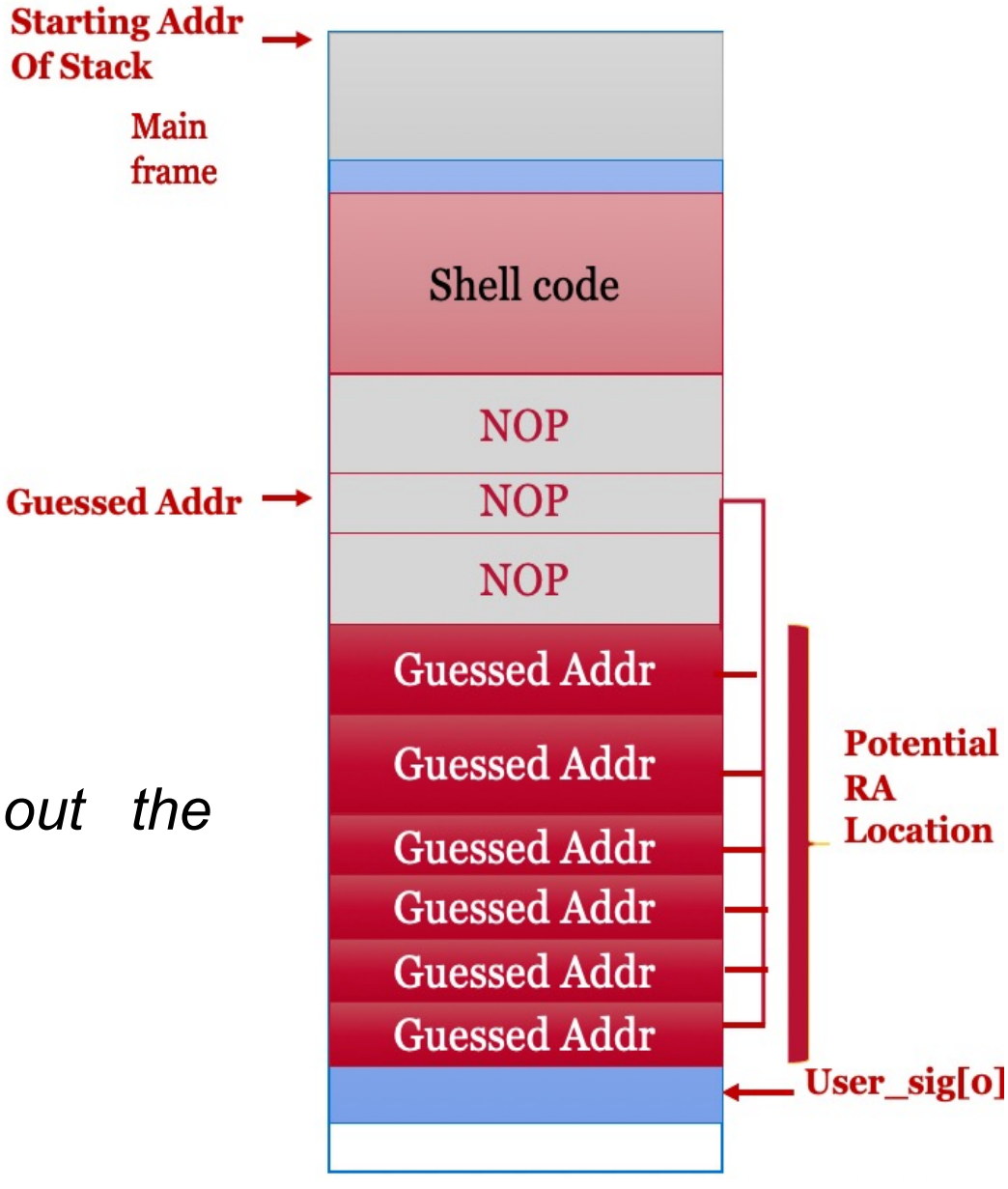

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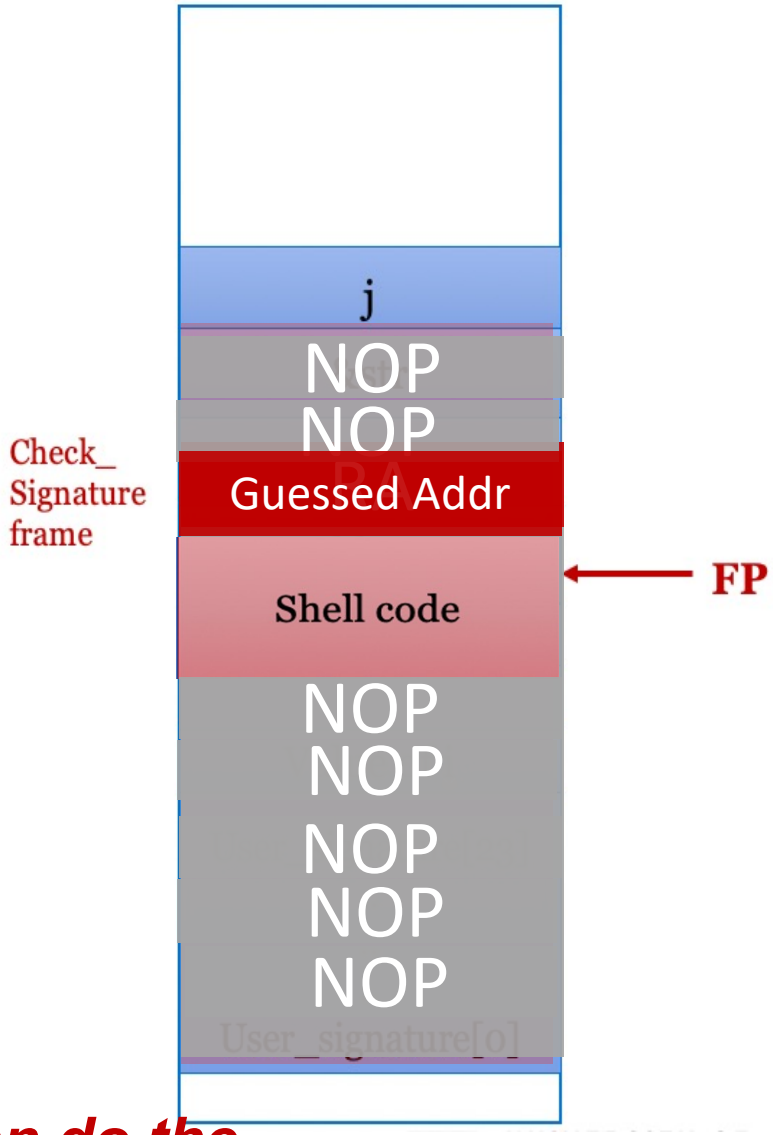
```



- *Attacker needs to figure out the following:*

1. *Content of injected code*
2. *Where to inject the code*
3. *Location of RA*
4. *Fill RA*

If we have the source code, we can do the following..

Kinds of buffer overflows

- In addition to the classic attack which overflows a buffer on the stack to jump to shellcode, there are many variants:
  - Attacks which work when a single byte can be written past the end of the buffer (often caused by a common off-by-one error)
  - Overflows of buffers on the heap instead of the stack
  - Jump to other parts of the program, or parts of standard libraries, instead of shellcode

Causes of buffer overflow

- What are the root causes of buffer overflow:
  - Missing boundary check
  - Ability to overwrite important memory regions
  - Data is treated as code and executed
  - Predictability of the addresses

Defences against buffer overflows

- Programmer: Use a language with bounds checking
- Compiler: Place padding between data and return address (“Canaries”)
  - Detect if the stack has been overwritten before the return from each function
- Memory: Non-executable stack
  - “W⊕X”, DEP (memory page is either writable or executable, but never both)
- OS: Stack (and sometimes code,heap,libraries) at random virtual addresses for each process
  - Address Space Layout Randomization (ASLR)
  - All mainstream OSes do this now
- Hardware-assistance: pointer authentication, shadow stack, memory tagging

Incomplete mediation

- Inputs to programs are often specified by untrusted users
  - Web-based applications are a common example
  - “Untrusted” to do what?
- Users sometimes mistype data in web forms
  - Phone number: `51998884567`
  - Email: `yafer#uwaterloo.ca`
- The web application needs to ensure that what the user has entered constitutes a meaningful request
- This is called mediation

Incomplete mediation

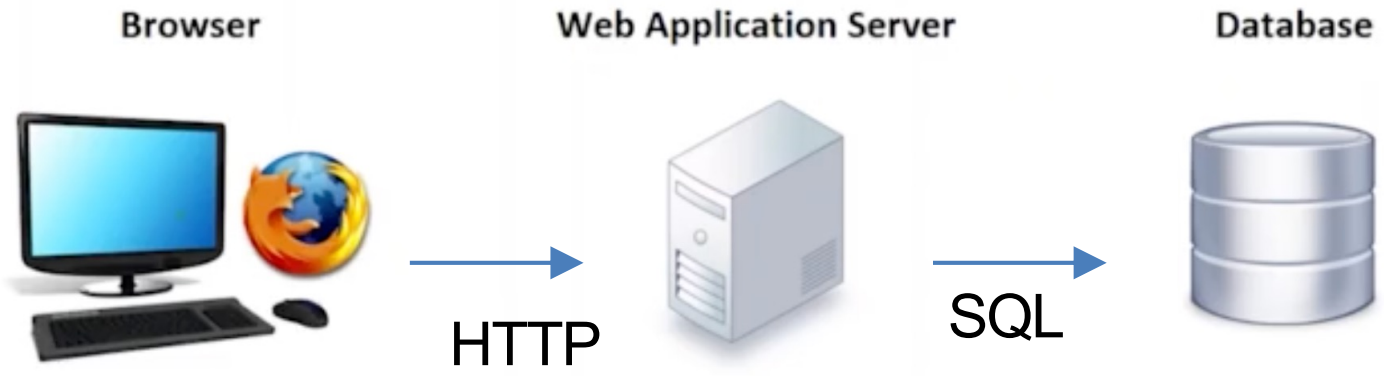
- Incomplete mediation occurs when the application accepts incorrect data from the user
- Sometimes this is hard to avoid
  - Uwaterloo Phone number: `519-886-4567`
  - This is a reasonable entry, that happens to be wrong
- We focus on catching entries that are clearly wrong
  - Not well formed
    - DOB: `1980-04-31`
  - Unreasonable values
    - DOB: `1876-10-12`
  - Inconsistent with other entries

Why do we care?

- What's the security issue here?
- What happens if someone fills in:
  - DOB: `9876487423649248364924783648923649 2`
    - Buffer overflow?
  - DOB: `'; --`
    - SQL injection?
- We need to make sure that any user-supplied input falls within well-specified values, known to be safe

SQL injection

- Architecture of a typical web application:



Source: Seed Labs https://seedsecuritylabs.org

SQL injection

- How web applications interact with databases

Application Server

```
$input_uname = $_GET['username'];
$input_pwd   = $_GET['Password'];

$sql = "SELECT name, eid, salary, email
        FROM credential
        WHERE name= '$input_uname' and Password='$input_pwd'";

$result = $conn->query($sql)
```

Database

```
SELECT name, eid, salary, email
FROM credential
WHERE name= 'alice' and Password='seedalice';
```

Source: Seed Labs https://seedsecuritylabs.org

Launching a SQL injection attack

- Can you log in into Alice's account without a password?


```
SELECT name, eid, salary, email
FROM credential
WHERE name= '                ' and Password='                '";
```

- Answer: **Alice' --**

Source: Seed Labs https://seedsecuritylabs.org

Launching a SQL injection attack

- You don't know a user. Can you log in into the website?


```
SELECT name, eid, salary, email
FROM credential
WHERE name= '                ' and Password='                '";
```

- Answer: **a' or 1=1 --**

Source: Seed Labs https://seedsecuritylabs.org

Launching a SQL injection attack

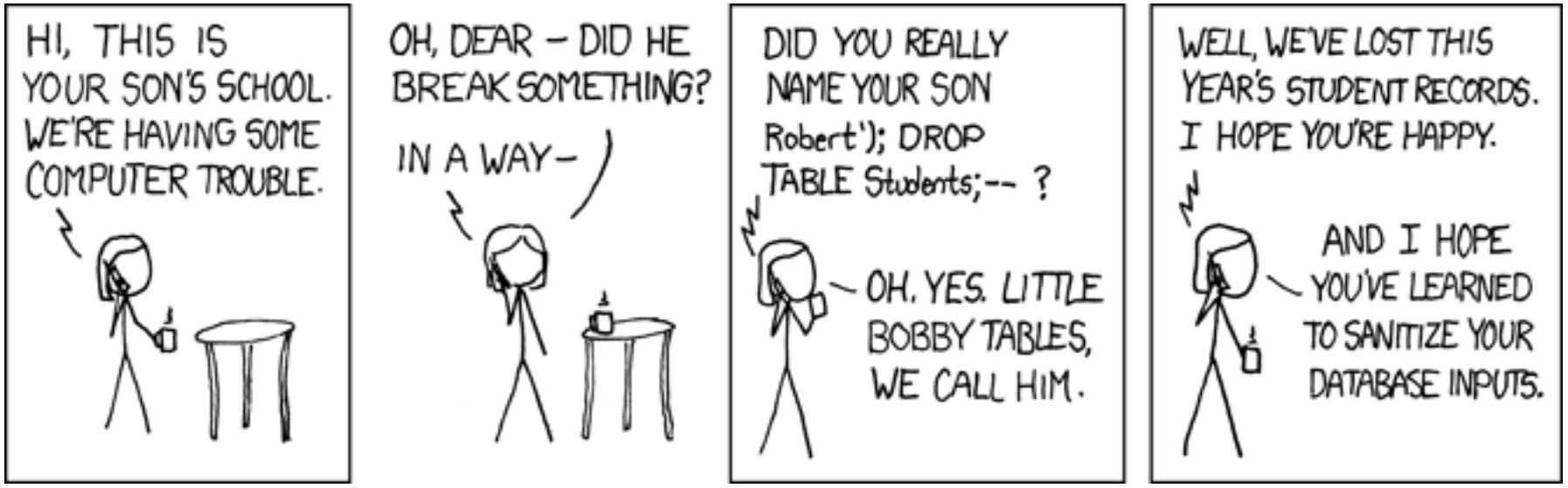
- Can you perform an operation on the db?


```
SELECT name, eid, salary, email
FROM credential
WHERE name= '                ' and Password='                '";
```

- Answer: **a'; DROP credential --**

Source: Seed Labs https://seedsecuritylabs.org

SQL injection

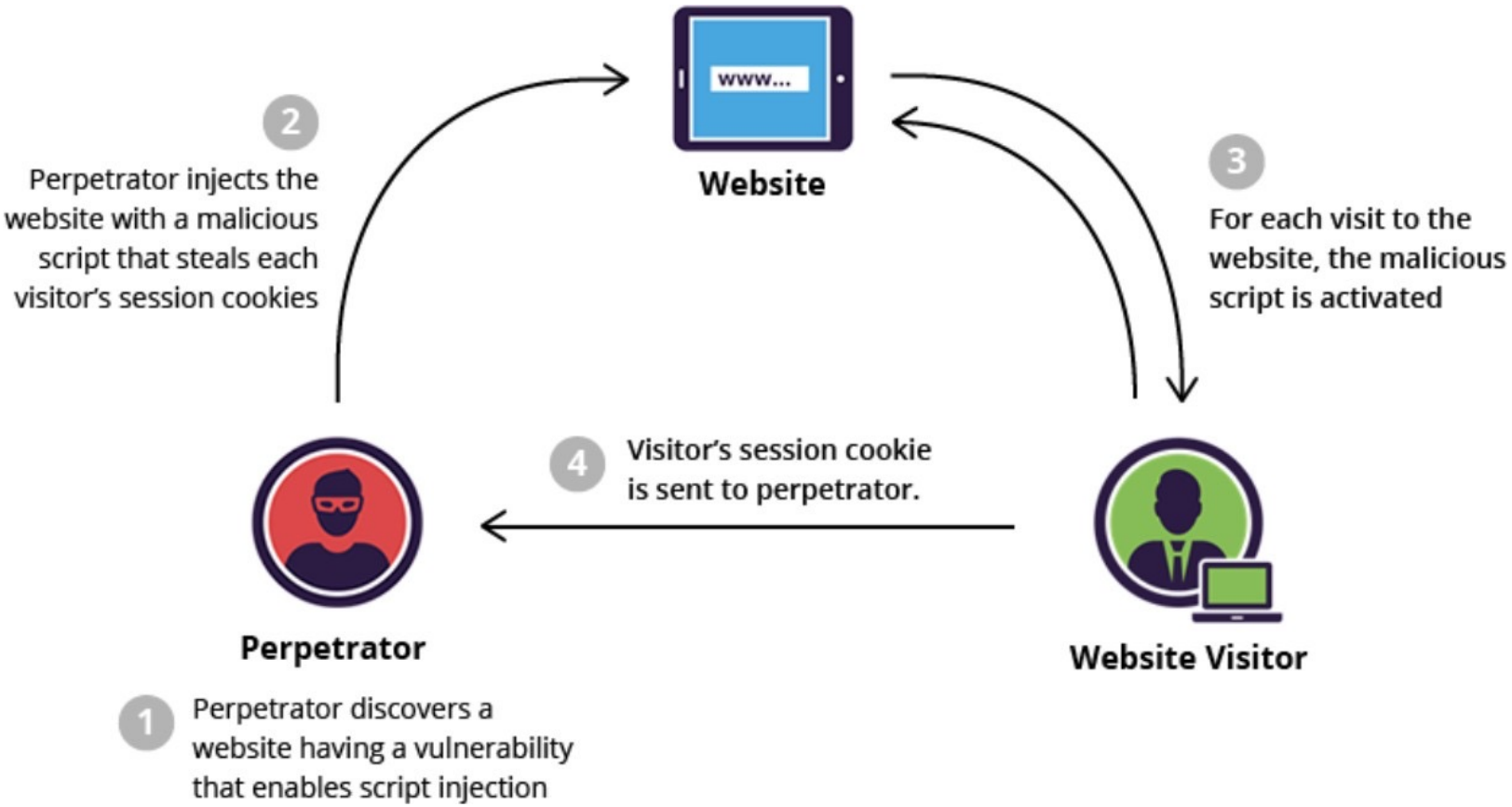


http://xkcd.com/327/

Cross-Site Scripting (XSS) Attacks

- Data enters a Web application through an untrusted source, most frequently a web request
- The data is included in dynamic content that is sent to a user
- User browser interprets the data as code

XSS Example

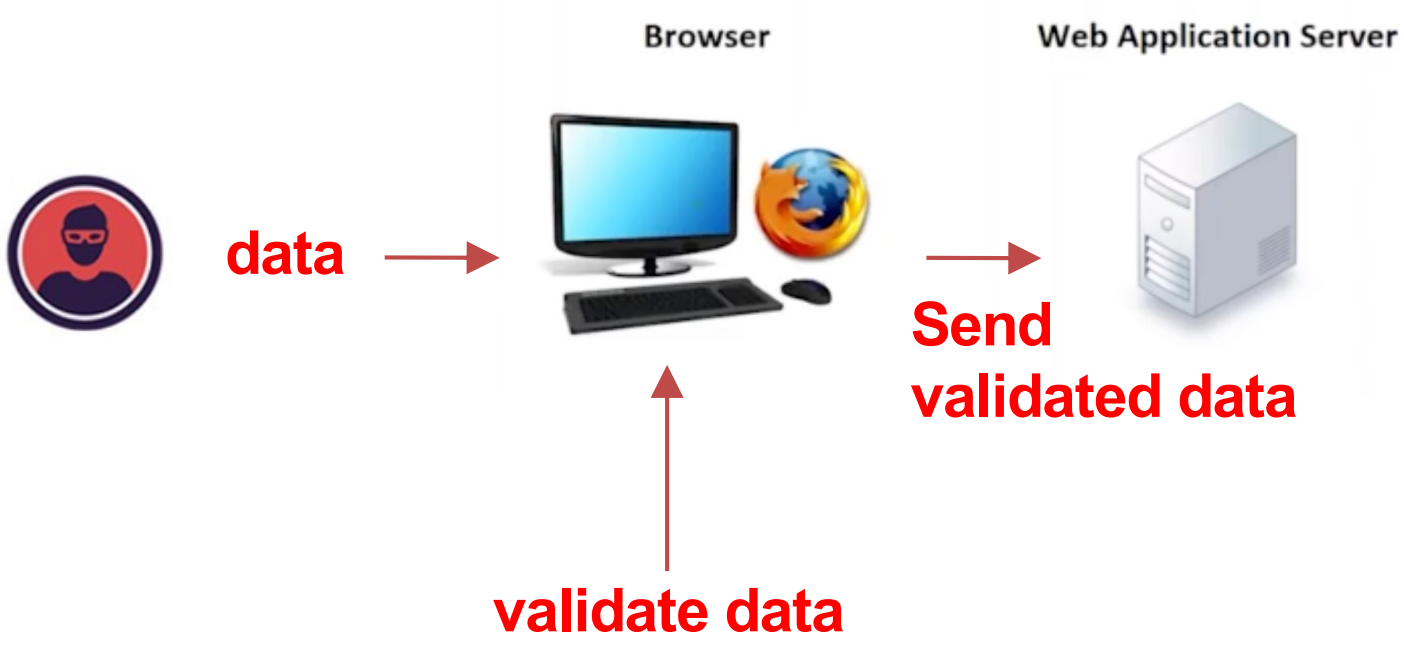

www...
Website
2
Perpetrator injects the website with a malicious script that steals each visitor's session cookies
3
For each visit to the website, the malicious script is activated
4
Visitor's session cookie is sent to perpetrator.
Perpetrator
Website Visitor
1
Perpetrator discovers a website having a vulnerability that enables script injection

Client-side mediation

- You've probably visited web sites with forms that do client-side mediation
  - When you click "submit", Javascript code will first run validation checks on the data you entered
  - If you enter invalid data, a popup will prevent you from submitting it

- Related issue: client-side state
  - Many web sites rely on the client to keep state for them
  - They will put hidden fields in the form which are passed back to the server when the user submits the form

Client-side mediation



Client-side mediation

Client-side mediation

- Problem: what if the user
  - Turns off Javascript?
  - Edits the form before submitting it? (Tampermonkey)
  - Writes a script that interacts with the web server instead of using a web browser at all?
  - Connects to the server "manually"?
    (telnet server.com 80)
- Note that the user can send arbitrary (unmediated) values to the server this way
- The user can also modify any client-side state

Example

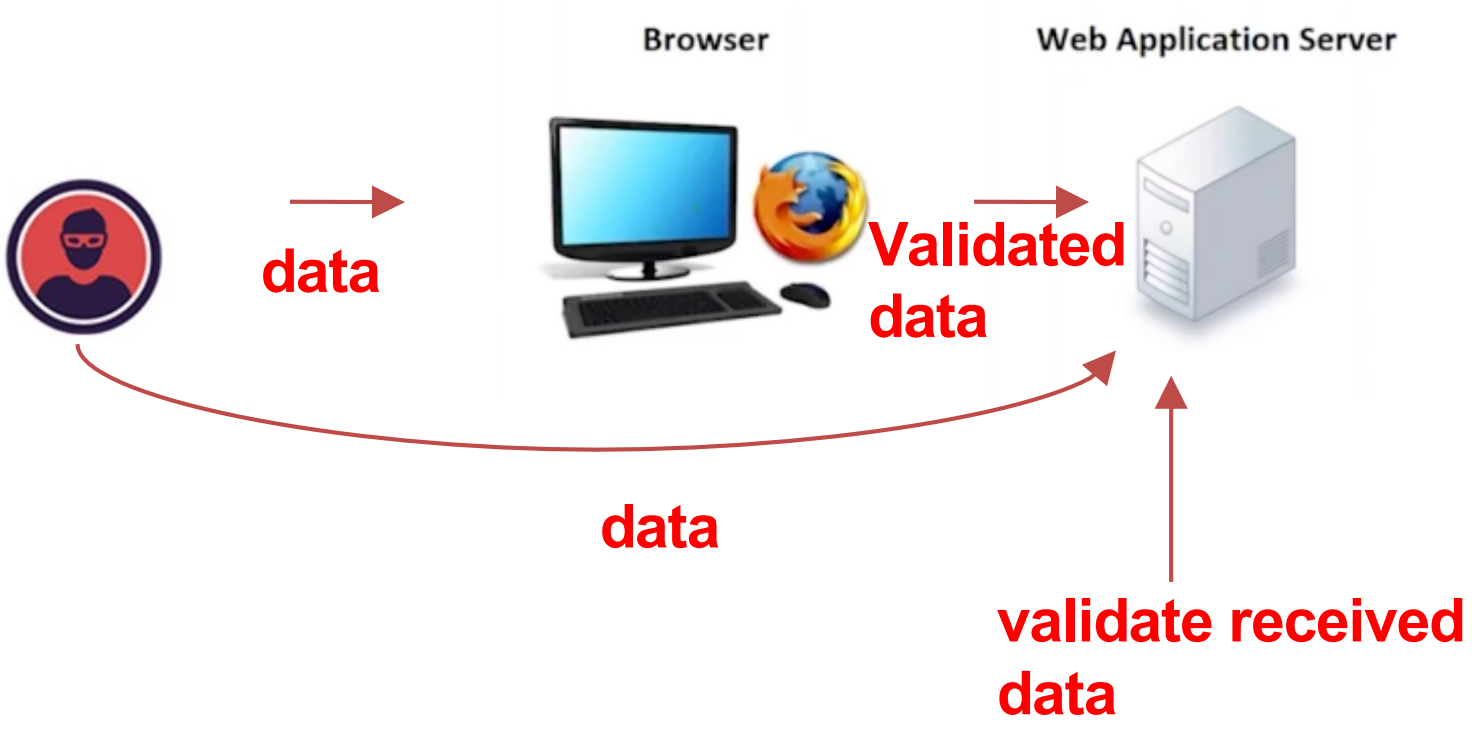
- At a bookstore website, the user orders a copy of the course text. The server replies with a form asking the address to ship to. This form has hidden fields storing the user's order
  - ```
    <input type="hidden"
    name="isbn" value="0-13-
    239077-9">
    <input type="hidden" name="quantity"
    value="1">
    <input type="hidden" name="unitprice"
    value="111.00">
    ```

- What happens if the user changes the "unitprice" value to "50.00" before submitting the form?
    ```

Defences against incomplete mediation

- Client-side mediation is an OK method to use in order to have a friendlier user interface, but is useless for security purposes.
- You have to do server-side mediation, whether or not you also do client-side.
- For values entered by the user:
  - Always do very careful checks on the values of all fields
  - These values can potentially contain completely arbitrary 8-bit data (including accented chars, control chars, etc.) and be of any length
- For state stored by the client:
  - Make sure client has not modified the data in any way

Client-side mediation



Format string vulnerabilities

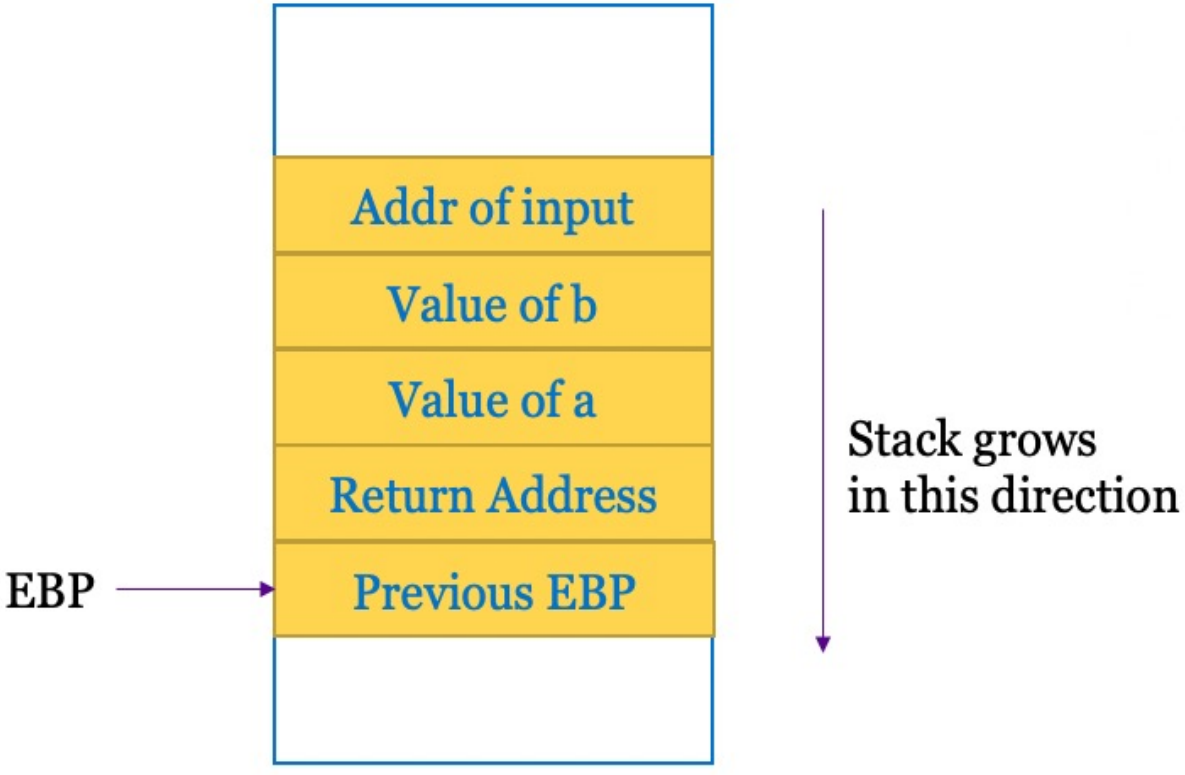
- Class of vulnerabilities discovered in 2000
- Unfiltered user input is used as format string in printf(), fprintf(), sprintf(),. . .
- `printf(buffer)` instead of `printf("%s", buffer)`
  - The first one will parse `buffer` for `%`'s and use whatever is currently on the stack to process found format parameters
- `printf("%s%s%s%s")` likely crashes your program
- `printf("%x%x%x%x")` dumps parts of the stack
- `%n` will write to an address found on the stack
- See course readings for more

Call stack

```
int main(int argc, char* argv[]){

        int a = 0, b = 0;
        char input[10];

        ...
        function(a, b, input);
        b = a+ 1;
```



Format string vulnerabilities

- What makes ANSI C conversion functions (like printf, fprintf) special?

```
int a = 0, b = 1;
printf("Message with no arguments");
printf("Message with 1 argument %d", a);
printf("Message with 2 arguments %d, %d", a, b);
```

- It takes a variable number of arguments, one of them is the “format string”

Format string vulnerabilities

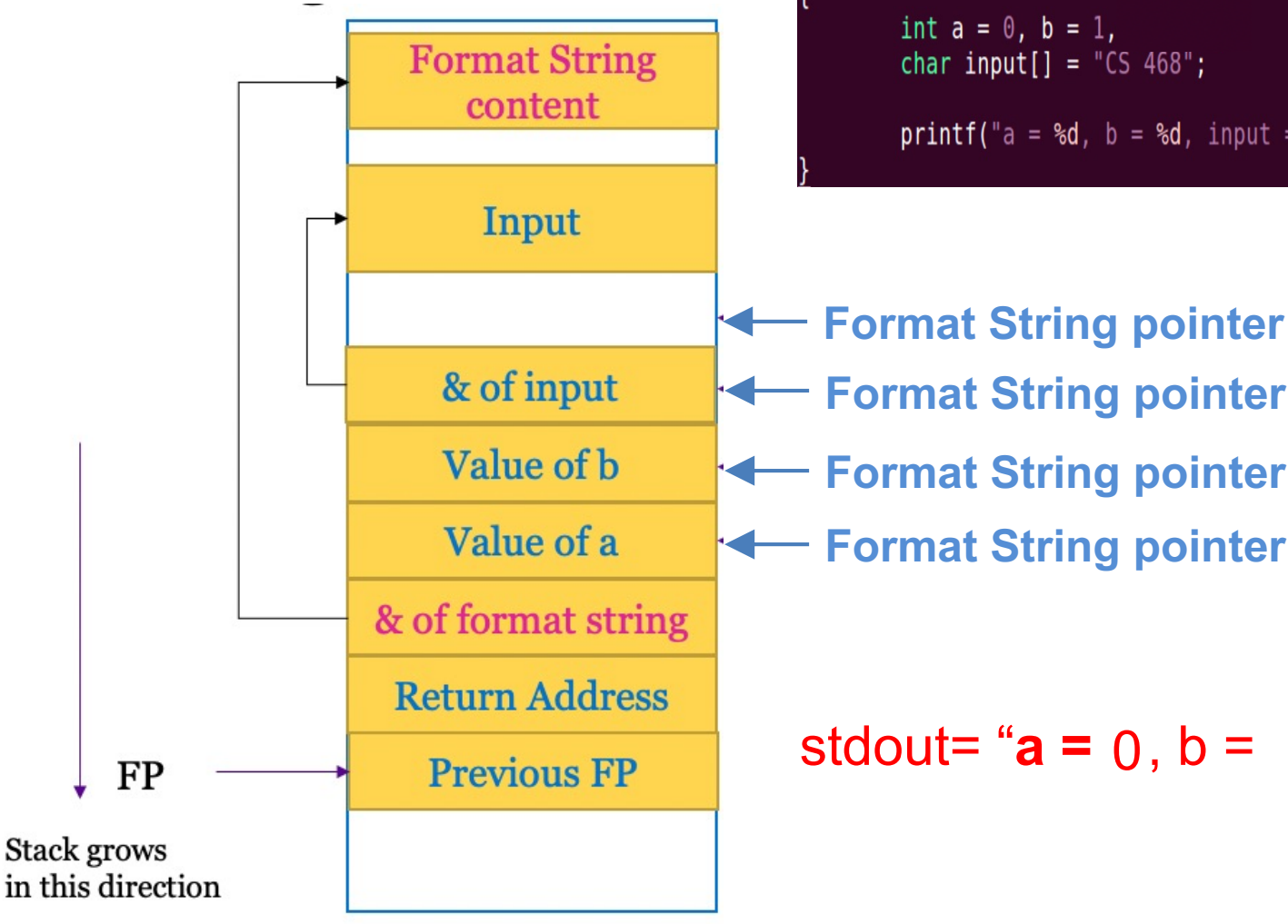
- Definition of printf

```
int printf ( const char * format, ... );
```

format: C string. It can contain embedded format specifiers that are replaced by values [specified in the additional arguments]

Format string vulnerabilities

```c
#include <stdio.h>

int main()
{
        int a = 0, b = 1,
        char input[] = "CS 468";

        printf("a = %d, b = %d, input = %s      \n", a, b, input);
}
```



stdout= "**a =** 0 , b = 1 , Input = CS468

Format string vulnerabilities

- Common format specifiers

Parameters	Output	Passed as
%%	% character (literal)	Reference
%p	External representation of a pointer to void	Reference
%d	Decimal	Value
%c	Character	
%u	Unsigned decimal	Value
%x	Hexadecimal	Value
%s	String	Reference
%n	Writes the number of characters into a pointer	Reference

Format string vulnerabilities

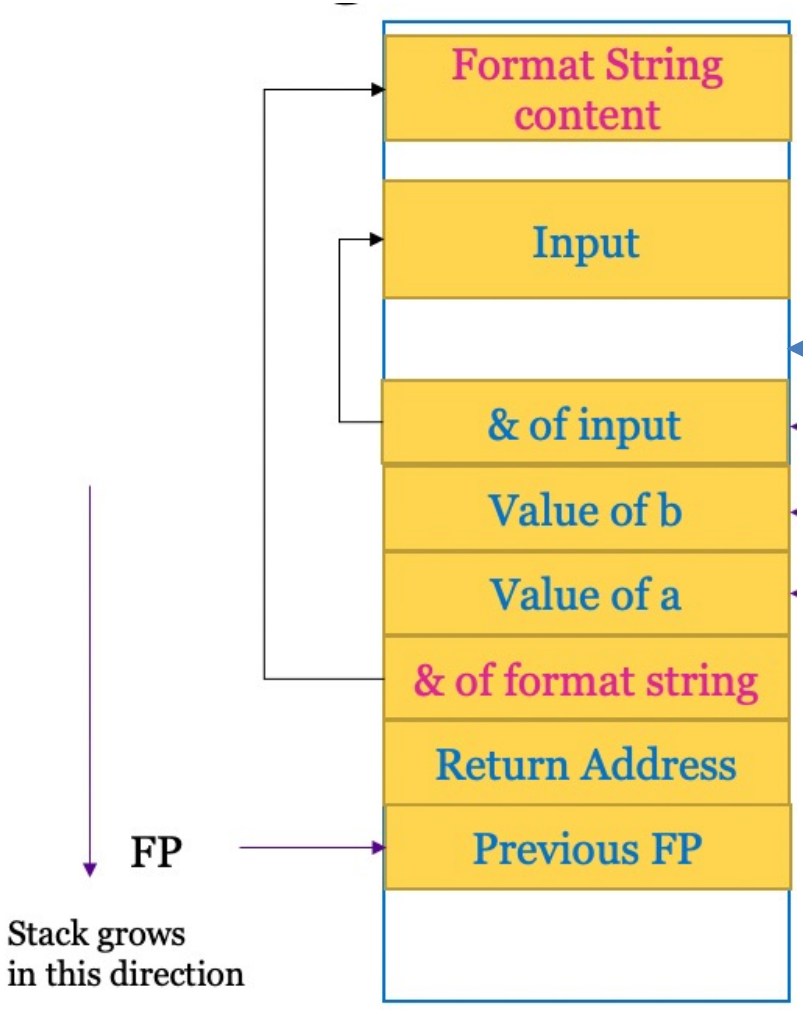
- Definition of printf

```
int printf ( const char * format, ... );
```

- **What could go wrong?**
  - What if there is an inconsistency between number of arguments and format specifiers?

Format string vulnerabilities

```c
#include <stdio.h>

int main()
{
        int a = 0, b = 1, d = 3;
        char input[] = "CS 468";

        printf("a = %d, b = %d, input = %s, %d \n", a, b, input);
}
```

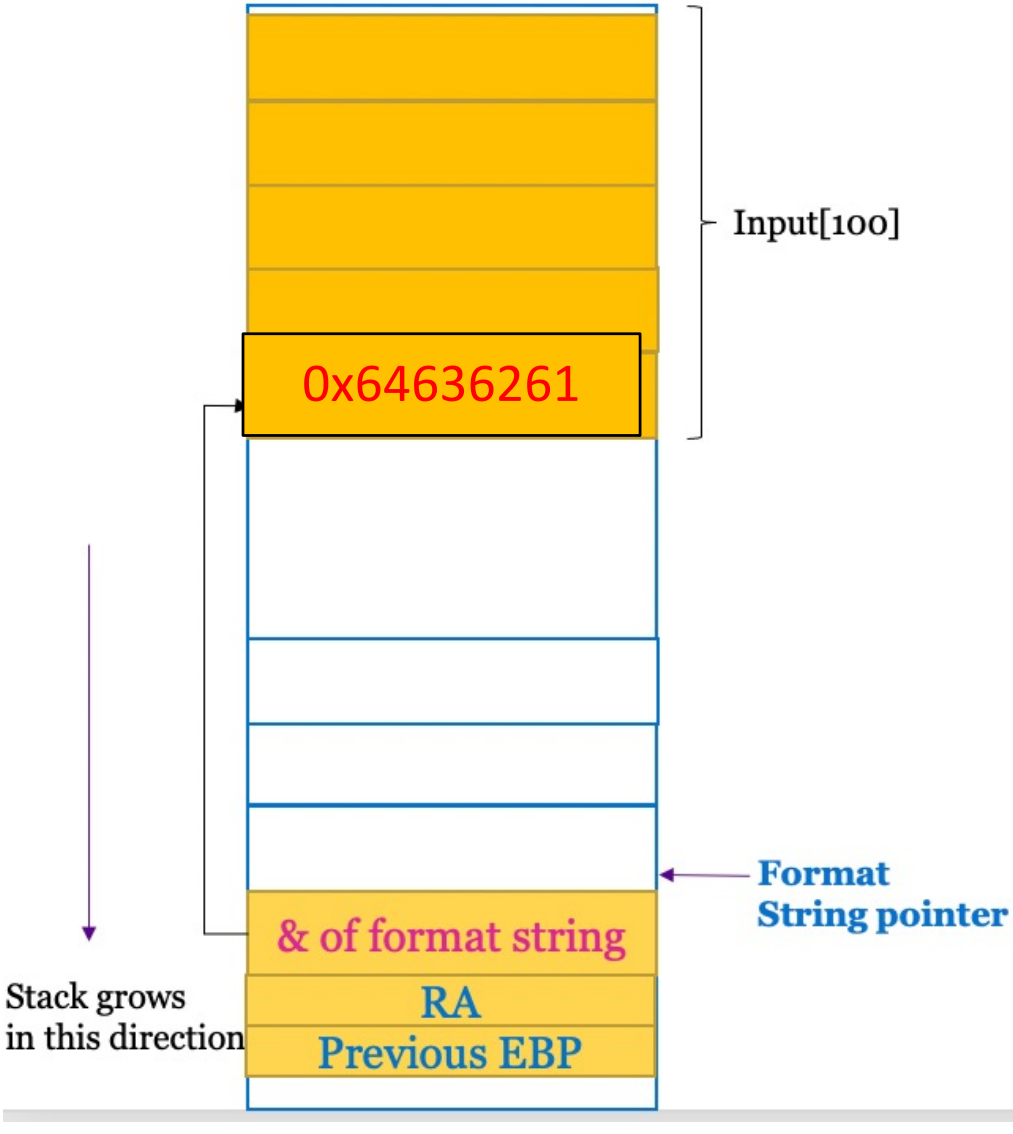


print content in this location

Format String pointer

stdout= "**a = 0, b = 1**, Input = CS468

Format string vulnerabilities

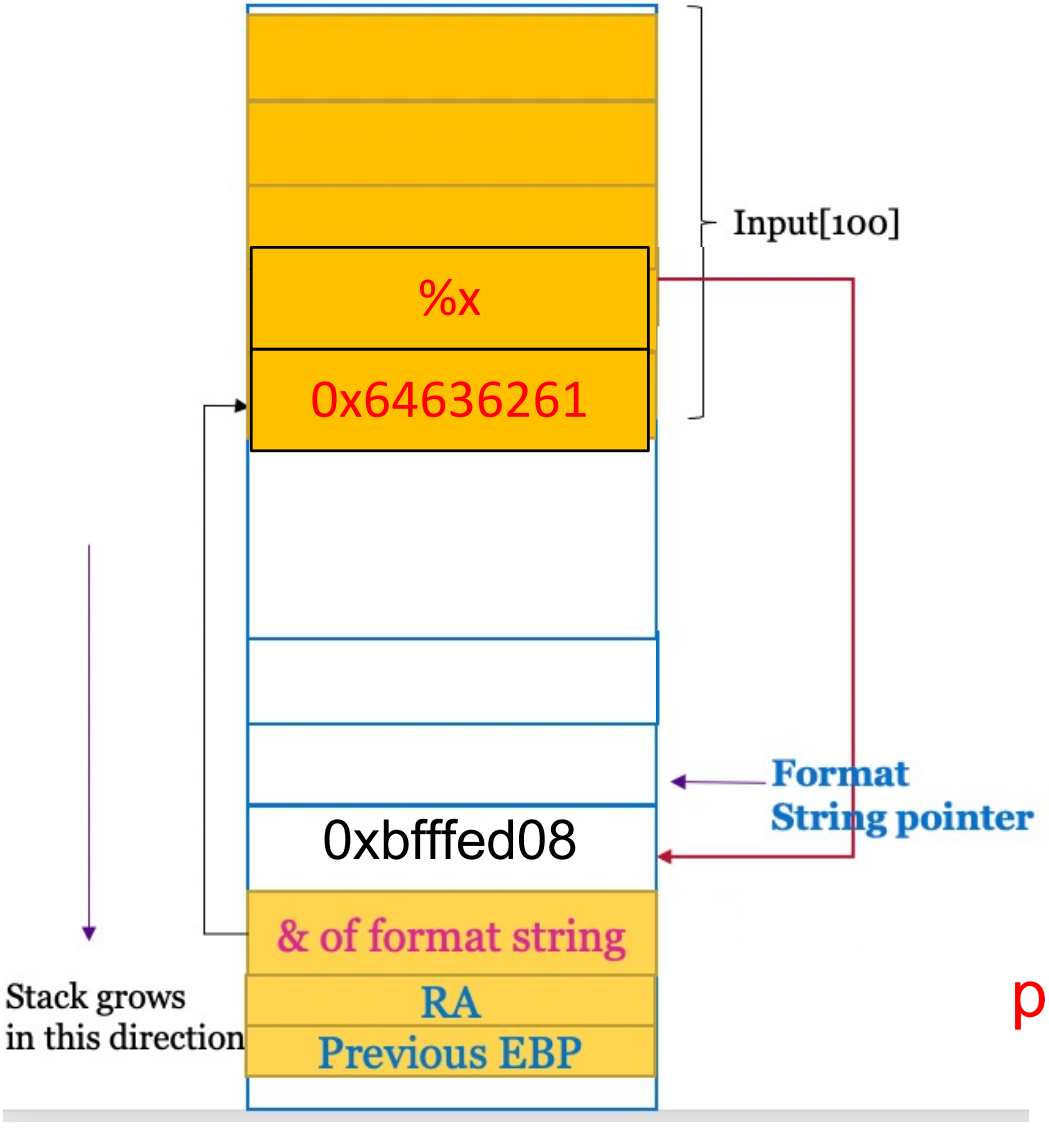



```c
#define PIN 0x44
#define PIN1 0x33

int main(int argc, char *argv[])
{
        char input[100];
        int *pin;

        pin = (int *) malloc(2* sizeof (int));
        pin[0] = PIN;
        pin[1] = PIN1;

        printf("Please enter a string \n");
        scanf("%s", input);

        printf(input);
        printf("\n");

        return 0;
}
```

input = “**abcd**”

printf output = “**abcd**”

Format string vulnerabilities

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        printf("Please enter a string \n");
        scanf("%s", input);

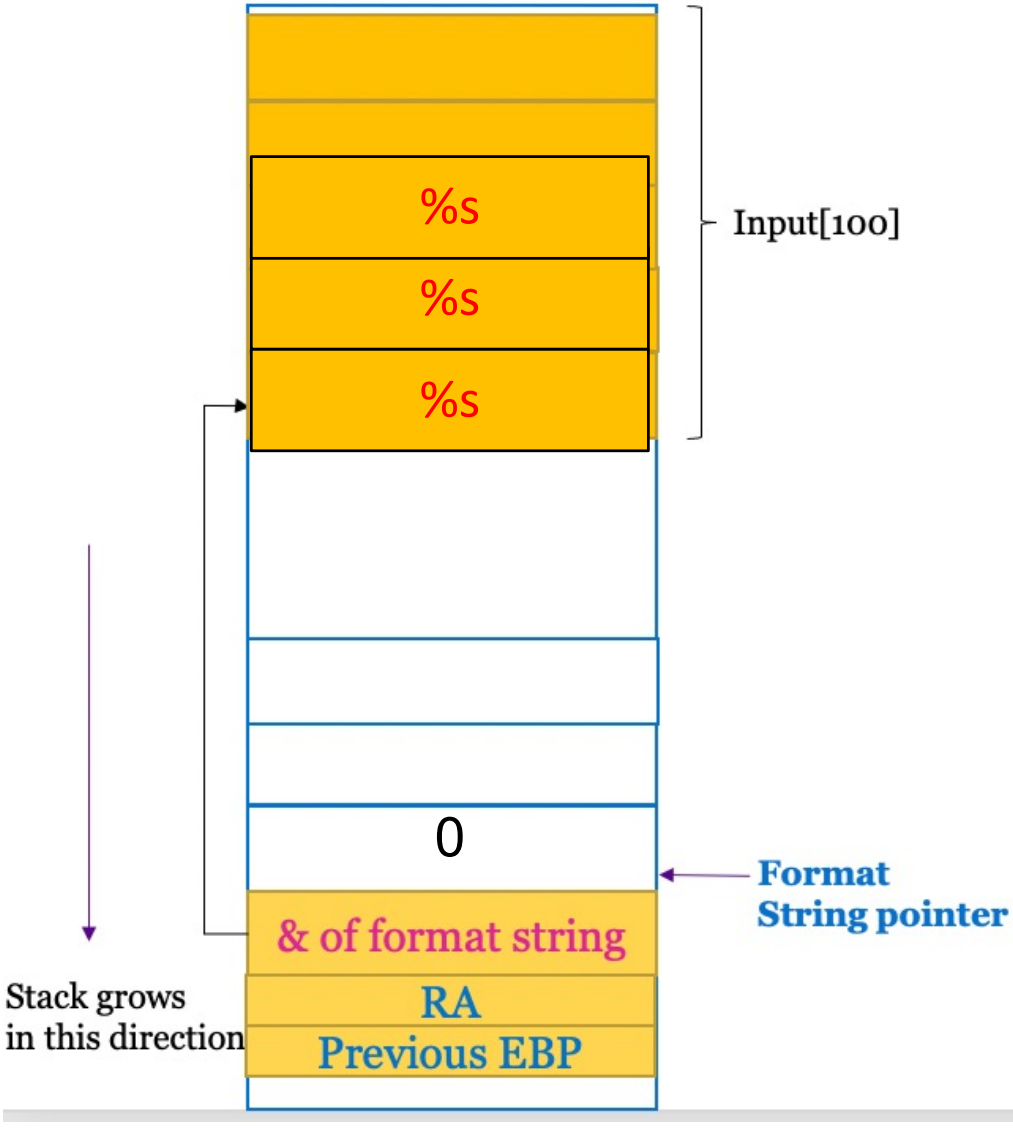
        printf(input);
        printf("\n");

        return 0;
}
```

input = **abcd%x**

printf output = **abcdbfffed08**

Format string vulnerabilities

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        pin[0] = PIN;
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        printf("Please enter a string \n");
        scanf("%s", input);

        printf(input);
        printf("\n");

        return 0;
}
```
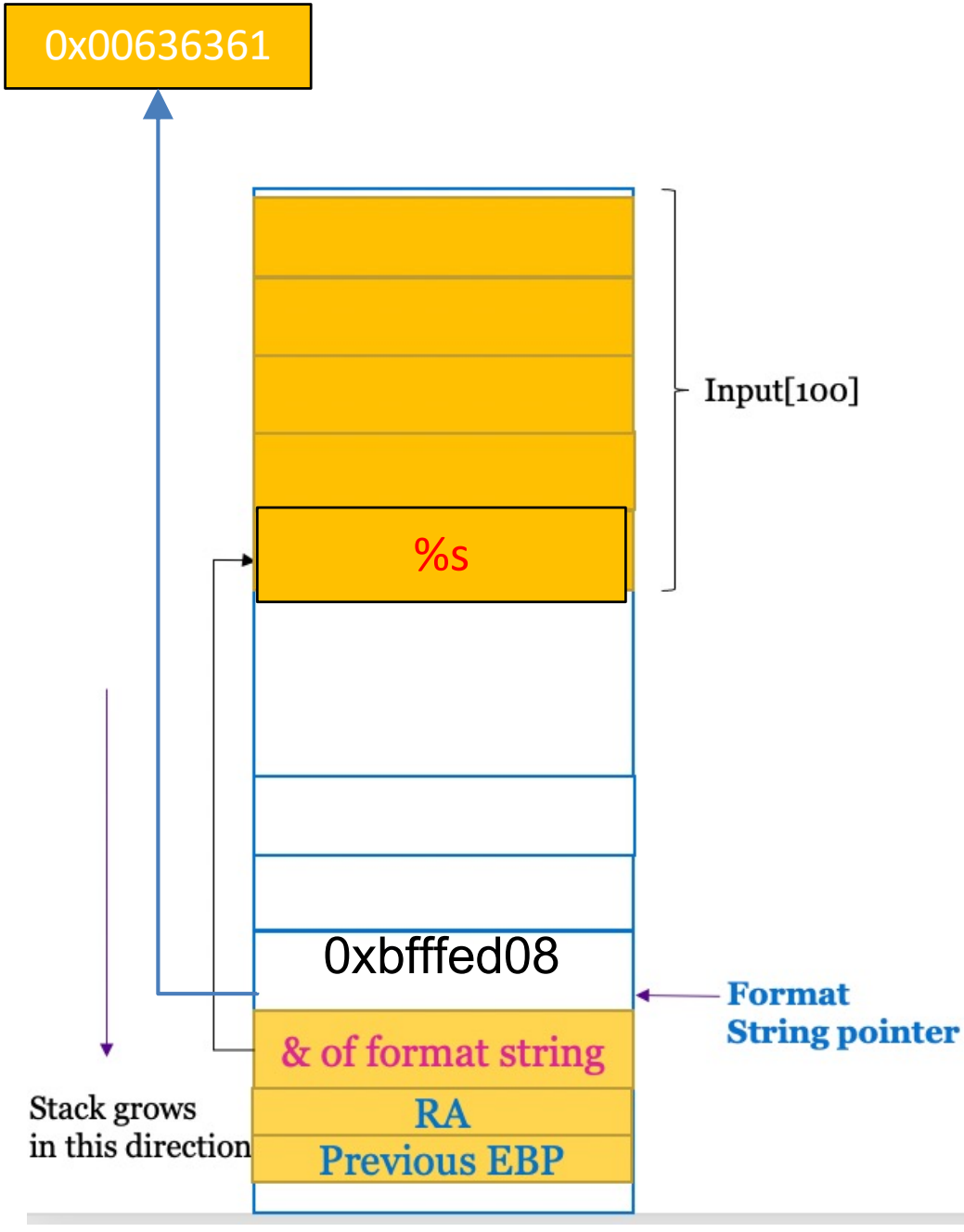

input = "**%s%s%s**"

CRASH!

Format string vulnerabilities

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        printf("Please enter a string \n");
        scanf("%s", input);

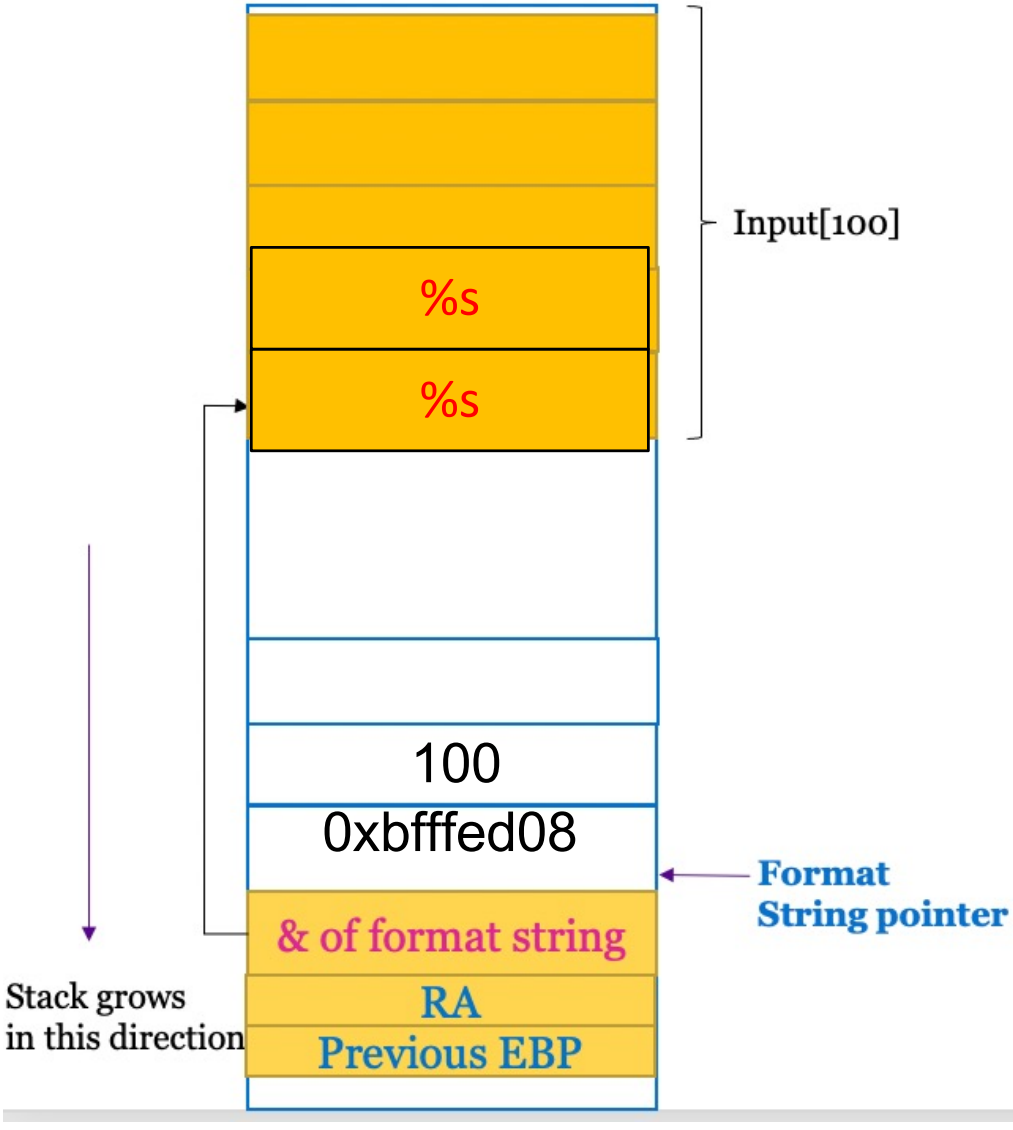
        printf(input);
        printf("\n");

        return 0;
}
```

input = "**%s**"

Output = acc

Format string vulnerabilities

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        scanf("%s", input);

        printf(input);
        printf("\n");

        return 0;
}
```
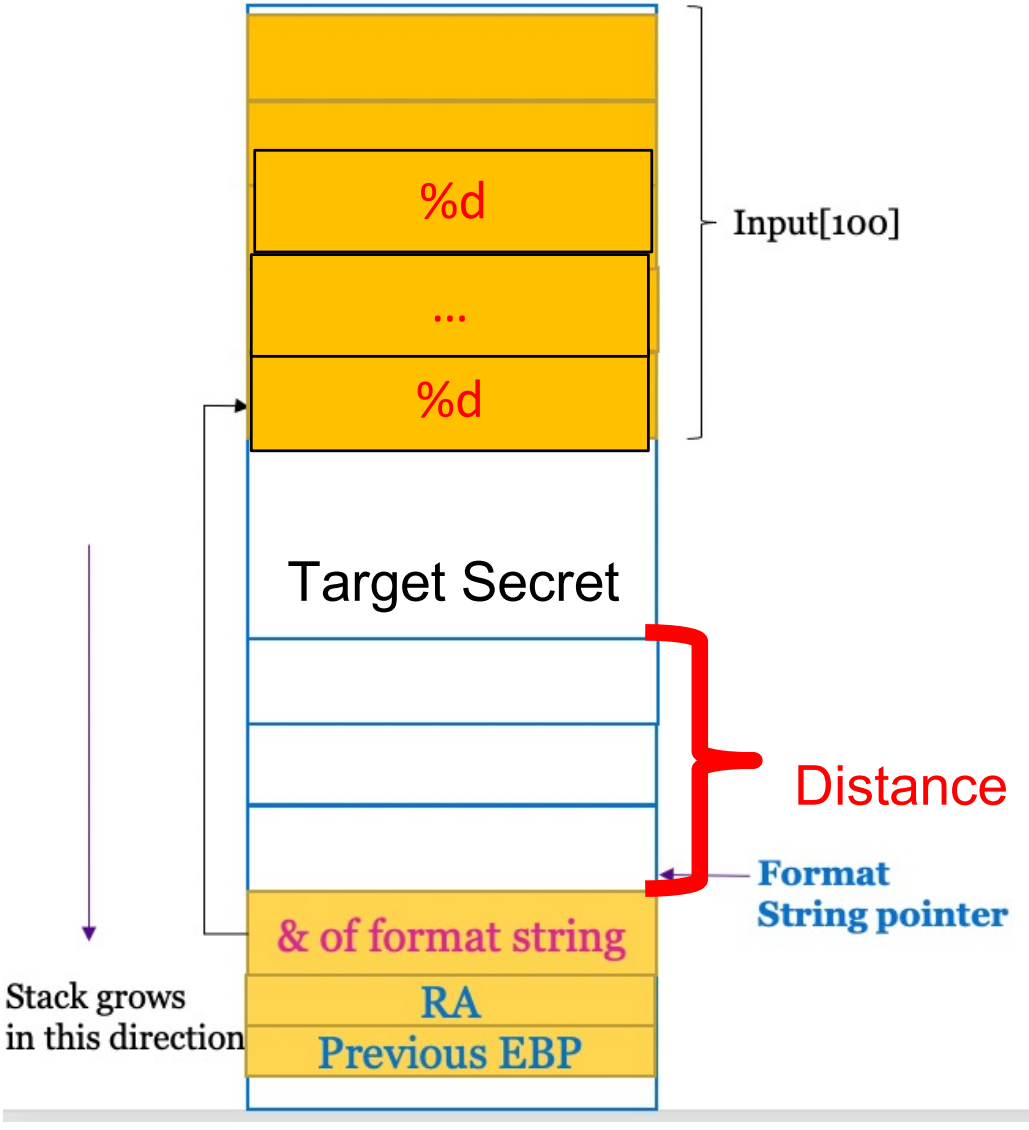

input = "**%s%s**"

CRASH!

Format string vulnerabilities

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        printf("Please enter a string \n");
        scanf("%s", input);

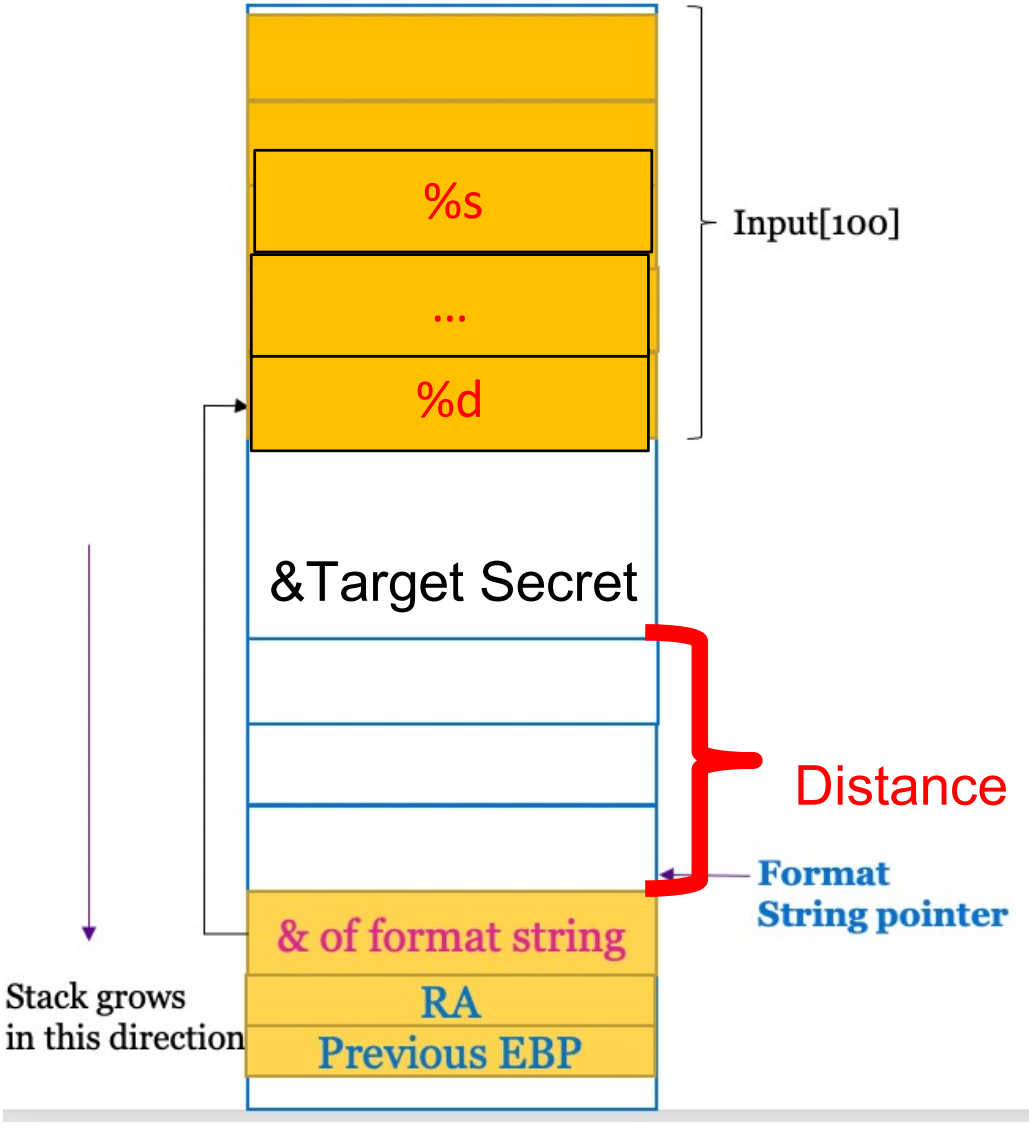
        printf(input);
        printf("\n");

        return 0;
}
```

Goal: read a secret int

Input: %d…%d

Format string vulnerabilities

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        printf("Please enter a string \n");
        scanf("%s", input);

        printf(input);
        printf("\n");

        return 0;
}
```
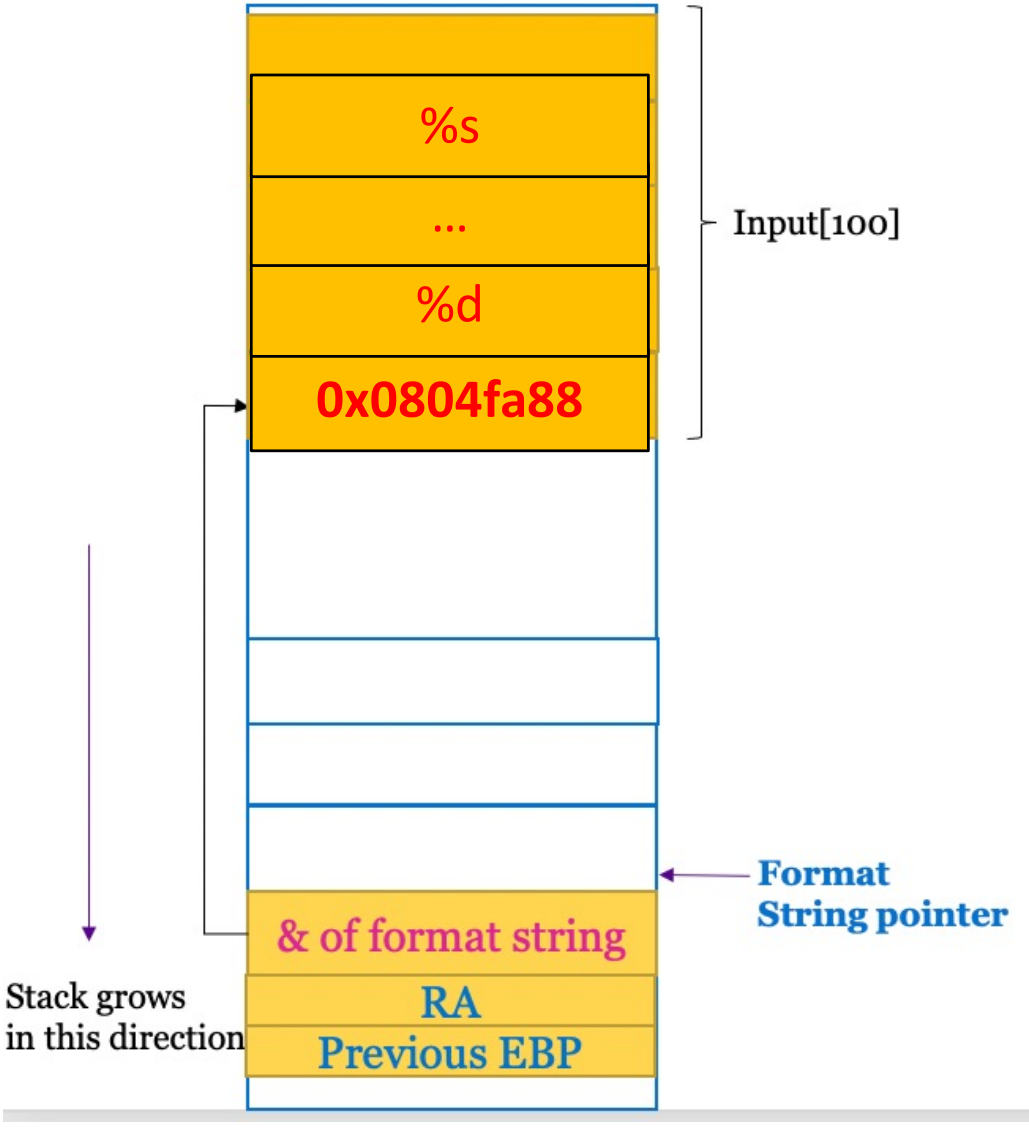

Goal: read a secret str

Input: %d…%s

Format string vulnerabilities




```c
#define PIN 0x44
#define PIN1 0x33

int main(int argc, char *argv[])
{
        char input[100];
        int *pin;

        pin = (int *) malloc(2* sizeof (int));
        pin[0] = PIN;
        pin[1] = PIN1;

        printf("Please enter a string \n");
        scanf("%s", input);

        printf(input);
        printf("\n");

        return 0;
}
```

Goal: read pin[0]

Through Debugging:
&pin is **0x0804fa88**

TOCTTOU errors

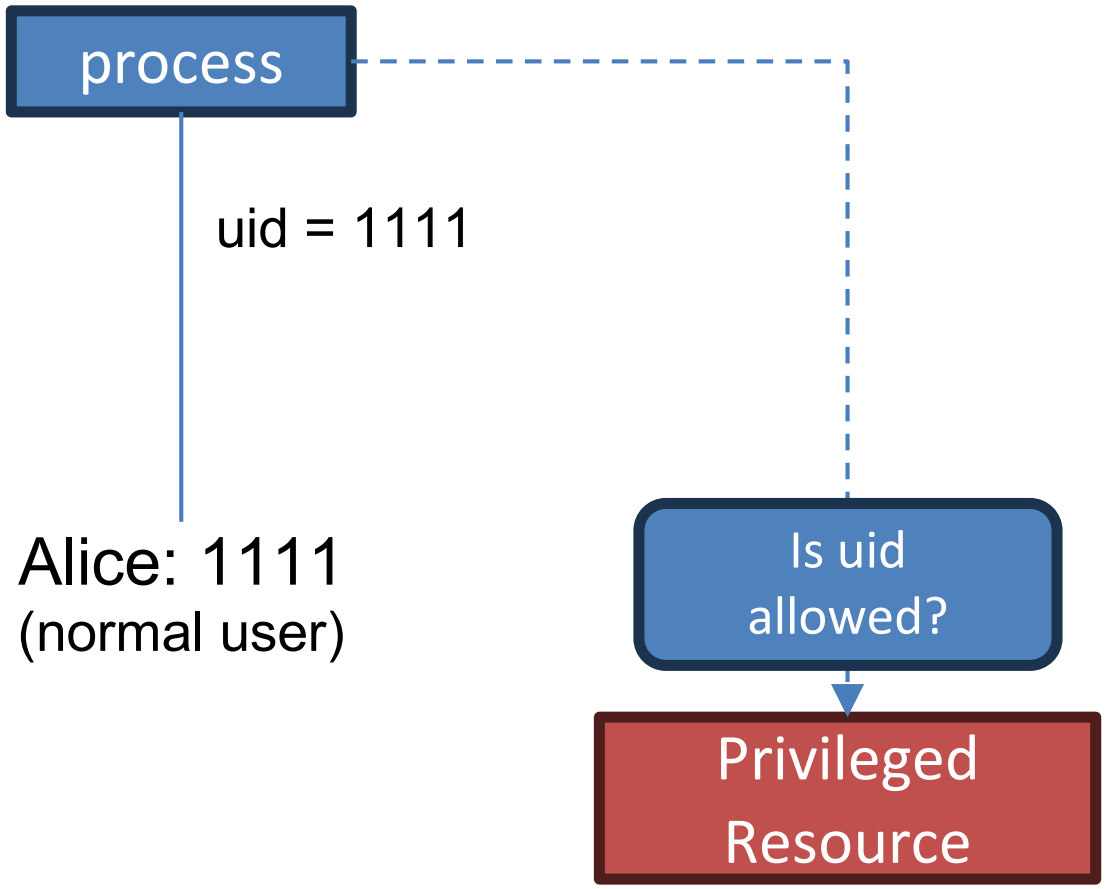
- TOCTTOU ("TOCK-too") errors
  - Time-Of-Check To Time-Of-Use
  - Also known as "race condition" errors

- These errors may occur when the following happens:
  1. User requests the system to perform an action
  2. The system verifies the user is allowed to perform the action
  3. The system performs the action

- What happens if the state of the system changes between steps 2 and 3?

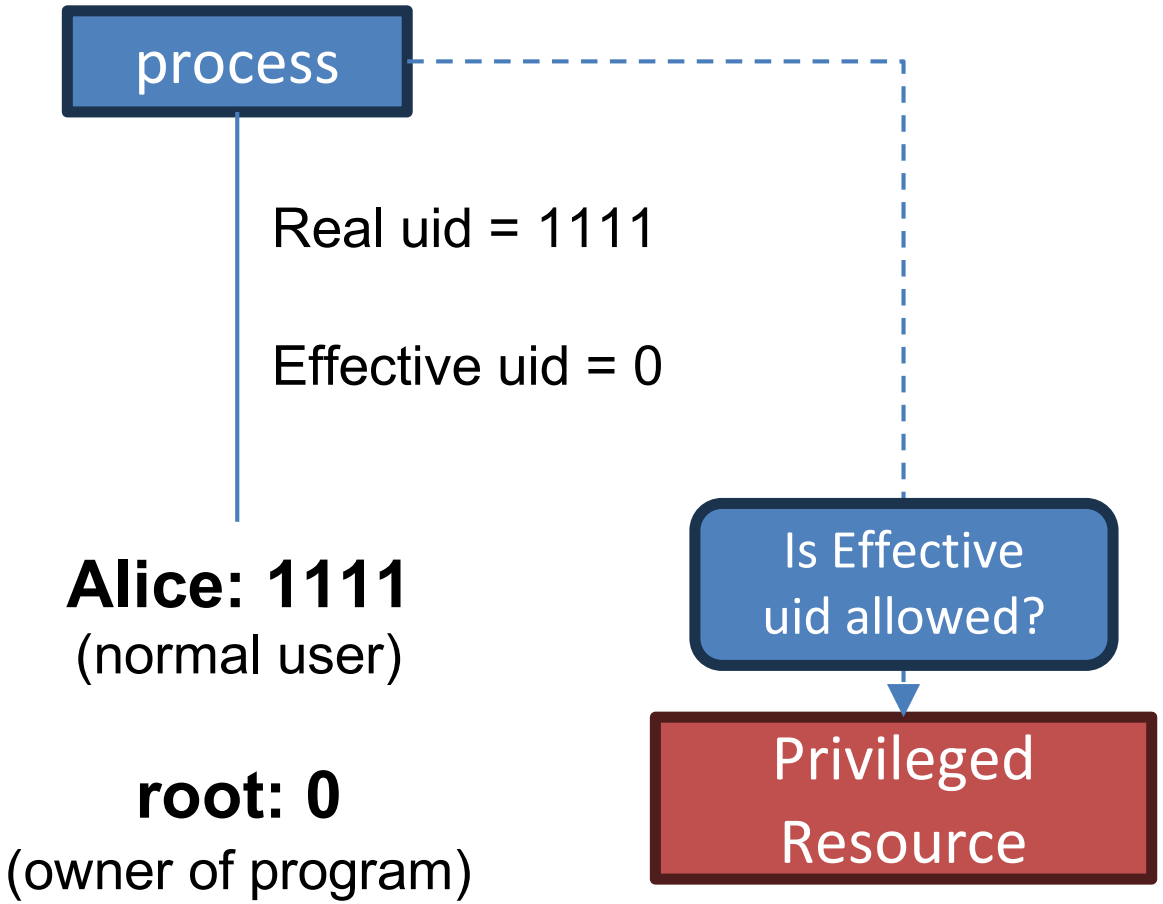
Exploiting TOCTTOU: Setuid programs

- Typical scenario for normal (non-setuid) programs



Exploiting TOCTTOU: Setuid programs

- Typical scenario for **setuid programs**



- Root-owned Setuid programs run with root privileges

TOCTTOU errors: Example

- Root-owned setuid program: it can write to all files in /tmp/
- The program enforces access control: it checks if the user running the program has write permission to the requested file

```
if (!access("/tmp/X", W_OK)){
    f = open("/tmp/X", O_WRITE);
    write_to_file(f);
}
else {
   /* the real user does not have the write permission */
   fprintf(stderr, "Permission denied\n");
}
```

checks the real uid

checks the effective uid (root)

TOCTTOU errors: Example

- Root-owned setuid program: it can write to all files in /tmp/
- The program enforces access control: it checks if the user running the program has write permission to the requested file

```
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}
else {
   /* the real user does not have the write permission */
   fprintf(stderr, "Permission denied\n");
}
```

checks the real uid

checks the effective uid (root)

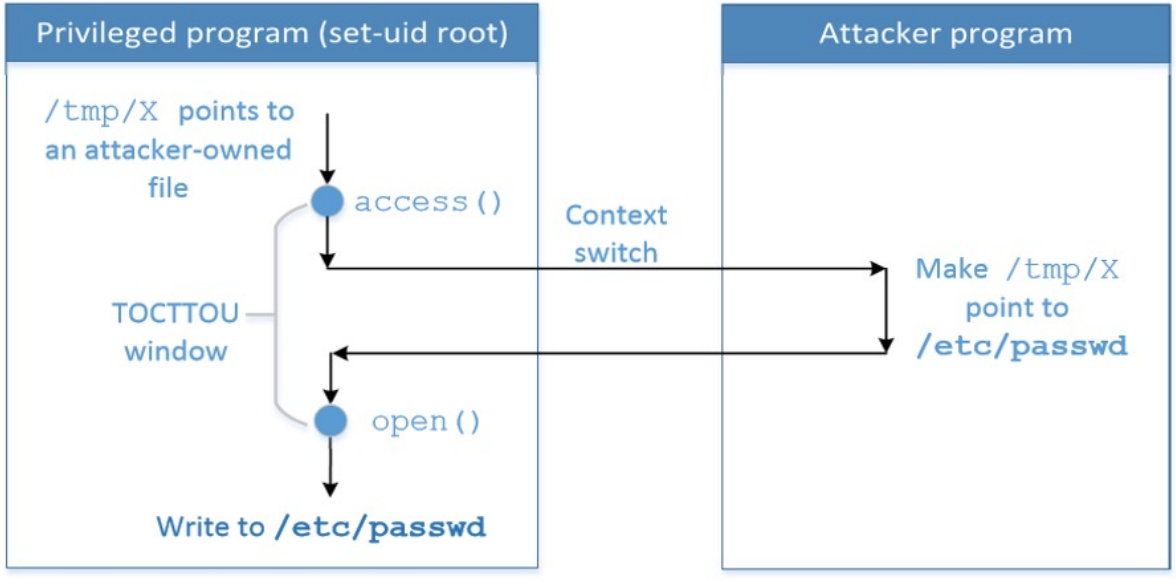
Goal : write to a protected file like `/etc/passwd`.

TOCTTOU errors

```
if (!access("/tmp/X", W_OK)) {
    /* the real user has the write permission*/
    f = open("/tmp/X", O_WRITE);
    write_to_file(f);
}
else {
   /* the real user does not have the write permission */
   fprintf(stderr, "Permission denied\n");
}
```

/tmp/X points to alice_file

/tmp/X points to etc/passwd



Another example: Unix Terminal program:

- A particular Unix terminal program is setuid (runs with superuser privileges) so that it can allocate terminals to users (a privileged operation)
- It supports a command to write the contents of the terminal to a log file
- It first checks if the user has permissions to write to the requested file; if so, it opens the file for writing
- The attacker makes a symbolic link:

  `logfile -> file_she_owns`

- Between the “check” and the “open”, she changes it:

  `logfile -> /etc/passwd`

The problem

- The state of the system changed between the check for permission and the execution of the operation

- The file whose permissions were checked for writeability by the user (`file_she_owns`) wasn't the same file that was later written to (`/etc/passwd`)
  - Even though they had the same name (`logfile`) at different points in time

- Q: Can the attacker really "win this race"?
- A: Yes.

Defences against TOCTTOU errors

- When performing a privileged action on behalf of another party, make sure all information relevant to the access control decision is **constant** between the time of the check and the time of the action ("the race")
  - Keep a private copy of the request itself so that the request can't be altered during the race
  - Where possible, act on the object itself, and not on some level of indirection
    - e.g. Make access control decisions based on filehandles, not filenames
  - If that's not possible, use locks to ensure the object is not changed during the race

Module outline

1. Flaws, faults, and failures
2. Unintentional security flaws
3. Malicious code: Malware
4. Other malicious code
5. Nonmalicious flaws
6. Controls against security flaws in programs

Malware

- Various forms of software written with malicious intent
- Common characteristic of all types of malware: needs to be executed in order to cause harm
- How might malware get executed?
  - User action
    - Downloading and running malicious software
    - Viewing a web page containing malicious code
    - Opening an executable email attachment
    - Inserting a CD/DVD or USB flash drive
  - Exploiting an existing fault in a system
    - Buffer overflows in network daemons
    - Buffer overflows in email clients or web browsers

Types of malware

- Virus
  - Malicious code that adds itself to benign programs/files
  - Code for spreading + code for actual attack
  - Usually activated by users
- Worms
  - Malicious code spreading with no or little user involvement

Types of malware (2)

- Trojans
  - Malicious code hidden in seemingly innocent program that you download
- Logic Bombs
  - Malicious code hidden in programs already on your machine

Viruses

- A virus is a particular kind of malware that infects other files
  - Traditionally, a virus could infect only executable programs
  - Nowadays, many data document formats can contain executable code (such as macros)
    - Many different types of files can be infected with viruses
- Typically, when the file is executed (or sometimes just opened), the virus activates, and tries to infect other files with copies of itself
- In this way, the virus can spread between files, or between computers

Infection

- What does it mean to “infect” a file?
- The virus wants to modify an existing (non-malicious) program or document (the host) in such a way that executing or opening it will transfer control to the virus
  - The virus can do its “dirty work” and then transfer control back to the host
- For executable programs:
  - Typically, the virus will modify other programs and copy itself to the beginning of the targets’ program code
- For documents with macros:
  - The virus will edit other documents to add itself as a macro which starts automatically when the file is opened

Infection

- In addition to infecting other files, a virus will often try to infect the computer itself
  - This way, every time the computer is booted, the virus is automatically activated
- It might put itself in the boot sector of the hard disk
- It might add itself to the list of programs the OS runs at boot time
- It might infect one or more of the programs the OS runs at boot time
- It might try many of these strategies
  - But it's still trying to evade detection!

Spreading

- How do viruses spread between computers?
- Usually, when the user sends infected files (hopefully not knowing they're infected!) or compromised website links to his friends
- A virus usually requires some kind of user action in order to spread to another machine
  - If it can spread on its own (via email, for example), it's more likely to be a worm than a virus

Payload

- In addition to trying to spread, what else might a virus try to do?
- Some viruses try to evade detection by disabling any active virus scanning software
- Most viruses have some sort of payload:
  - Erase your hard drive, or make your data inaccessible
  - Subtly corrupt some of your spreadsheets
  - Install a keystroke logger to capture your online banking password
  - Start attacking a particular target website

Spotting viruses

- When should we look for viruses?
  - As files are added to our computer
    - Via portable media
    - Via a network
  - From time to time, scan the entire state of the computer
    - To catch anything we might have missed on its way in
    - But of course, any damage the virus might have done may not be reversible
- How do we look for viruses?
  - Signature-based protection
  - Behaviour-based protection

Signature-based protection

- Keep a list of all known viruses
- For each virus in the list, store some characteristic feature (the signature)
  - Most signature-based systems use features of the virus code itself
    - The infection code
    - The payload code
  - Can also try to identify other patterns characteristic of a particular virus
    - Where on the system it tries to hide itself
    - How it propagates from one place to another

Polymorphism

- To try to evade signature-based virus scanners, some viruses are polymorphic
  - This means that instead of making perfect copies of itself every time it infects a new file or host, it makes a modified copy instead
  - This is often done by having most of the virus code encrypted
    - The virus starts with a decryption routine which decrypts the rest of the virus, which is then executed
    - When the virus spreads, it encrypts the new copy with a newly chosen random key
- How would you scan for polymorphic viruses?

Behaviour-based protection

- Signature-based protection systems have a major limitation
  - You can only scan for viruses that are in the list!
  - But there are brand-new viruses identified every day
  - What can we do?
- Behaviour-based systems look for suspicious patterns of behaviour, rather than for specific code fragments
  - Some systems run suspicious code in a sandbox first

False negatives and positives

- Any kind of test or scanner can have two types of errors:
  - False negatives: fail to identify a threat that is present
  - False positives: claim a threat is present when it is not
- Which is worse?
- How do you think signature-based and behaviour-based systems compare?

Worms

- A worm is a self-contained piece of code that can replicate with little or no user involvement
- Worms often use security flaws in widely deployed software as **a path to infection**
- Typically:
  - A worm exploits a security flaw in some software on your computer, infecting it
  - The worm immediately starts searching for other computers (on your local network, or on the Internet generally) to infect
  - There may or may not be a payload that activates at a certain time, or by another trigger

The Morris worm

- The first Internet worm, launched by a graduate student at Cornell in 1988
- Once infected, a machine would try to infect other machines in three ways:
  - Exploit a buffer overflow in the “finger” daemon
  - Use a back door left in the “sendmail” mail daemon
  - Try a “dictionary attack” against local users’ passwords. If successful, log in as them, and spread to other machines they can access without requiring a password
- All three of these attacks were well known!
- First example of buffer overflow exploit in the wild
- Thousands of systems were offline for several days

The Code Red worm

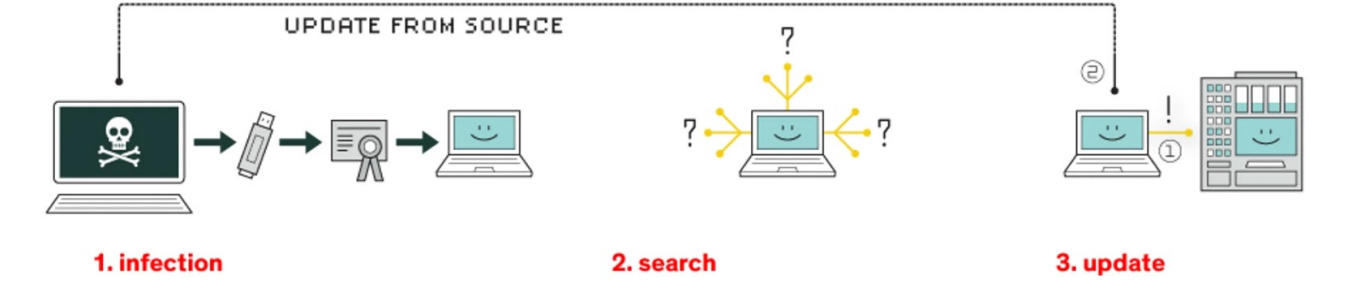
- Launched in 2001
- Exploited a buffer overflow in Microsoft's IIS web server (for which a patch had been available for a month)
- An infected machine would:
  - Deface its home page
  - Launch attacks on other web servers (IIS or not)
  - Launch a denial-of-service attack on a handful of web sites, including www.whitehouse.gov
  - Installed a back door to deter disinfection
- Infected 250,000 systems in nine hours

Stuxnet

- Discovered in 2010
- Allegedly created by the US and Israeli intelligence agencies
- Allegedly targeted Iranian uranium enrichment program
- Targets Siemens SCADA systems installed on Windows. One application is the operation of centrifuges
- It tries to be very specific and uses many criteria to select which systems to attack after infection

Stuxnet

- Used 4(!) different zero-day attacks to spread. Has to be installed manually (USB drive) for air-gapped systems.
- Very stealthy and targeted: Intercepts commands to SCADA system and hides its presence



IoT Malware

- Internet-of-Things (IoT): connected home, industry automation etc.
- Cheap commodity devices with Internet connectivity.
- Dismal security: lack of expertise, lack of resources (CPU, memory, etc.)
- e.g., Mirai (2016): Took out DNS provider Dyn, making many popular services unreachable.

Trojan horses

http://www.sampsonuk.net/B3TA/TrojanHorse.jpg

Trojan horses

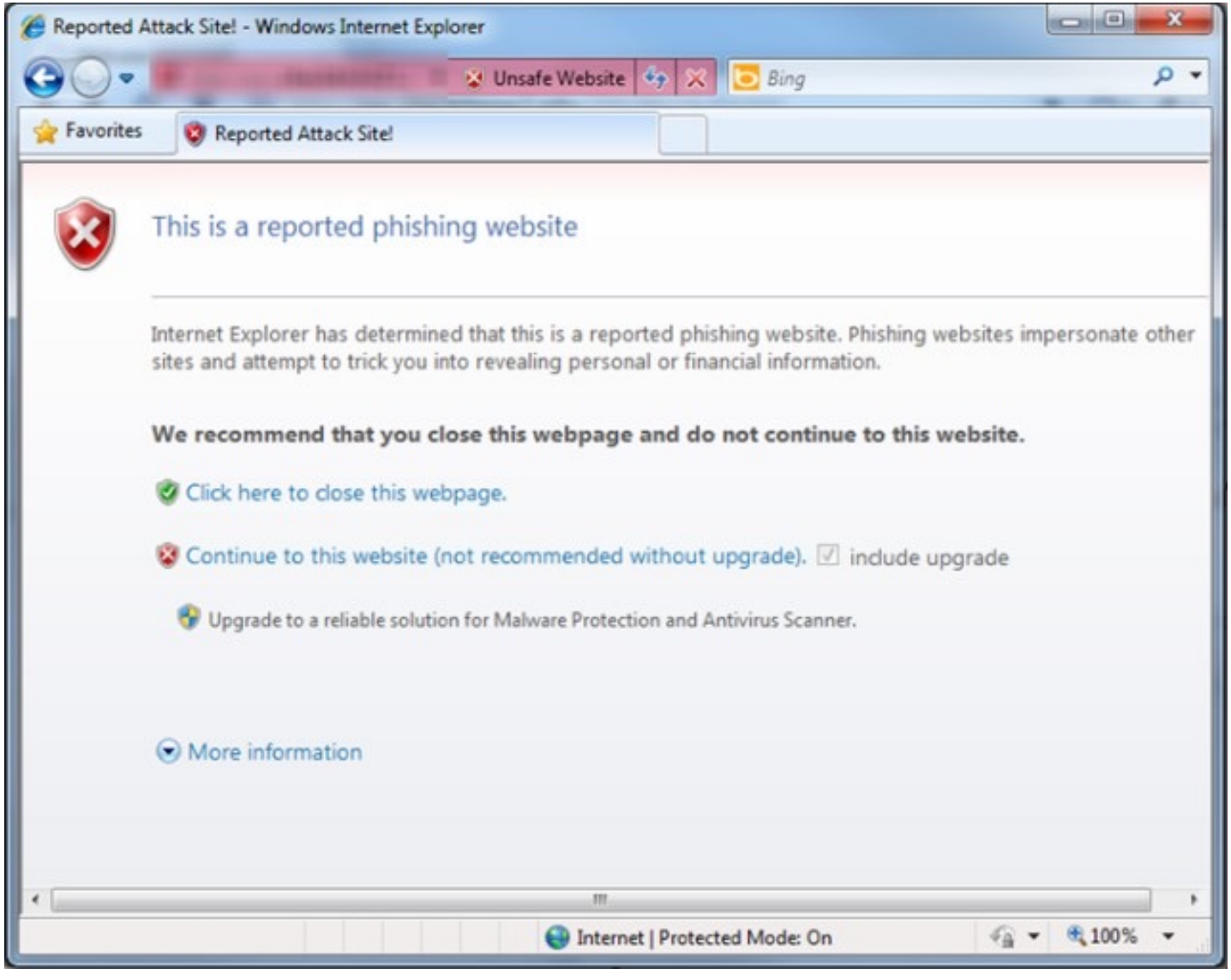
- Trojan horses are programs which claim to do something innocuous (and usually do), but which also hide malicious behaviour

You're surfing the Web and you see a button on the Web site saying, "Click here to see the dancing pigs." And you click on the Web site and then this window comes up saying, "Warning: this is an untrusted Java applet. It might damage your system. Do you want to continue? Yes/No." Well, the average computer user is going to pick dancing pigs over security any day. And we can't expect them not to. — Bruce Schneier

Trojan horses

- Gain control by getting the user to run code of the attacker's choice, usually by also providing some code the user wants to run
  - "PUP" (potentially unwanted programs) are an example
- The payload can be anything; sometimes the payload of a Trojan horse is itself a virus, for example

Scareware



http://static.arstechnica.com/malware_warning_2010.png

Ransomware

/en.wikipedia.org/wiki/WannaCry_ransomware_attack#/media/File:Wana_Decrypt0r_screensh

Ransomware

- Demands ransom to return some hostage resource to the victim
- CryptoLocker in 2013:
  - Spread with spoofed e-mail attachments from a botnet
  - Encrypted victim's hard drive
  - Demanded ransom for private key
  - Botnet taken down in 2014; estimated ransom collected between $3 million to $30 million
- Could also be scareware

Logic bombs

- A logic bomb is malicious code hiding in the software already on your computer, waiting for a certain trigger to "go off" (execute its payload)

- Logic bombs are usually written by "insiders", and are meant to be triggered sometime in the future
  - After the insider leaves the company

- The payload of a logic bomb is usually pretty dire
  - Erase your data
  - Corrupt your data
  - Encrypt your data, and ask you to send money to some offshore bank account in order to get the decryption key!

Spotting Trojan horses and logic bombs

- Spotting Trojan horses and logic bombs is extremely tricky. Why?
- The user is intentionally running the code!
  - Trojan horses: the user clicked “yes, I want to see the dancing pigs”
  - Logic bombs: the code is just (a hidden) part of the software already installed on the computer
- Don’t run code from untrusted sources?
- Better: prevent the payload from doing bad things
  - More on this later

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Other malicious code

- Back doors
- Keystroke logging
- Interface illusions
- Privilege escalation
- Rootkits

Back doors

- A back door (also called a trapdoor) is a set of instructions designed to bypass the normal authentication mechanism and allow access to the system to anyone who knows the back door exists
  - Sometimes these are useful for debugging the system, but don't forget to take them out before you ship!

Back doors

- Interesting example:

Backdoor in D-Link routers

```
xmlset_roodkcableoj28840ybtide
```

Examples of back doors

- Real examples:
  - Debugging back door left in sendmail
  - Back door planted by Code Red worm
  - Attempted hack to Linux kernel source code
    - ```
      if ((options == (__WCLONE|__WALL)) &&
      (current->uid = 0))
        retval = -EINVAL;
      ```
      ```

Sources of back doors

- Forget to remove them
- Intentionally leave them in for testing purposes
- Intentionally leave them in for maintenance purposes
  - Field service technicians
- Intentionally leave them in for legal reasons
  - “Lawful Access”
- Intentionally leave them in for malicious purposes
  - Note that malicious users can use back doors left in for non-malicious purposes, too!

Keystroke logging

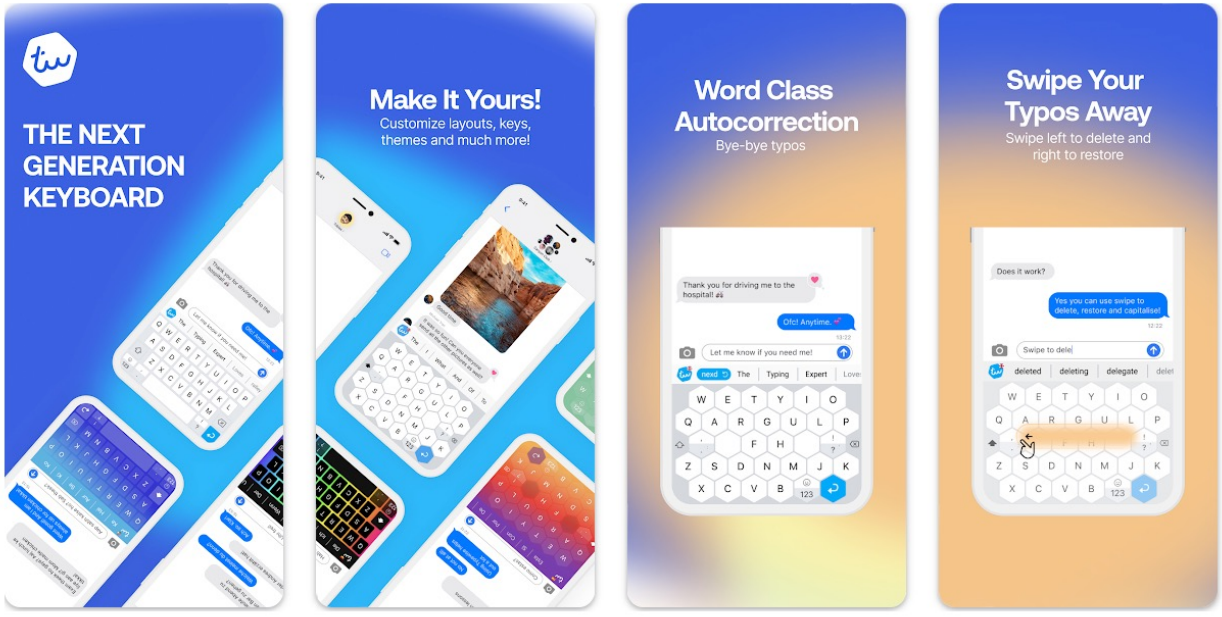
- Almost all of the information flow from you (the user) to your computer (or beyond, to the Internet) is via the keyboard
  - A little bit from the mouse, a bit from devices like USB keys
- An attacker might install a keyboard logger on your computer to keep a record of:
  - All email / IM you send
  - All passwords you type
- This data can then be accessed locally, or it might be sent to a remote machine over the Internet

Who installs keyboard loggers?

- Some keyboard loggers are installed by malware
  - Capture passwords, especially banking passwords
  - Send the information to the remote attacker
- Others are installed by one family member to spy on another
  - Spying on children
  - Spying on spouses
  - Spying on boy/girlfriends

Kinds of keyboard loggers

- Application-specific loggers:
  - Record only those keystrokes associated with a particular application, such as an IM client



Kinds of keyboard loggers

- Application-specific loggers:
  - Record only those keystrokes associated with a particular application, such as an IM client
- System keyboard loggers:
  - Record all keystrokes that are pressed (maybe only for one particular target user)
- Hardware keyboard loggers:
  - A small piece of hardware that sits between the keyboard and the computer
    - Works with any OS
    - Completely undetectable in software

Interface illusions

- You use user interfaces to control your computer all the time
- For example, you drag on a scroll bar to see offscreen portions of a document
- But what if that scrollbar isn't really a scrollbar?
- What if dragging on that "scrollbar" really dragged a program (from a malicious website) into your "Startup" folder (in addition to scrolling the document)?
  - This really happened

Interface Illusion by Conficker worm

Another example of Interface Illusion

Interface illusions

- We think we're doing one thing, but we're really doing another
- How might you defend against this?

Clickjacking

- Clickjacking is an example of an interface illusion

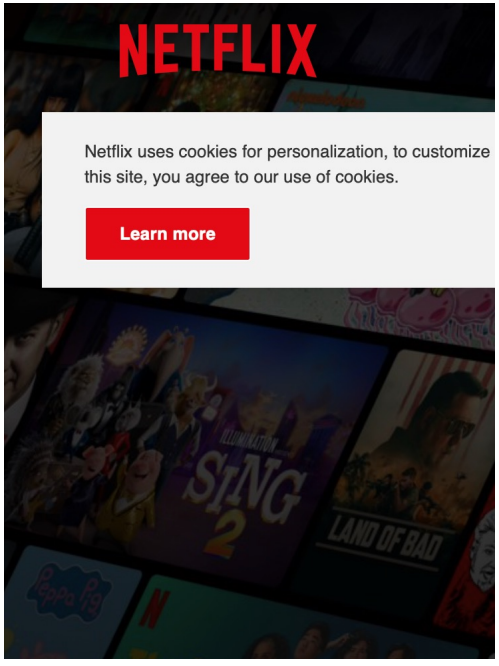
- Clickjacking is an attack that tricks the user into clicking a UI element which is invisible or disguised as another UI element.

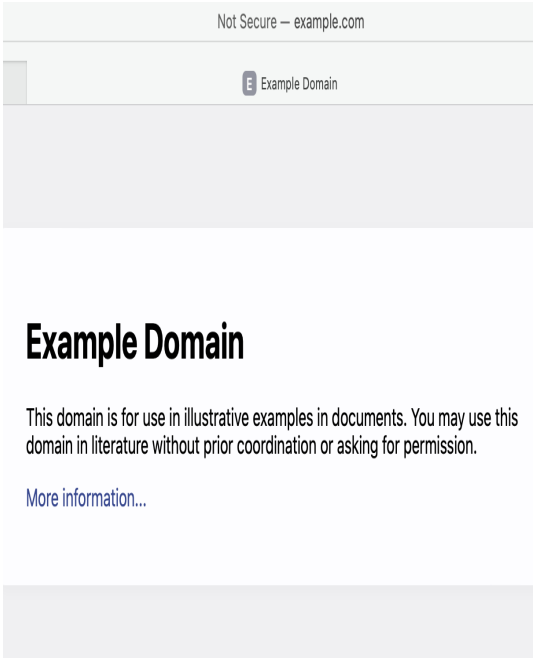
Clickjacking

- Iframe-based Clickjacking:

- An Iframe is an inline frame

```
<iframe src=www.netflix.com></iframe>
<iframe src=www.example.com></iframe>
```

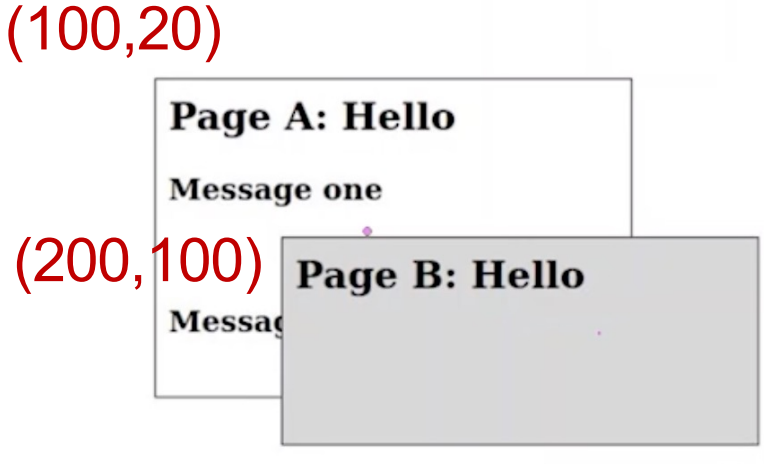




Clickjacking: overlapping iframes

```
<iframe id="A" src="http://www.attacker32.com/hello.html"></iframe>
<iframe id="B" src="http://www.bank32.com/hello.html"></iframe>

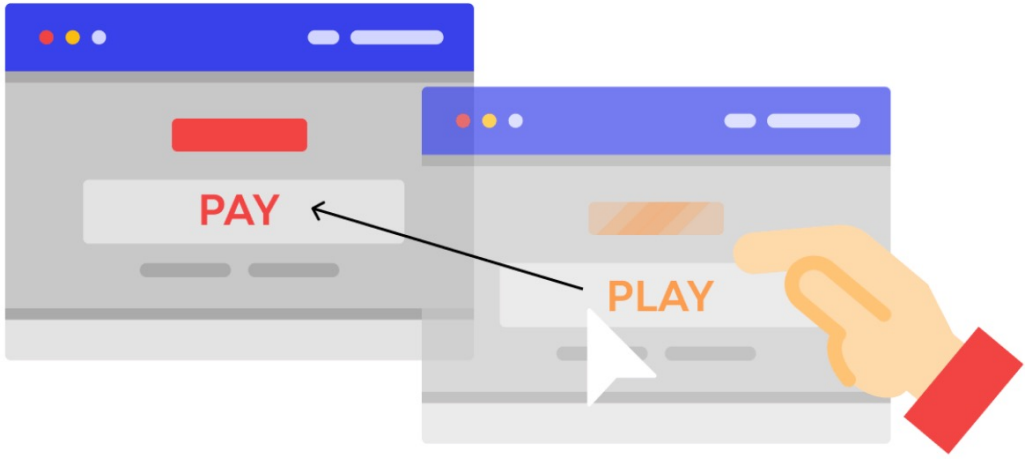
<style type="text/css">
  #A  { position:absolute; top:100px; left:20px;
        width:300px; height:200px;
        border:1px solid black;
        background-color: white; }
  #B  { position:absolute; top:200px; left:100px;
        width:300px; height:130px;
        border:1px solid black;
        background-color: lightgrey; }
</style>
```



Clickjacking: transparent iframe

```
<iframe id="A" src="http://www.attacker32.com/hello.html"></iframe>
<iframe id="B" src="http://www.bank32.com/hello.html"></iframe>

<style type="text/css">
  #A  { position:absolute; top:100px; left:20px;
        width:300px; height:200px;
        border:1px solid black;
        background-color: white;
      }
  #B  { position:absolute; top:200px; left:100px;
        width:300px; height:130px;
        border:1px solid black;
        background-color: lightgrey;
        opacity:0.7;
      }
</style>
```



Phishing

- Phishing is an example of an interface illusion
- It looks like you're visiting Paypal's website, but you're really not.
  - If you type in your password, you've just given it to an attacker
  - paypal.com (what is wrong with this site?)
- Advanced phishers can make websites that look every bit like the real thing
  - Even if you carefully check the address bar, or even the SSL certificate!

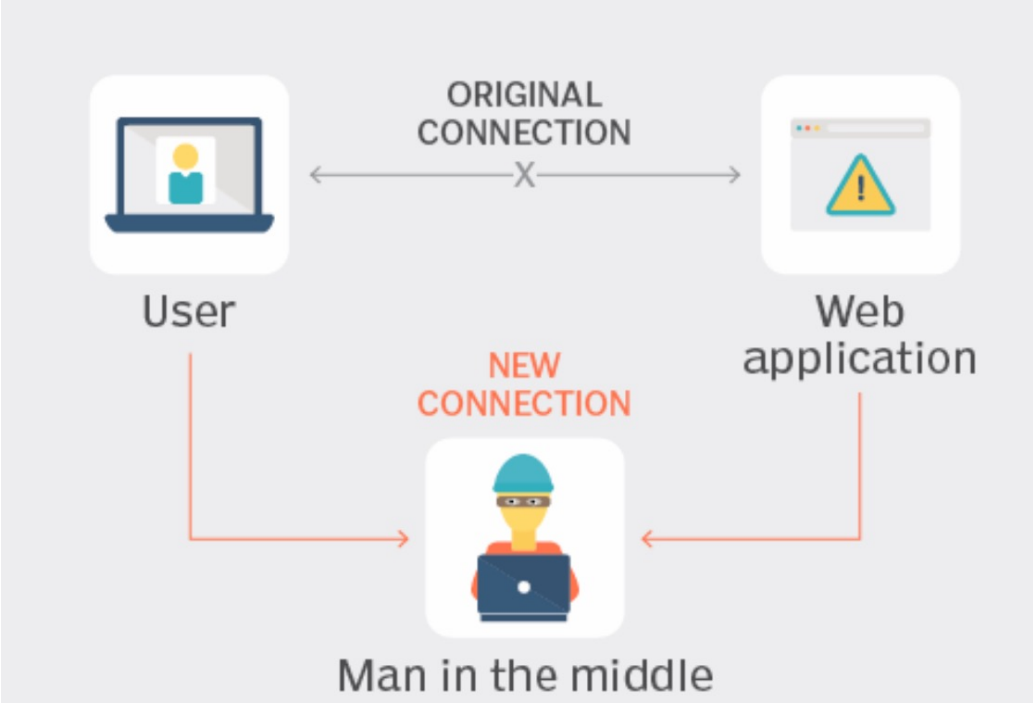
Phishing Detection

- Unusual email/URL
  - Especially if similar to known URL/email
  - Email that elicits a strong emotional response and requests fast action on your part
- Attachments with uncommon names
- Typos, unusual wording
- No https (not a guarantee)

Man-in-the-middle attacks

- Keyboard logging, interface illusions, and phishing are examples of man-in-the-middle attacks
- The website/program/system you're communicating with isn't the one you think you're communicating with
- A man-in-the-middle intercepts the communication from the user, and then passes it on to the intended other party
  - That way, the user thinks nothing is wrong, because his password works, he sees his account balances, etc.

Man-in-the-middle attacks



Rootkits

- A rootkit is a tool often used by “script kiddies”
- It has two main parts:
  - A method for gaining unauthorized root / administator privileges on a machine (either starting with a local unprivileged account, or possibly remotely)
    - This method usually expoits some known flaw in the system that the owner has failed to correct
    - It often leaves behind a back door so that the attacker can get back in later, even if the flaw is corrected
  - A way to hide its own existence
    - “Stealth” capabilities
    - Sometimes just this stealth part is called the rootkit

Stealth capabilities

- How do rootkits hide their existence?
  - Clean up any log messages that might have been created by the exploit
  - Modify commands like `ls` and `ps` so that they don't report files and processes belonging to the rootkit
  - Alternately, modify the kernel so that no user program will ever learn about those files and processes!

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Covert channels

- An attacker creates a capability to transfer sensitive/unauthorized information through a channel that is not supposed to transmit that information.

Covert channels

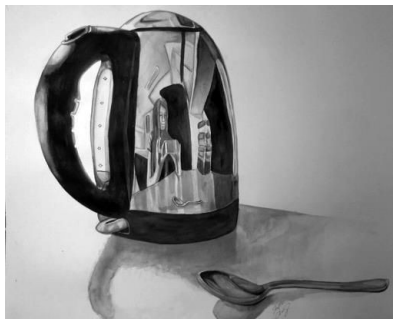
- Assume that Eve can arrange for malicious code to be running on Alice's machine
  - But Alice closely watches all Internet traffic from her computer
  - Better, she doesn't connect her computer to the Internet at all!
- Suppose Alice publishes a weekly report summarizing some (nonsensitive) statistics
- Eve can "hide" the sensitive data in that report!
  - Modifications to spacing, wording, or the statistics itself
  - This is called a covert channel

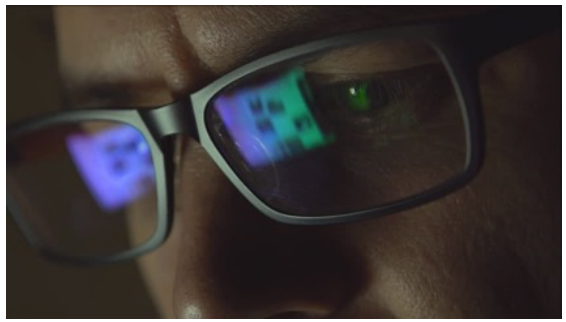
Side channels

- What if Eve can't get Trojaned software on Alice's computer in the first place?
- It turns out there are some very powerful attacks called side channel attacks
  - Eve watches how Alice's computer behaves when processing the sensitive data
  - Eve usually has to be somewhere in the physical vicinity of Alice's computer to pull this off

Example of side channels: Reflections

- Alice types her password on a device in a public place
- Alice hides her screen
- But there is a reflecting surface close by

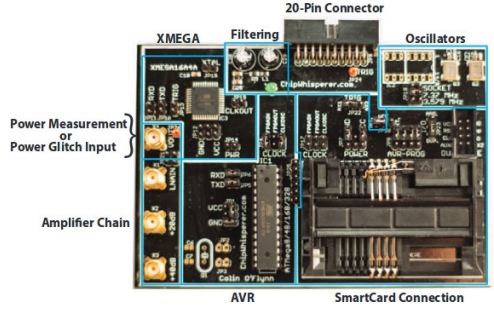




Reflections: Defense

Other potential attack vectors

- Bandwidth consumption
- Timing computations
- Cache timing
- Electromagnetic emission
- Sound emissions
- Power consumption
- Differential power analysis
- Differential fault analysis



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6. Controls against security flaws in programs

The picture so far

- We've looked at a large number of ways an attacker can compromise program security
  - Exploit unintentional flaws
  - Introduce malicious code, including malware
  - Exploit intentional, but nonmalicious, behaviour of the system
- The picture looks pretty bleak
- Our job is to control these threats
  - It's a tough job

Software lifecycle

- Software goes through several stages in its lifecycle:
  - Specification
  - Design
  - Implementation
  - Change management
  - Code review
  - Testing
  - Documentation
  - Maintenance
- At which stage should security controls be considered?

Security controls—Design

- How can we design programs so that they're less likely to have security flaws?

- Modularity
- Encapsulation
- Information hiding
- Mutual suspicion
- Confinement

Modularity

- Break the problem into a number of small pieces ("modules"), each responsible for a single subtask
- The complexity of each piece will be smaller, so each piece will be far easier to check for flaws, test, maintain, reuse, etc.
- Modules should have low coupling
  - A coupling is any time one module interacts with another module
  - High coupling is a common cause of unexpected behaviours in a program

Encapsulation

- Have the modules be mostly self-contained, sharing information only as necessary
- This helps reduce coupling
- The developer of one module should not need to know how a different module is implemented
  - She should only need to know about the published interfaces to the other module (the API)

Information hiding

- The internals of one module should not be visible to other modules
- This is a stronger statement than encapsulation: the implementation and internal state of one module should be hidden from developers of other modules
- Why is information hiding important?

Information hiding

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- This prevents accidental reliance on behaviours not promised in the API

Information Hiding

```
version#1
// Delete wifi connections

void deleteWifiConnections(int type)
{
    connectionManager.deleteConnection(type);
}

version#2
// Delete wifi connections

void deleteWifiConnections(int type)
{
    if (type != 1) return;
    connectionManager.deleteConnection(type);
}
```

Information hiding

- The internals of one module should not be visible to other modules
- This is a stronger statement than encapsulation: the implementation and internal state of one module should be hidden from developers of other modules
- This prevents accidental reliance on behaviours not promised in the API
- It also hinders some kinds of malicious actions by the developers themselves!

Information Hiding

Location Service

```
coordinates getLocation(…)
{
   if( caller.hasPermission(“ACCESS_FINE_LOCATION”)
       || caller.hasPermission(“ACCESS_COARSE_LOCATION”)
        || caller.name.startsWith(“samsung.pck”))
   {
            return this.currentCoordinates;
   }
   else
            // throw Security Exception
}
```

Mutual suspicion

- It's a good idea for modules to check that their inputs are sensible before acting on them
- Especially if those inputs are received from untrusted sources
  - Where have we seen this idea before?

Security controls—Implementation

- When you're actually coding, what can you do to control security flaws?

- Don't use C (but this might not be an option)
- Static code analysis
- Hardware assistance
- Formal methods
- Genetic diversity
- Finally: learn more!

Static code analysis

- There are a number of software products available that will help you find security flaws in your code
  - These work for various languages, including C, C++, Java, Perl, PHP, Python
- They often look for things like buffer overflows, but some can also point out TOCTTOU and other flaws
- These tools are not perfect!
  - They're mostly meant to find suspicious things for you to look at more carefully
  - They also miss things, so they can't be your only line of defence

Hardware assistance

- ARM Pointer Authentication
  https://lwn.net/Articles/718888/
- Hardware-assisted shadow stack
  https://lwn.net/Articles/758245/
- ...

Genetic diversity

- The reason worms and viruses are able to propagate so quickly is that there are many, many machines running the same vulnerable code
  - The malware exploits this code
- If there are lots of different HTTP servers, for example, there's unlikely to be a common flaw
- This is the same problem as in agriculture
  - If everyone grows the same crop, they can all be wiped out by a single virus

Security controls—Code review

- Empirically, code review is the single most effective way to find faults once the code has been written
- The general idea is to have people other than the code author look at the code to try to find any flaws
- This is one of the benefits often touted for open-source software: anyone who wants to can look at the code
  - Given enough eyeballs, all bugs are shallow?

Security controls—Code review

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- The general idea is to have people other than the code author look at the code to try to find any flaws
- This is one of the benefits often touted for open-source software: anyone who wants to can look at the code
  - But this doesn't mean people actually do!
  - Even open-source security vulnerabilities can sit undiscovered for years, in some cases

Kinds of code review

- There are a number of different ways code review can be done
- The most common way is for the reviewers to just be given the code
  - They look it over, and try to spot problems that the author missed
  - This is the open-source model

Guided code reviews

- More useful is a guided walk-through
  - The author explains the code to the reviewers
  - Justifies why it was done this way instead of that way
  - This is especially useful for changes to code
    - Why each change was made
    - What effects it might have on other parts of the system
    - What testing needs to be done
- Important for safety-critical systems!

“Easter egg” code reviews

- One problem with code reviews (especially unguided ones) is that the reviewers may start to believe there’s nothing there to be found
  - After pages and pages of reading without finding flaws (or after some number have been found and corrected), you really just want to say it’s fine
- A clever variant: the author inserts intentional flaws into the code
  - The reviewers now know there are flaws
  - The theory is that they’ll look harder, and are more likely to find the unintentional flaws
  - It also makes it a bit of a game

Security controls—Testing

- The goal of testing is to make sure the implementation meets the specification
- But remember that in security, the specification includes “and nothing else”
  - How do you test for that?!
- Two main strategies:
  - Try to make the program do unspecified things just by doing unusual (or attacker-like) things to it
  - Try to make the program do unspecified things by taking into account the design and the implementation

Black-box testing

- A test where you just have access to a completed object is a black-box test
    - This object might be a single function, a module, a program, or a complete system, depending on at what stage the testing is being done
- What kinds of things can you do to such an object to try to get it to misbehave?
- `int sum(int inputs[], int length)`

Fuzz testing

- One easy thing you can do in a black-box test is called fuzz testing

- Supply completely random data to the object
  - As input in an API
  - As a data file
  - As data received from the network
  - As UI events

- This causes programs to crash surprisingly often!
  - These crashes are violations of Availability, but are often indications of an even more serious vulnerability

White-box testing

- If you're testing conformance to a specification by taking into account knowledge of the design and implementation, that's white-box testing
  - Also called clear-box testing

Security controls—Documentation

- How can we control security vulnerabilities through the use of documentation?

- Write down the choices you made
  - And why you made them
- Just as importantly, write down things you tried that didn't work!
  - Let future developers learn from your mistakes
- Make checklists of things to be careful of

Security controls—Documentation

```
@Override
public boolean havePassword(int userId) throws RemoteException {
    // Do we need a permissions check here?
    return new File(getLockPasswordFilename(userId)).length() > 0;
}

@Override
public boolean havePattern(int userId) throws RemoteException {
    // Do we need a permissions check here?
    return new File(getLockPatternFilename(userId)).length() > 0;
}
```

Security controls—Maintenance

- By the time the program is out in the field, one hopes that there are no more security flaws
  - But there probably are
- We've talked about ways to control flaws when modifying programs
  - code review, testing, documentation
- Is there something we can use to try to limit the number of flaws that make it out to the shipped product in the first place?

Standards, process, and audit

- Within an organization, have rules about how things are done at each stage of the software lifecycle
- These rules should incorporate the controls we've talked about earlier
- These are the organization's standards
- For example:
  - What design methodologies will you use?
  - What kind of implementation diversity?
  - Which change management system?
  - What kind of code review?
  - What kind of testing?

Standards, process, and audit

- Make formal processes specifying how each of these standards should be implemented
  - For example, if you want to do a guided code review, who explains the code to whom? In what kind of forum? How much detail?
- Have audits, where somebody (usually external to the organization) comes in and verifies that you're following your processes properly
- This doesn't guarantee flaw-free code, of course!

Recap

- Flaws, faults, and failures
- Unintentional security flaws
- Malicious code: Malware
- Other malicious code
- Nonmalicious flaws
- Controls against security flaws in programs

Recap

- Various controls applicable to each of the stages in the software development lifecycle
- To get the best chance of controlling all of the flaws:
  - Standards describing the controls to be used
  - Processes implementing the standards
  - Audits ensuring adherence to the processes