Aalto University

Software security

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Outline

- Untrusted input
- SQL injection
- Buffer overrun
- Web vulnerabilities: CSRF, XSS
- Input validation

There is no one simple solution that would make programs secure. → A competent programmer must learn about all the things that can go wrong. This lecture is only a starting point.

Untrusted input

- User and network input is untrusted

- Does my software get input from the Internet?
  - Documents, streams, messages, photos may all be untrusted
  - All modern applications are Internet clients or servers
  - Intranet hosts, backend databases, office appliances etc. are directly or indirectly exposed to input from the Internet

→ All software must be able to handle malformed and malicious input safely

Example: format string vulnerability

- Vulnerable C code:

```
int process_text(const char *input){
  char buffer[1000];
  snprintf(buffer, 1000, input);
  ...
}
```

- User input in the format string:
  - Input "**%x%x%x%x%x…**" will print data from the memory
  - Input "**%s%s%s%s%s…**" will probably crash the program
  - Input "**ABC%n**" will write value 3 to somewhere in the memory

SQL INJECTION

SQL injection example

- SQL query:

```
SELECT * FROM users WHERE username = 'Alice';
```

- Code with embedded SQL:

```
"SELECT * FROM users WHERE username = '" + input + "';"
```

- Attacker sends input:

```
input = "Bob'; DROP TABLE users; --"
```

- The query evaluated by the SQL database:

```
SELECT * FROM users WHERE username = 'Bob';
  DROP TABLE users; --';
```

SQL injection example 2

- Application greets the user by first name:

```
"SELECT firstname FROM users WHERE username = '" + input + "';"
```

- Attacker enters username:

```
input = "nobody' UNION SELECT password FROM users WHERE username
= 'alice'; --"
```

- The query evaluated by the SQL database:

```
SELECT firstname FROM users WHERE username = 'nobody' UNION
SELECT password FROM users WHERE username = 'alice'; --';
```

- This is why we should always assume that the attacker can read the password database

Mitigating SQL injection

- Minimum privilege: set tables as read-only; run different services as different users
- Sanitize input: allow only the necessary characters and string formats – but it is hard to do correctly!
- Escape input strings with safe library functions, e.g.
  - mysql_real_escape_string() in PHP
  - MySQLdb.escape_string(), MySQLdb.execute(), sqlalchemy.text() in Python

Mitigating SQL injection

- Prepared statements and stored procedures: precompiled SQL queries that can be executed many times with different parameter values

Use these!

- Disable SQL error messages to normal users
  → harder to build exploits

Do not make this mistake

- Jonne heard prepared statements are good for security:

```
$stmt = $conn->prepare("SELECT * FROM users WHERE username
= '" + input + "';");
$stmt->execute();
```

- Why is this wrong?

Swedish parliamentary election 2010

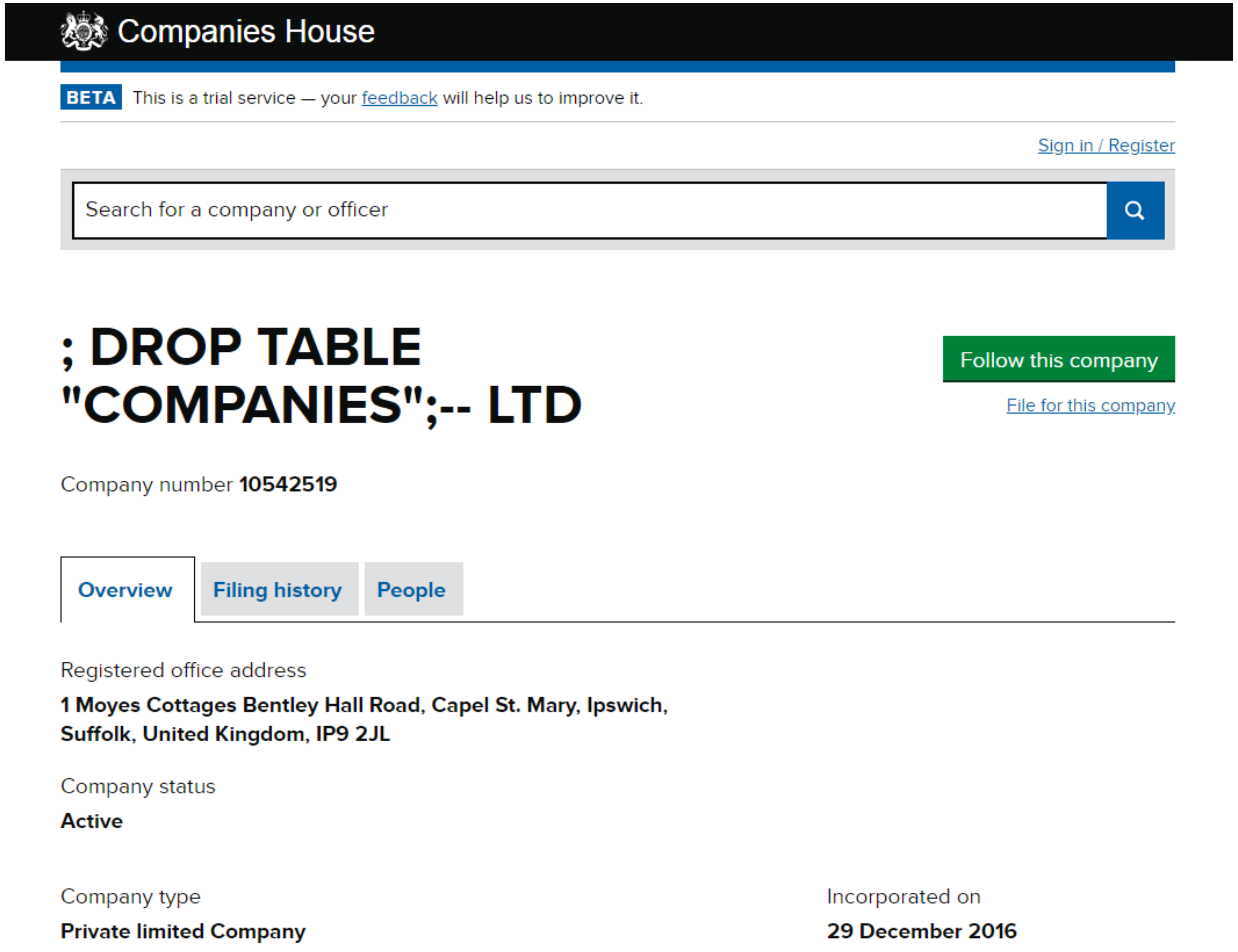
Some hand-written votes scanned by machine:

```
:Halmstads västra valkrets;0903;Söndrum 3;Feministiskt initiativ;3
:Halmstads västra valkrets;0903;Söndrum 3;Piratpartiet;1
:Halmstads västra valkrets;0903;Söndrum 3;Syndikalisterna;1
:Halmstads västra valkrets;0904;Söndrum 4;pwn DROP TABLE VALJ;1
:Halmstads västra valkrets;0904;Söndrum 4;pwn DROP TABLE VALJ;1
:Halmstads västra valkrets;0905;Söndrum 5;Feministiskt initiativ;1
:Halmstads västra valkrets;0906;Söndrum 6;Feministiskt initiativ;1
:Halmstads västra valkrets;1001;Holm-Vapnö;Raggarpartiet;1
:Halmstads västra valkrets;1001;Holm-Vapnö;Raggarpartiet;1
```

```
Centrum, Övre Johanneberg;Klassiskt liberala partiet;1
Centrum, Övre Johanneberg;Svenskarnas parti;1
Centrum, Övre Johanneberg;Ett fristående frisinnat parti med fokus på miljö
Centrum, Övre Johanneberg;(Script src=http://hittepa.webs.com/x.txt);1
Centrum, Landalabergen m fl;Tillit;1
Centrum, Landalabergen m fl;SPI;1
Centrum, Landalabergen m fl;TilliT;1
```

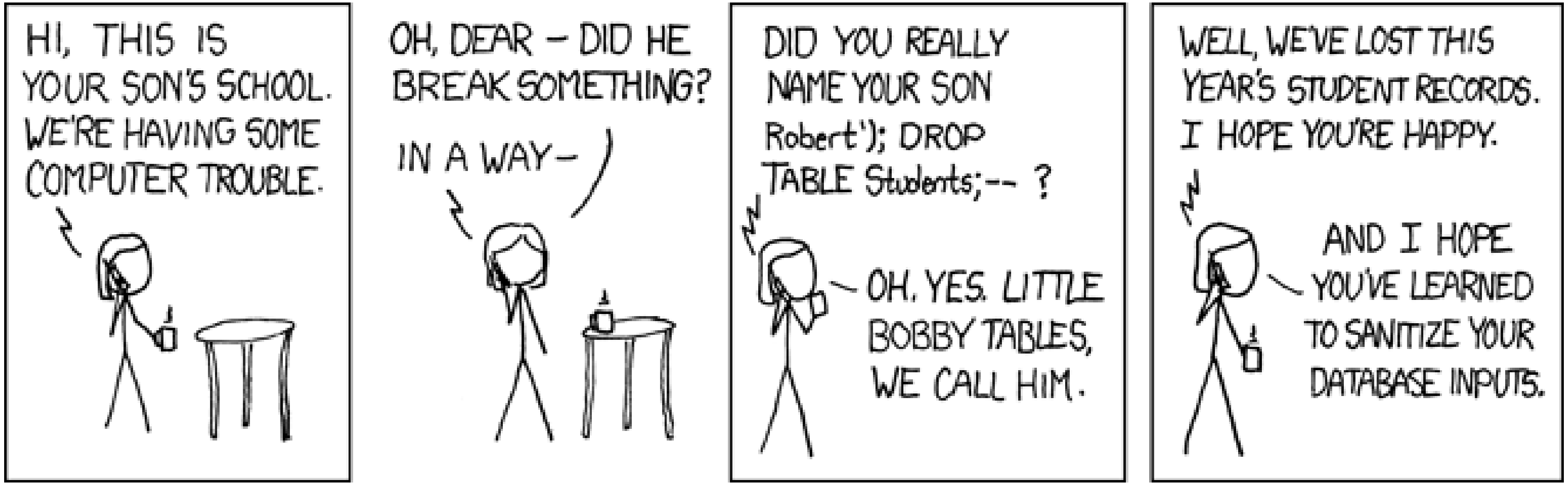
http://www.val.se/val/val2010/handskrivna/handskrivna.skv

List of UK Registered Companies



https://web.archive.org/web/20171107023155/https://beta.companieshouse.gov.uk/company/10542519

XKCD: Exploits of a Mom



https://xkcd.com/327/

BUFFER OVERRUN

Used to be the number one software security problem. Still common in embedded devices and the Internet of Things.

Buffer overrun

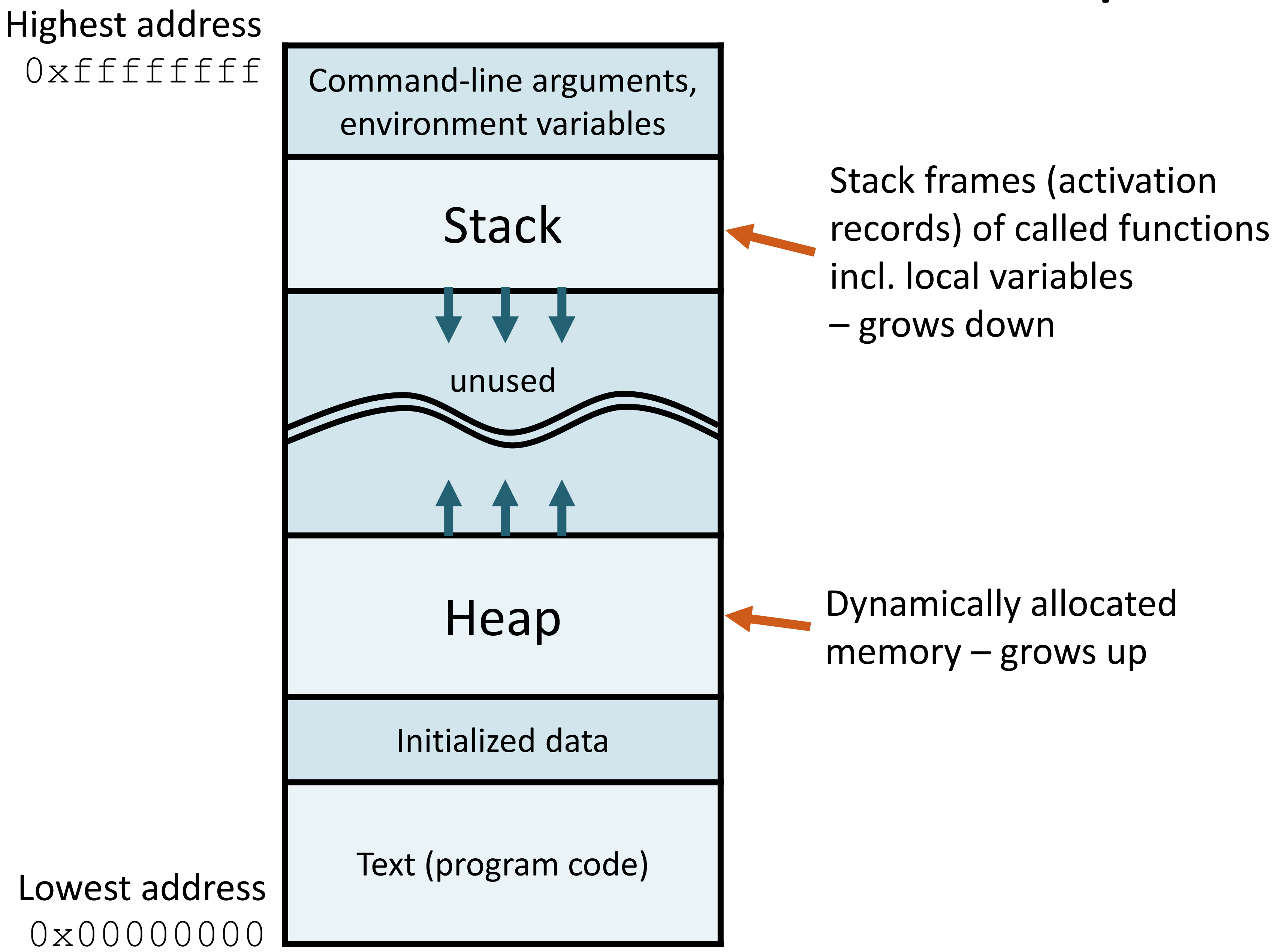
- Bug: failure to check for array boundary

```
#define MAXLEN 1000

char *process_input (char *input) {
  char buffer[MAXLEN];
  int i;
  for (i = 0; input[i] != 0; i++) {
    buffer[i] = input[i];
    ...
  }
```

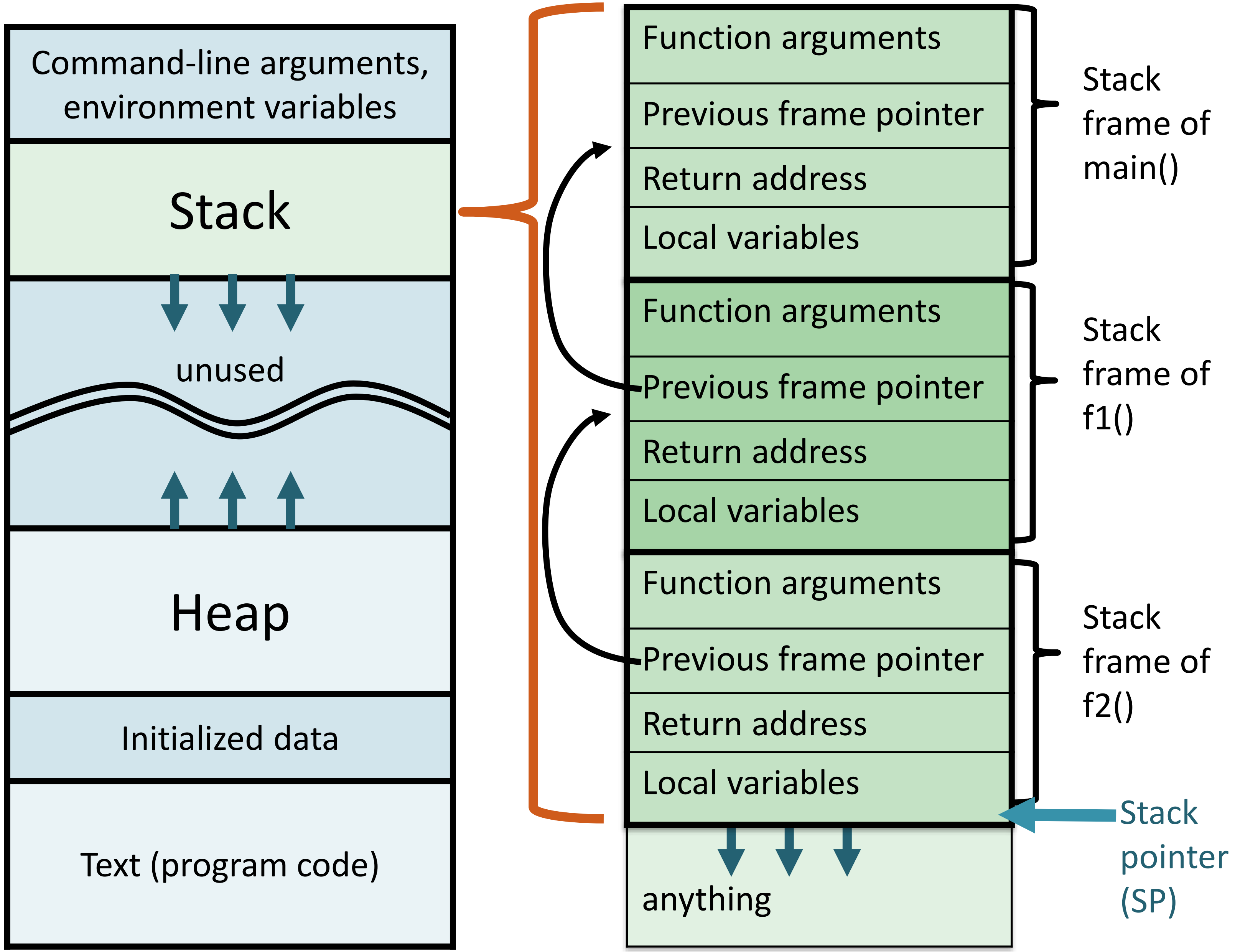
Loops until a null character found;
should check also for `i < MAXLEN`

Process virtual address space



Call stack (single-threaded program)

Details depend on processor architecture and programming language



Stack smashing

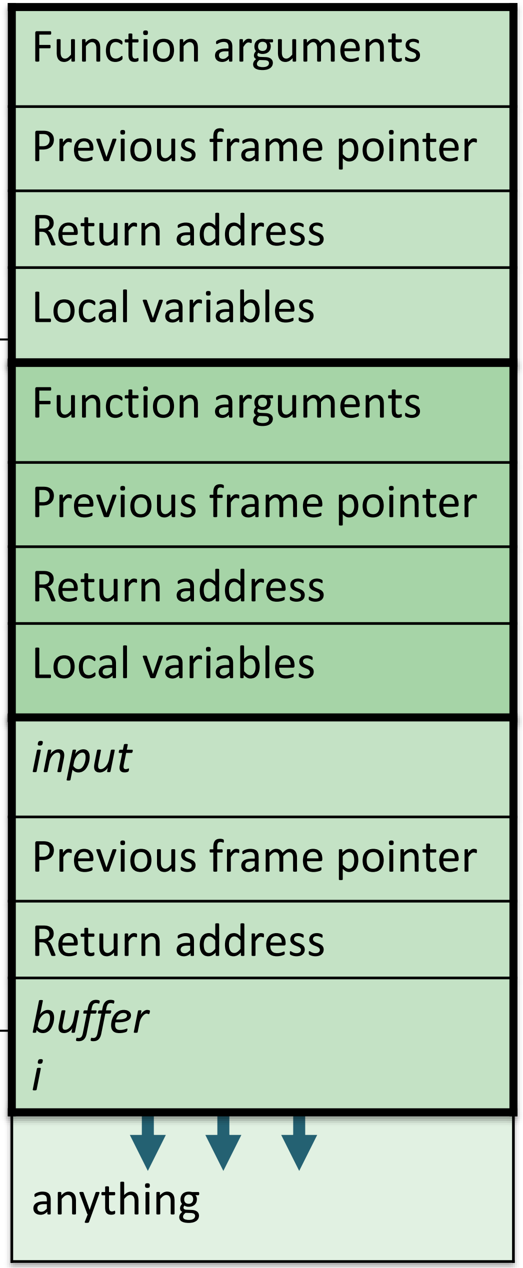
- Why are buffer overruns a security issue?

```
#define MAXLEN 1000

char *process_input (char *input) {
  char buffer[MAXLEN];
  int i;
  for (i = 0; input[i] != 0; i++) {
    buffer[i] = input[i];
    ...
  }
```

Loops until a null character found; should check also for **`i < MAXLEN`**

Call stack



Stack smashing

- Why are buffer overruns a security issue?

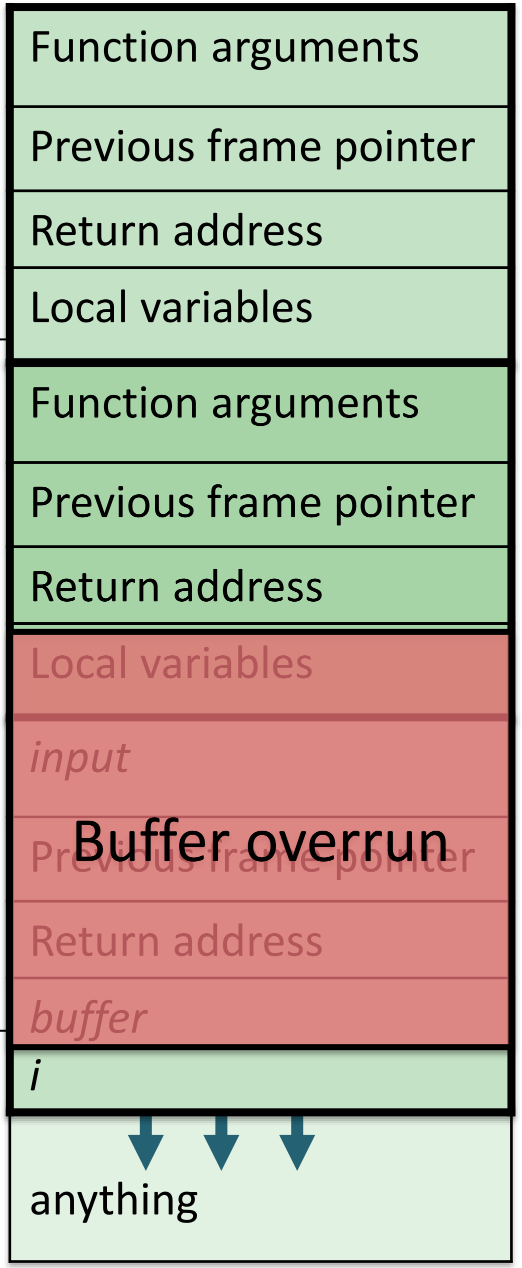
Too long input overwrites variables in the stack

```
#define MAXLEN 1000

char *process_input (char *input) {
  char buffer[MAXLEN];
  int i;
  for (i = 0; input[i] != 0; i++) {
    buffer[i] = input[i];
    ...
  }
```

Loops until a null character found; should check also for **`i < MAXLEN`**

Call stack



Malicious code execution

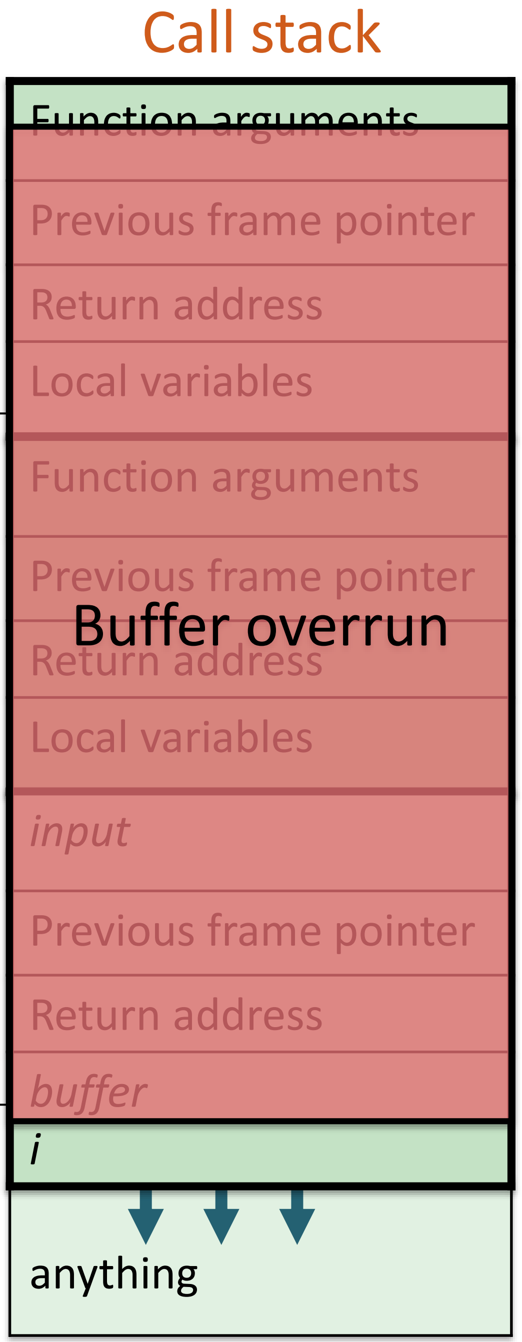
- Why are buffer overruns a security issue?

```
#define MAXLEN 1000

char *process_input (char *input) {
  char buffer[MAXLEN];
  int i;
  for (i = 0; input[i] != 0; i++) {
    buffer[i] = input[i];
    ...
  }
```

Loops until a null ch
should check also fo

Much too long input overwrites the function return address and previous stack frames



Malicious code execution

- Why are buffer overruns a security issue?

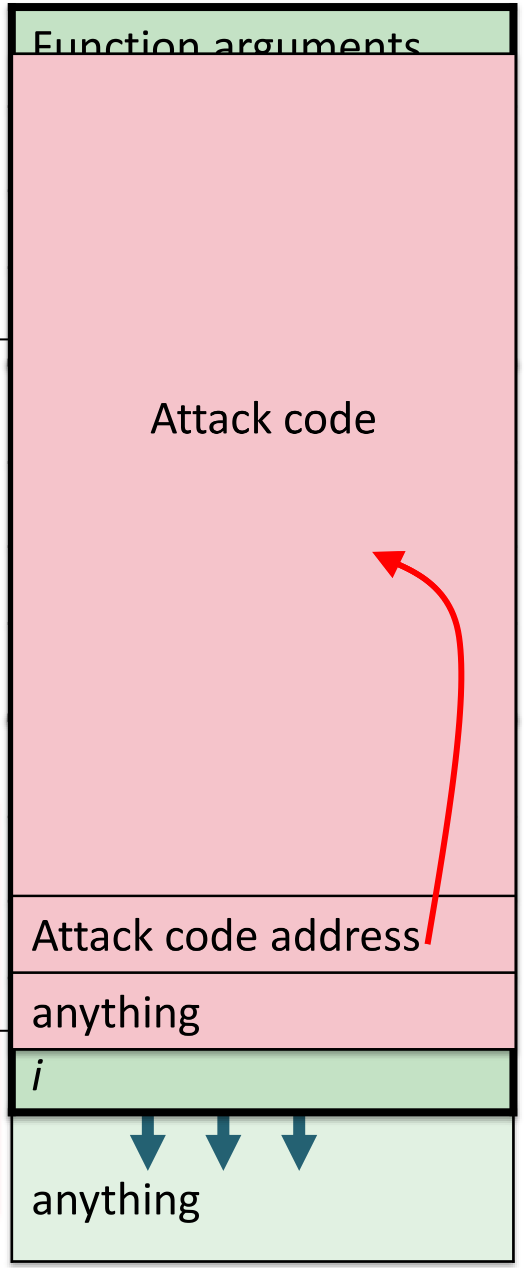
```
#define MAXLEN 1000

char *process_input (char *input) {
  char buffer[MAXLEN];
  int i;
  for (i = 0; input[i] != 0; i++) {
    buffer[i] = inp
    ...
  }
```

Loops until a null
should check als

When the function returns, execution will jump to the new return address, which points to attack code → malicious code execution with the process's permissions

Call stack



Buffer overruns

- Buffer overruns may cause
  - data modification → unstable program behavior
  - access violation “segmentation fault” → process crashing
  - malicious data modification
  - code injection → attacker gains full control of the process

Running exploit code

- How attacker gains control:
  - Stack overruns may overwrite function return address or exception handler address
  - Heap overruns may overwrite function pointer or virtual method table
- How difficult is writing an exploit?
  - Instructions and code widely available
  - There are people and companies actively developing exploits

Another example

- Vulnerabilities can be difficult to spot

```
#define BUFLEN 4

void vulnerable(void) {
  wchar_t buf[BUFLEN];
  int val;

  val = MultiByteToWideChar(
    CP_ACP, 0, "1234567", -1, buf, sizeof(buf));
  printf("%d\n", val);
}
```

Expected size of the destination buffer in wide characters , but sizeof gives bytes

Should calculate target buffer size as
`sizeof(buf)/sizeof(buf[0])`

[Code Red vulnerability, example thanks to Ulfar Erlingsson]

Buffer overrun prevention

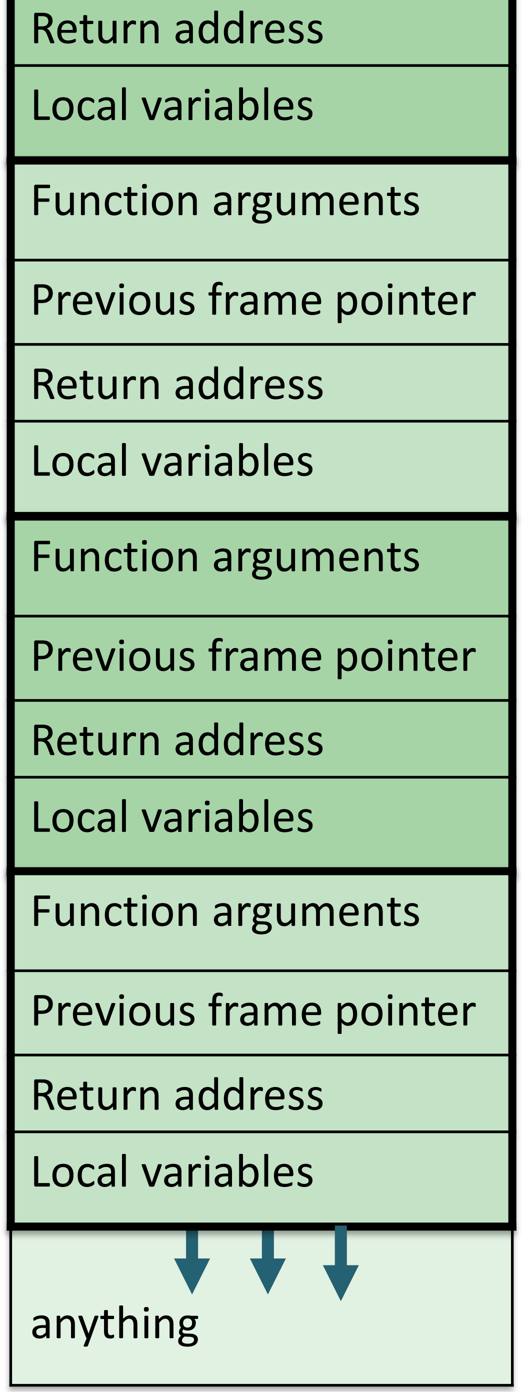
- Preventing buffer overruns:
  - Type-safe languages (e.g. Java, C#)
  - Programmer training, code reviews
  - Avoiding unsafe and difficult-to-use libraries: **`strcpy`**, **`gets`**, **`scanf`**, **`MultiByteToWideChar`**, etc.
  - Fuzz testing
  - Static code analysis, symbolic model checking: proving safety
- No reliable way to find all buffer overrun vulnerabilities → need to also mitigate consequences

Buffer overrun mitigation

- Stack canary
  - Store an unguessable value on the top of the stack frame in function prologue; check before returning
  - GCC -fstack-protector-all, Visual Studio /GS
- Non-executable (NX) bit
  - Set the stack and heap memory pages as non-executable
  - Breaks some code, e.g. JIT compilation
  - Often combined with memory layout randomization

Return to libc

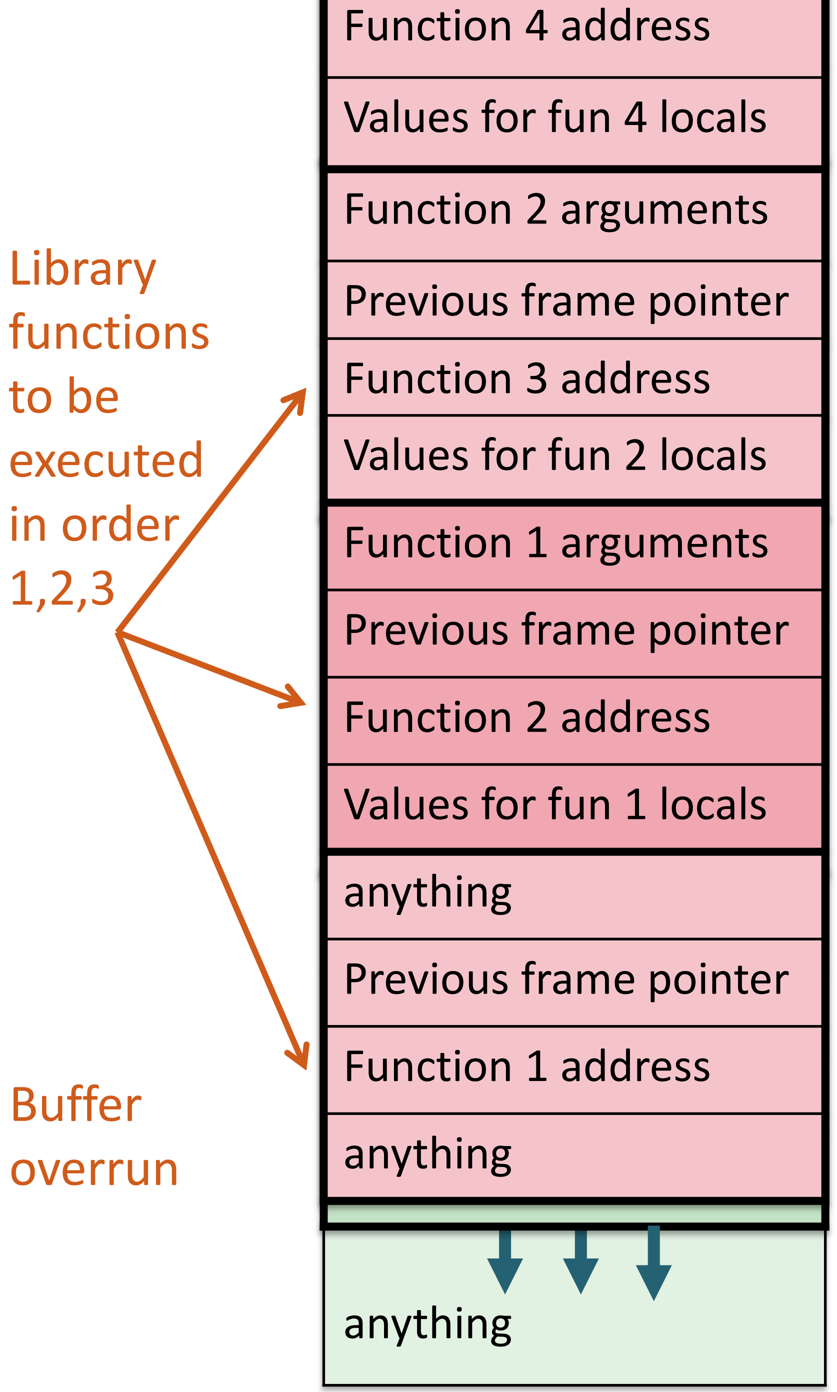
- NX prevents machine code insertion to stack
- However, there is another attack: return to libc, which uses existing executable code in the memory
  - e.g. standard library functions in libc



Extra material

Return to libc

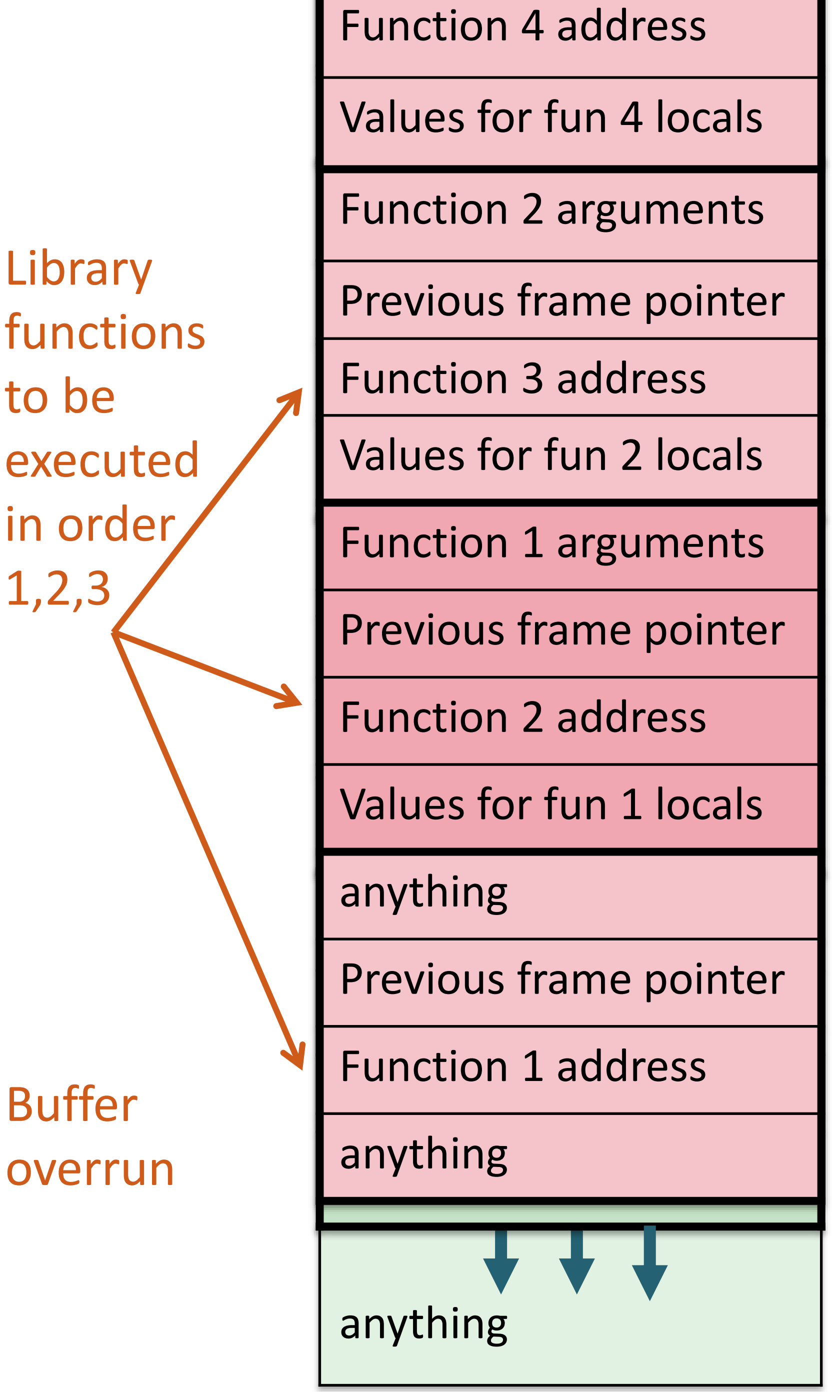
- When function returns, execution jumps to the return address in stack
  - Point the return addresses to the beginnings of library (libc) functions
  - Set arguments as desired
- Typical exploit creates an executable page, copies attack code there, and runs it



Extra material

Return to libc

- Solution: combine NX with memory layout randomization
  - Load libc and other library code at a random memory offset → attacker does not know where to jump
- New solutions:
  e.g. Windows control flow guard



Extra material

Integer overflow

- Integers in programming languages are not ideal mathematical integers
- Integer overflow can cause buffer overrun

Vulnerable code:

```
nBytes = (nBits + 7) >> 3;
if (nBytes <= bufferSize)
  copyBits(input, buffer, nBits);
```

Attacker input:

```
nBits = UINT_MAX
```

Evaluation

```
nBytes = (UINT_MAX + 7) >> 3
→ 6 >> 3 → 0

nBytes <= bufferSize
→ (0 <= bufferSize) → 1
```

WEB VULNERABILITIES: CSRF, XSS

Cross-site request forgery (CSRF)

- Fictional example:
  - Users on *social.net* stay logged in with a session cookie
  - JavaScript on Bob's web page *bobs.org*:

```
<script type="text/javascript">
frames['hidden'].window.location =
'http://social.net/AddFriend.php?name=Bob';
</script>
```

- Why possible? Interaction between web sites is usually prevented by the same origin policy. However, web links and HTTP GET and POST redirection to another site is allowed.

Preventing CSRF

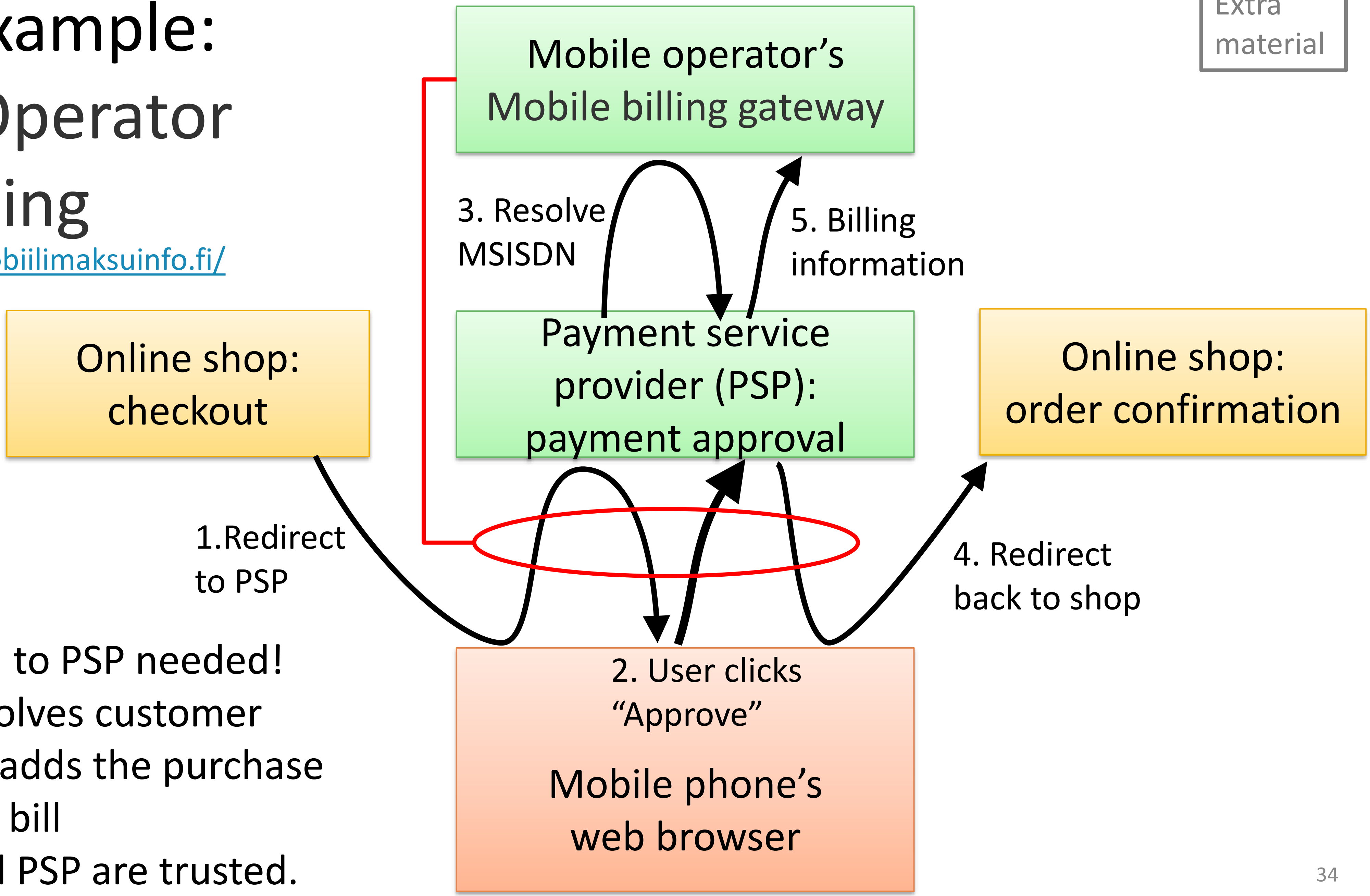
- Server checks Referer (sic) field in HTTP requests
- CSRF token i.e. secret session identifier in all GET URLs or POST payloads; attacker would need to guess it

Modern web application frameworks prevent CSRF with good session management (including CSRF token)

Extra material

CSRF example: Direct Operator Billing

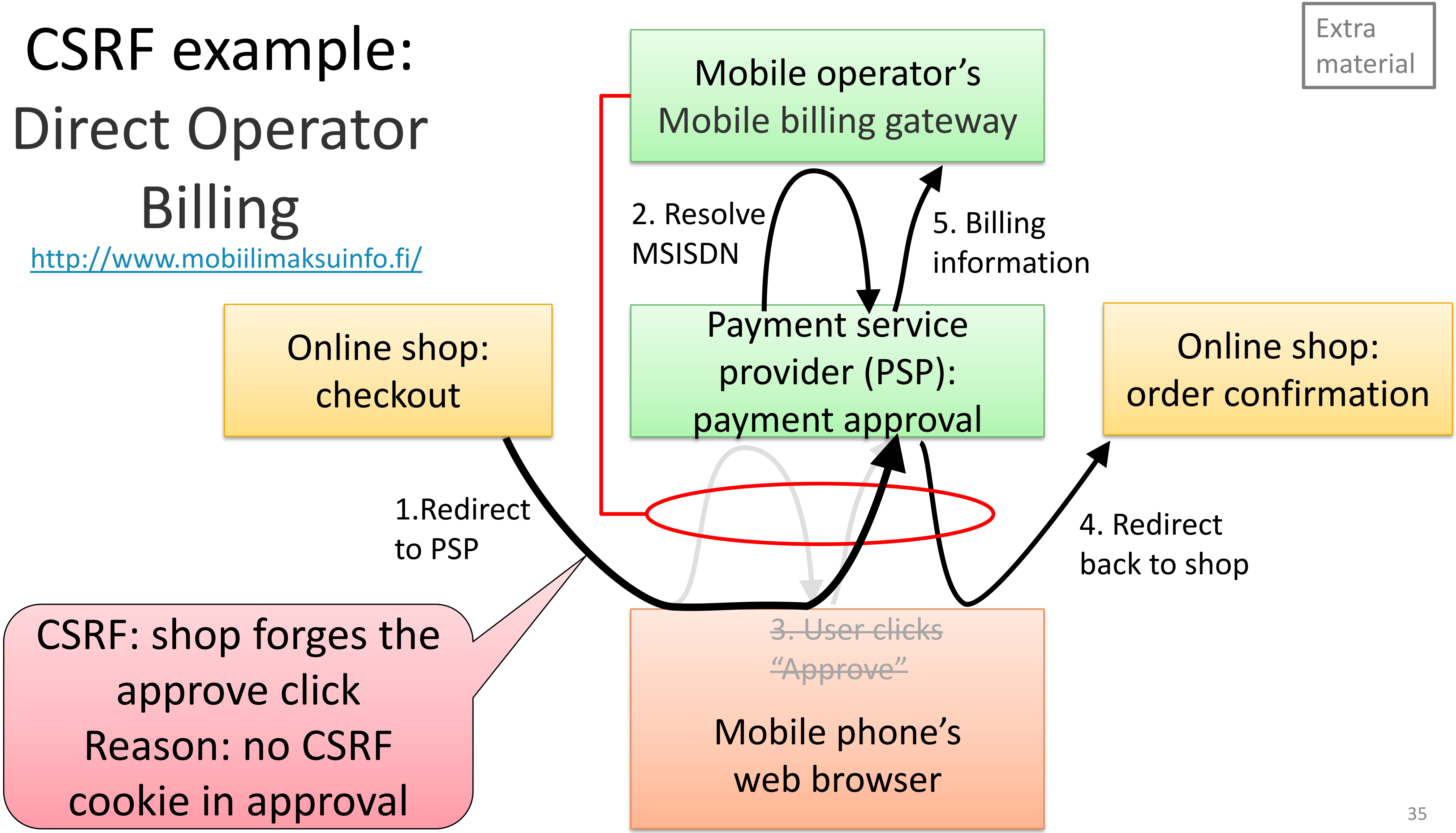
http://www.mobiilimaksuinfo.fi/



- No user login to PSP needed! Operator resolves customer MSISDN and adds the purchase to the phone bill
- Operator and PSP are trusted.

CSRF example: Direct Operator Billing

http://www.mobiilimaksuinfo.fi/



Cross-site scripting (XSS)

- User-posted content on web sites may contain malicious JavaScript
- Fictional example:
  – Social.net allows users to post comments. Bob’s comment:

```
<b onmouseover="$.get('
http://social.net/AddFriend.php?name=Bob′);">
Be my friend!<b>
```

  – Another user reads the blog and moves mouse over the text
- This is stored XSS: malicious script stored on the server

Reflected XSS

- PHP code on a web server:

```
<html><body><?php
print "Page not found: ". urldecode($_SERVER["REQUEST_URI"]);
?></body></html>
```

- Typical output: `Page not found: /foo.html`

- Bob tricks Alice to follow this URL-encoded link:

```
http://social.net/%3Cscript%3E%3D%22%24.get%28%27http%3A%2F%2Fsoci
al.net%2FAddFriend.php%3Fname%3DBob%E2%80%99%29%3B%3C%2Fscript%3E
```

- The error page on social.net will contain this:

```
Page not found: /<script>="$.get('http://social.net/AddFriend.php
?name=Bob');</script>
```

- This is reflected XSS: malicious script sent via the server but not stored there

Preventing XSS on web servers

- Browsers try to detect XSS, but they are not perfect. A lot still depends on the web application programmer

- Avoid embedding input into output; generate the output from scratch when possible
- Filter <tags>, Javascript or all angled brackets from user-posted content
- When you need to embed untrusted data into a web page, encode it first as HTML entities
- Do not embed untrusted data into <script>, <style>, URL, tag attributes or other unusual places
- Content Security Policy (CSP) allows web servers to declare in response headers what types of active content the response may contain, e.g. to exclude scripts

What is untrusted input to web server?

- Inputs that may contain XSS or other malicious content:
  - Input from web client or user, or REST API client
  - Data read from database
  - Messages between servers
- Should escape or validate all these inputs

INPUT VALIDATION

Example: File path vulnerability

Vulnerable code:

```
char docRoot[] = "/usr/www/";
char fileName[109];
strncpy(fileName, docRoot, 9);
strncpy(fileName+9, input, 100);
file = fopen(fileName, "r");
// Next, send file to client
```

User input:

```
input =
"../../etc/passwd"
```

- The same file path has many representations → use the realpath(3) function to obtain the canonical representation
- Online services should be executed in a sandbox to limit their access: chroot(2), virtual machine or container

Sanitizing input

- Sanitizing input is not easy
- Escape sequences enable many encodings for the same character and string:
  - URL escapes: `%2e%2e%2f2e%2e%2f` = `../../`
  - HTML entities:

    `<SCRIPT>` =<SCRIPT>
- Not sufficient to filter out `..` or `<`

SUMMARY

Why security failures?

- Why does software have security failures?
  - Greedy business sells dangerous products?
  - Lack of professional pride and ethics?

- Software is specified with use cases that describe the desired functionality. Security is about undesired functionality

- Market forces and software development practices encourage releasing a minimum viable product (MVP) – security not included

- Threats and attacks evolve. Software security is never ready

Other types of security bugs

- Injection of untrusted input into the command line, JavaScript, HTML, XML, format string, file path etc.
- Logical errors, e.g. time of check—time of use, use after free
- Integer overruns or signed/unsigned confusion
- Crypto mistakes, bad random numbers
- Insecure direct references
- Most software bugs first seem harmless but eventually someone figures out how to build an exploit

How to produce secure code?

- Programming:
  - Learn about bugs and vulnerabilities by example
  - Adopt secure coding guidelines
  - Use safe languages, libraries and tools
  - Code reviews, static checkers
  - Fuzz testing, penetration testing
- Software process:
  - Threat modelling
  - Define security requirements
  - Define quality assurance process

Security principles

- Keep it simple
- Minimize attack surface
- Sanitize input and output
- Least privilege
- Defense in depth
- Isolation
- Secure defaults
- Secure failure modes
- Separation of duties
- No security through obscurity
- Fix even potential bugs

List of key concepts

- Untrusted input, input validation or sanitization
- Buffer overrun call stack, heap, stack frame, malicious code execution, integer overrun, safe language, stack cookies, NX bit, return to libc, memory layout randomization
- SQL injection, code injection, stored procedure or prepared statement, escaping,
- Same-origin policy, cross-site request forgery CSRF, Referer, CSRF token, cross-site scripting XSS
- Input validation, canonical form, isolation
- Fuzz testing, penetration testing

Reading material

- Dieter Gollmann: Computer Security, 2nd ed. chapter 14; 3rd ed. Chapters 10, 18, 20.5–20.6
- Stallings and Brown: Computer security, principles and practice, 4th ed., chapter 10-11
- Michael Howard and David LeBlanc, Writing Secure Code, 2nd ed.
- Online:
  - Top 25 Most Dangerous Software Errors, http://cwe.mitre.org/top25/
  - SQL Injection Attacks by Example, http://unixwiz.net/techtips/sql-injection.html
  - OWASP, https://www.owasp.org/, see especially Top Ten
  - CERT Secure Coding Standards, https://www.securecoding.cert.org/confluence/display/seccode/SEI+CERT+Coding+Standards
  - Aleph One, Smashing The Stack For Fun And Profit (classic paper) http://inst.eecs.berkeley.edu/~cs161/fa08/papers/stack_smashing.pdf

Exercises

- Find examples of actual security flaws in different categories. Try to understand how they can or have been exploited.
- Which features in code may indicate poor quality and potential security vulnerabilities?
- When you find a security vulnerability, it is worth the trouble to write an exploit to prove how serious it is?
- How can error messages help an attacker?
- Buffer overrun in a type-safe language like Java will raise an exception. Problem solved — or can there still be a security issue?
- What is insecure direct object reference? Find some examples.
- What security bugs can occur in concurrent systems, e.g. multiple web servers that use one shared database?
- Find out what carefully designed string sanitization functions, such as *mysql_real_escape_string* or the OWASP Enterprise Security API, actually do.